PUBLIC CORRESPONDENCE

The following is public correspondence received by the City Clerk's Office after the posting of the original agenda. Individual contact information has been redacted for privacy. This may *not* be a comprehensive collection of the public correspondence, but staff makes its best effort to include all correspondence received to date.

To send correspondence to the City Council, on matters listed on the agenda please email PublicComment@losaltosca.gov

From:	Peter Gise
To:	Public Comment
Subject:	Wireless Ordinance
Date:	Monday, May 9, 2022 2:35:57 PM

Dear Mayor and Council Members,

We would like to request that Council create a 3-tier preference element in the wireless ordinance (Most preferred, less preferred, and least preferred) as presented in the council meeting on 4/12/22. San Diego County first came up with the tiered order of preference 20 years ago so that industry would go to industrial zones first, and residential last. The County of San Diego had 4 different tiers. They pioneered this order of preference for the entire country because when Sprint sued County of San Diego, San Diego defended their right to suggest an order of preference for telecom coming into their communities. This case went all the way to the U.S. Supreme Court and was upheld. Therefore, this tiered order preference has been challenged to the highest court in the land and upheld.

We are only asking for 3 tiers. We would like to have residential and schools including daycare centers in the third and most protected tier. We are writing to you as a voice for the children, including very little ones in daycare/preschool facilities where escape in the midst of the fire is going to be more difficult and potentially deadly.

We have been advised by a Fire Consultant that cell tower fires are electrical fires, and they cannot be extinguished conventionally. First the power has to be cut and then someone from PG&E has to arrive on scene before the firefighters can fight the fire through conventional means. Otherwise, anyone attempting to extinguish the fire will be electrocuted. Because of this unique fire risk and the need for escape, we are asking for more time to escape for certain groups of people. Anyone caring for babies or young children in the daycare setting should be allowed to have this extra time & space for escape, as should a classroom full of children of any age, and the same for residential. We have residents in Los Altos who have special needs in a variety of ways from the wheelchair-bound with ALS, to those walking with walkers, and some residents with cognitive decline who are going to need assistance.

The recent fires have been a lesson in which many cities understand how important having a 3-tier order of preference would be to ensure public safety. Having the additional tier will limit fire exposure and provide time for residents to be able to escape safely. Please make public safety a top priority and return it to the 3 tiers of preferences.

Sincerely,

Dr. Peter Gise

Susan Gise

1540 Oak Ave

Los Altos CA 94024

From: Jane Osborn
To: arodriquez@losaltosca.gov; Public Comment
Cc: Jane Osborn; Jonathan Shores
Subject: Fw: Public Comment, Agenda Item #9, May 10, 2022, Wireless Facilities Ordinance
Date: Monday, May 9, 2022 3:14:25 PM

Dear Angel,

I am re-sending the email I sent last night, but adding the public comment address, in case it would be more likely to reach your attention. In retrospect, I should have included the public comment address in my email I sent last night.   I wanted to clarify that the email below is a *re*-edited version of a previously edited version I sent on Sunday April 10, 2022.   I had previously edited a version I had sent for a PC meeting in March 2022, in order to add some more references. It was this version that I did not find in the public correspondence for the Council Meeting held on April 12th, even though I had sent it on Sunday April 10th. The email below has the same content as that previous email, but is shorter. Primarily I had thought the references might be useful to some people in the public who might be new to this issue. Thank you again.

Best Regards,
Jane Osborn, Los Altos Resident

----- Forwarded Message -----
From: Jane Osborn [redacted]
To: arodriquez@losaltosca.gov <arodriquez@losaltosca.gov>
Cc: Jane Osborn [redacted] Jonathan Shores [redacted]>
Sent: Sunday, May 8, 2022, 11:54:46 PM PDT
Subject: Public Comment, Agenda Item #9, May 10, 2022, Wireless Facilities Ordinance

Dear Angel,

Below is an edited version of an email I sent on Sunday April 10, 2022, as a "public Comment," for the Council Meeting that was held on April 12, 2022, (in regard to Item #6, Wireless Facilities Ordinance). I did not see it included in the public correspondence for that meeting.

If possible, could you please include the email below as part of the public correspondence for the upcoming City Council Meeting being held on May 10th, 2022, for Agenda Item #9. Thank you very much.

With regards,
Jane Osborn

----- Forwarded Message -----
From: Jane Osborn [redacted]
To: PublicComments@losaltosca.gov <publiccomments@losaltosca.gov>; City Council <council@losaltosca.gov>
Cc: Jonathan Shores [redacted] Jane Osborn <[redacted]
Planning Services <planning@losaltosca.gov>

Sent: Sunday, April 10, 2022, 7:14:58 PM PDT
Subject: Public Comment, Agenda Item #6, April 12, 2022, Wireless Facilities Ordinance

This is an edited, expanded version of a letter that was sent to the Planning Commission on March 17th, 2022.

Dear Honorable Mayor, Vice Mayor and Council Members,

Jon and I are very aware that section 704 of the incredibly outdated Telecommunications Act of 1996 prohibits cities from denying a wireless carrier's request to place small cell facilities in the city. based on health concerns related to Rf emissions.

In spite of this, we believe it is of value for people to know about potential and suspected biological and health concerns that have been raised by numerous scientists and physicians, based on well-designed research, and reported in peer reviewed literature. In addition, we feel that residents should not be discouraged from raising or expressing these concerns, which in our opinion usually are reasonable. We believe it helps for city officials to be aware of the perspectives of a large number of residents--in other words, to know "where they are coming from."

Our impressions are based on having reviewed at least a portion of the growing body of scientific literature (and videos) on this topic, particularly on Jon's part, over a period of several years. We both have a background in science, including life-sciences/biological science, so this topic has been of great interest to us. Jon in particular has a significant background in science, especially life sciences, but also in areas such as physics and chemistry.

There are numerous resources we could recommend. However, we realize you all have many demands on your time, so I would like to recommend one resource in particular, which is a presentation given by **Joel Moskowitz, PhD, Director, Center for Family and Community Health, School of Public Health, U.C. Berkeley.** He gave this presentation on February 27, 2019. The link below is for the slides he used in his presentation. They provide a quick overview of some of the issues that are related to wireless technology, including suspected biological and health effects..

The topic of Dr. Moskowitz's presentation is: Cell Phones, Cell Towers, and Wireless Safety:

https://uhs.berkeley.edu/sites/default/files/cellphonescelltowerswirelesssafety.pdf

Jon and I may be somewhat biased, but we believe most people consider U.C. Berkeley to be a reputable source for scientific, technological and medical information, including research findings.

In his concluding remarks, Dr. Moskowitz makes this statement:

" We are guinea pigs in a massive technological experiment that threatens our health. Our government needs to determine what constitutes a safe level of long term exposure to wireless radiation and strengthen the FCC's radio frequency exposure guidelines. In the meantime, the government should impose a moratorium on technologies that increase our exposure to wireless radiation, especially new forms of wireless radiation

like 5G cellphone radiation."

Additional Resources Compiled by Joel Moskowitz, PhD., U.C. Berkeley School of Public Health:

https://www.saferemr.com/2016/08/key-cell-phone-radiation-research.html (Updated April 1, 2022; Joel Moskowitz, Ph.D.)

Key Cell Phone Radiation Research Studies (Updated November 1, 2021; Joel Moskowitz, Ph.D.)

These resources provide a compilation of links to videos, papers, presentations, overviews, and literature reviews of scientific research findings, focusing primarily on the possible biological and health effects of wireless technology, including Rf radiation exposure.

The following websites also are highly recommended as a resource for people interested in researching some of the literature related to possible effects of wireless technology, including peer reviewed studies reported in respected scientific and medical journals:

https://mdsafetech.org/cell-tower-health-effects/ (Physicians for Safe Technology)

https://www.americansforresponsibletech.org/scientific-studies (Americans for Responsible Technology)

These websites are well organized into topics and categories, and you can scroll through and select links to articles that are of particular interest. Also. they appear to be frequently updated.

Hopefully you will have time to check out some of these resources, and get a sense for what is available in a significant body of scientific literature, based on research, with regard to possible biological and health effects of wireless technology.

Thank you very much for your time and consideration.

Respectfully,
Jane Osborn and Jonathan Shores
Los Altos Residents

E. Jane Osborn, Ph.D. Nationally Certified School Psychologist, [redacted] Licensed Educational Psychologist, [redacted] Cognitive and Developmental Psychology. [redacted]

From:	Couture, Terri
To:	City Council; Public Comment
Cc:	Andrea Chelemengos
Subject:	City council members Agenda item 9 Tuesday May 10 meeting
Date:	Monday, May 9, 2022 3:37:14 PM
Attachments:	05092022145216-0001.pdf

Wire Fraud is Real. Before wiring any money, call the intended recipient at a number you know is valid to confirm the instructions. Additionally, please note that the sender does not have authority to bind a party to a real estate contract via written or verbal communication.

Dear Mayor and Councilmembers,

I would like to request that Council create a 3-tier preference element in the wireless ordinance (Most preferred, less preferred, and least preferred) as presented in the council meeting on 4/12/22. San Diego County first came up with the tiered order of preference 20 years ago so that industry would go to industrial zones first, and residential last. The County of San Diego had 4 different tiers. They pioneered this order of preference for the entire country because when Sprint sued County of San Diego, San Diego defended their right to suggest an order of preference for telecom coming into their communities. This case went all the way to the U.S. Supreme Court and was upheld. Therefore, this tiered order preference has been challenged to the highest court in the land and upheld.

We are only asking for 3 tiers. We would like to have residential and schools including daycare centers in the third and most protected tier. We are writing to you as a voice for the children, including very little ones in daycare/preschool facilities where escape in the midst of the fire is going to be more difficult and potentially deadly.

We have been advised by a Fire Consultant that cell tower fires are electrical fires, and they cannot be extinguished conventionally. First the power has to be cut and then someone from PG&E has to arrive on scene before the firefighters can fight the fire through conventional means. Otherwise, anyone attempting to extinguish the fire will be electrocuted. Because of this unique fire risk and the need for escape, we are asking for more time to escape for certain groups of people. Anyone caring for babies or young children in the daycare setting should be allowed to have this extra time & space for escape, as should a classroom full of children of any age, and the same for residential. We have residents in Los Altos who have special needs in a variety of ways from the wheelchair-bound with ALS, to those walking with walkers, and some residents with cognitive decline who are going to need assistance.

The recent fires have been a lesson in which many cities understand how important having a 3-tier order of preference would be to ensure public safety. Having the additional tier will limit fire exposure and provide time for residents to be able to escape safely. Please make public safety a top priority and return it to the 3 tiers of preferences.

Sincerely,

Fred Tuerk + Terri Couture

From: Kerry Lindell
To: Anita Enander; City Council; Public Comment
Subject: 3-Tier Fire Escape Wireless Ordinance
Date: Monday, May 9, 2022 8:42:33 PM

Dear Mayor and Council Members,

I would like to request that the Los Altos City Council create a 3-tier preference element in the wireless ordinance (Most preferred, less preferred, and least preferred) as presented in the council meeting on 4/12/22. San Diego County first came up with the tiered order of preference 20 years ago so that industry would go to industrial zones first, and residential last. The County of San Diego had 4 different tiers. They pioneered this order of preference for the entire country because when Sprint sued County of San Diego, San Diego defended their right to suggest an order of preference for telecom coming into their communities. This case went all the way to the U.S. Supreme Court and was upheld. Therefore, this tiered order preference has been challenged to the highest court in the land and upheld.

I am only asking for 3 tiers. I would like to have residential and schools including daycare centers in the third and most protected tier. I am writing to you as a voice for the children, including very little ones in daycare/preschool facilities where escape in the midst of the fire is going to be more difficult and potentially deadly.

Fire Consultants have advised that cell tower fires are electrical fires, and they cannot be extinguished conventionally. First the power has to be cut and then someone from PG&E has to arrive on scene before the firefighters can fight the fire through conventional means. Otherwise, anyone attempting to extinguish the fire will be electrocuted. Because of this unique fire risk and the need for escape, we are asking for more time to escape for certain groups of people. Anyone caring for babies or young children in the daycare setting should be allowed to have this extra time & space for escape, as should a classroom full of children of any age, and the same for residential. Los Altos has resi
dents who have special needs in a variety of ways from the wheelchair-bound with ALS, to those walking with walkers, and some residents with cognitive decline and dementia who are going to need assistance.

The recent fires have been a lesson in which many cities understand how important having a 3-tier order of preference would be to ensure public safety. Having the additional tier will limit fire exposure and provide time for residents to be able to escape safely. Please make public safety a top priority and return it to the 3 tiers of preferences.

In appreciation for making a firm stance in a positive direction to keep our residents safe,

Dr. Kerry Lindell
(Los Altos resident and Small Business Owner)

From:	ana pareja
To:	City Council; Public Comment
Subject:	Wireless Ordinance: Fire Escape 3-Tiers
Date:	Monday, May 9, 2022 8:46:19 PM

Dear Mayor and Councilmembers,

I would like to request that Council create a 3-tier preference element in the wireless ordinance :

1 - Most preferred
2- less preferred
3- least preferred

This was presented in the council meeting on 4/12/22. San Diego County first came up with the tiered order of preference 20 years ago so that industry would go to industrial zones first, and residential last. The County of San Diego had 4 different tiers. They pioneered this order of preference for the entire country because when Sprint sued County of San Diego, San Diego defended their right to suggest an order of preference for telecom coming into their communities. This case went all the way to the U.S. Supreme Court and was upheld. Therefore, this tiered order preference has been challenged to the highest court in the land and upheld.

We are only asking for 3 tiers. We would like to have residential and schools including daycare centers in the third and most protected tier. We are writing to you as a voice for the children, including very little ones in daycare/preschool facilities where escape in the midst of the fire is going to be more difficult and potentially deadly.

We have been advised by a Fire Consultant that cell tower fires are electrical fires, and they cannot be extinguished conventionally. First the power has to be cut and then someone from PG&E has to arrive on scene before the firefighters can fight the fire through conventional means. Otherwise, anyone attempting to extinguish the fire will be electrocuted. Because of this unique fire risk and the need for escape, we are asking for more time to escape for certain groups of people. Anyone caring for babies or young children in the daycare setting should be allowed to have this extra time & space for escape, as should a classroom full of children of any age, and the same for residential. We have residents in Los Altos who have special needs in a variety of ways from the wheelchair-bound with ALS, to those walking with walkers, and some residents with cognitive decline who are going to need assistance.
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The recent fires have been a lesson in which many cities understand how important having a 3-tier order of preference would be to ensure public safety. Having the additional tier will limit fire exposure and provide time for residents to be able to escape safely. Please make public safety a top priority and return it to the 3 tiers of preferences.

Sincerely,

Ana Pareja

From: [redacted]
To: City Council; Public Comment
Subject: Wireless Ordinance: Fire Escape 3-Tiers
Date: Tuesday, May 10, 2022 9:38:49 AM

Dear Mayor and Councilmembers,

I would like to request that Council create a 3-tier preference element in the wireless ordinance (Most preferred, less preferred, and least preferred) as presented in the council meeting on 4/12/22. San Diego County first came up with the tiered order of preference 20 years ago so that industry would go to industrial zones first, and residential last. The County of San Diego had 4 different tiers. They pioneered this order of preference for the entire country because when Sprint sued County of San Diego, San Diego defended their right to suggest an order of preference for telecom coming into their communities. This case went all the way to the U.S. Supreme Court and was upheld. Therefore, this tiered order preference has been challenged to the highest court in the land and upheld.

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We have been advised by a Fire Consultant that cell tower fires are electrical fires, and they cannot be extinguished conventionally. First the power has to be cut and then someone from PG&E has to arrive on scene before the firefighters can fight the fire through conventional means. Otherwise, anyone attempting to extinguish the fire will be electrocuted. Because of this unique fire risk and the need for escape, we are asking for more time to escape for certain groups of people. Anyone caring for babies or young children in the daycare setting should be allowed to have this extra time & space for escape, as should a classroom full of children of any age, and the same for residential. We have residents in Los Altos who have special needs in a variety of ways from the wheelchair-bound with ALS, to those walking with walkers, and some residents with cognitive decline who are going to need assistance.

The recent fires have been a lesson in which many cities understand how important having a 3-tier order of preference would be to ensure public safety. Having the additional tier will limit fire exposure and provide time for residents to be able to escape safely. Please make public safety a top priority and return it to the 3 tiers of preferences.

Sincerely,

Nancy Colace

From: Karen Haberstock
To: City Council; Public Comment
Subject: Wireless Ordinance: Fire Escape 3-Tiers
Date: Tuesday, May 10, 2022 1:27:36 PM

Dear Mayor and Councilmembers,

I would like to request that Council create a 3-tier preference element in the wireless ordinance (Most preferred, less preferred, and least preferred) as presented in the council meeting on 4/12/22. San Diego County first came up with the tiered order of preference 20 years ago so that industry would go to industrial zones first, and residential last. The County of San Diego had 4 different tiers. They pioneered this order of preference for the entire country because when Sprint sued County of San Diego, San Diego defended their right to suggest an order of preference for telecom coming into their communities. This case went all the way to the U.S. Supreme Court and was upheld. Therefore, this tiered order preference has been challenged to the highest court in the land and upheld.

I am asking for 3 tiers. Residential areas and schools, including daycare centers, should be included in the third and most protected tier. I am writing to you as a voice for the children, including very little ones in daycare/preschool facilities where escape amid a fire is going to be more difficult and potentially deadly.

A Fire Consultant has advised that cell tower fires are electrical fires, and they cannot be extinguished conventionally. First, the power must be cut and then someone from PG&E must arrive on scene before the firefighters can fight the fire through conventional means. Otherwise, anyone attempting to extinguish the fire will be electrocuted. Because of this unique fire risk and the need for escape, I am asking for more time to escape for certain groups of people. Anyone caring for babies or young children in the daycare setting should be allowed to have this extra time & space for escape, as should a classroom full of children of any age, and the same for residential. There are residents in Los Altos who have special needs in a variety of ways, from the wheelchair-bound with ALS to those walking with walkers and some residents with cognitive decline, who are going to need assistance.

The recent fires have been a lesson in which many cities understand how important a 3-tier order of preference would be to ensure public safety. Having the additional tier will limit fire exposure and provide time for residents to be able to escape safely. Please make public safety a top priority and return it to the 3 tiers of preferences.

Sincerely,

Karen Haberstock

From: Melissa Smith
To: City Council; Public Comment
Subject: Studies showing environmental impact of wireless
Date: Tuesday, May 10, 2022 2:10:20 PM
Attachments: Radio-Frequency Electromagnetic Field Exposure of Western Honey Bees.pdf
Tree damage caused by mobile phone base stations An observation guide.pdf
EMF and Wildlife Part 3 Levitt Lai Manville .pdf
Electromagnetic radiation as an emerging driver factor for the declineof insects Balmori copy.pdf
EMF and Wildlife Part 1.pdf
EMF and Wildlife Part 2.pdf
Santa Fe New Mexican Report says wireless radiation may harm wildlife copy.pdf

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Dear Los Altos City Council,

Please include in the record of public comment the attached studies demonstrating adverse environmental impact of wireless:

The studies show damage to trees, bees and wildlife from wireless emissions. Please vote against the Negative Declaration of Environmental Impact.

Thank you,
Melissa Smith
Los Altos resident

www.nature.com/scientificreports

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natureresearch

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Radio-Frequency Electromagnetic Field Exposure of Western Honey Bees

Arno Thielens[1,2*], Mark K. Greco[3], Leen Verloock[1], Luc Martens[1] & Wout Joseph[1]

Radio-frequency electromagnetic fields (RF-EMFs) can be absorbed in all living organisms, including Western Honey Bees (*Apis Mellifera*). This is an ecologically and economically important global insect species that is continuously exposed to environmental RF-EMFs. This exposure is studied numerically and experimentally in this manuscript. To this aim, numerical simulations using honey bee models, obtained using micro-CT scanning, were implemented to determine RF absorbed power as a function of frequency in the 0.6 to 120 GHz range. Five different models of honey bees were obtained and simulated: two workers, a drone, a larva, and a queen. The simulations were combined with *in-situ* measurements of environmental RF-EMF exposure near beehives in Belgium in order to estimate realistic exposure and absorbed power values for honey bees. Our analysis shows that a relatively small shift of 10% of environmental incident power density from frequencies below 3 GHz to higher frequencies will lead to a relative increase in absorbed power of a factor higher than 3.

Wireless communication is a widespread and growing technology. Most of the wireless networks and personal devices operate using Radio-Frequency (RF) electromagnetic fields (EMFs). The current networks rely on frequencies between 0.1 GHz and 6 GHz[1]. These EMFs can be absorbed in dielectric media and can cause dielectric heating[2]. This dielectric heating can occur in any living organism, including insects.

Absorption of RF EMFs in insects has been studied previously. Wang *et al.*[3] studied absorption of RF EMFs in mashed codling moth larvae at 27 MHz and 915 MHz. Shrestha *et al.*[4] studied dielectric heating of Cryptolestes ferrungineus S. in different stages (eggs, larvae, pupae, and adults) at 27 MHz. Shayesteh *et al.*[5] exposed Tribolium confusum and Plodia interpunctella to RF EMFs at 2450 MHz[6–8]. are reviews of RF heating of insects. Dielectric porperties of insects are measured by Nelson *et al.*[9] from 0.2 to 20 GHz through the determination of loss of RF EMF power in insect samples (rice weevil, red flour beetle, saw-toothed grain beetle, and lesser grain borer). Absorption of RF EMFs was studied by Halverson *et al.*[10] in insects between 10–50 GHz. Thielens *et al.*[11] used numerical simulations to study absorption of RF EMFs from 2–120 GHz in four insect models. The main conclusions from the aforementioned studies are that (i) RF EMFs can be absorbed and can cause dielectric heating in insects and (ii) this absorption of RF-EMFs is frequency dependent. This frequency dependency is important since 5th generation (5 G) networks are expected to partially operate at higher frequencies (up to 300 GHz)[12,13]. This shift might induce a change in RF EMF absorption for insects[11].

Western Honey Bees (*Apis Mellifera*) are particularly important insects because of the environmental and economical importance of this species. Therefore, previous studies have focused on the potential effects of EMF exposure of Western Honey Bees. Low-frequency EM properties and exposure of honeybees was studied in[14]. The influence of Low-frequency magnetic fields on honey bee orientation has been studied in[15]. There have also been some studies on effects of RF EMF on honey bees. Potential effects of RF EMF exposure on reproduction of honey bee queens were investigated in[16]. Behavioral effects potentially caused by exposure to RF EMFs in honey bees have been investigated in[17–19]. A disadvantage is that these studies are lacking a quantification of the amount of power that is absorbed in the studied honey bees, so called RF dosimetry[20]. On the other hand, this absorption has been determined for a single honey bee worker in[11]. However, Thielens *et al.*[11] do not provide any coupling of this absorption to a real RF-EMF exposure situation and only study a single honey bee, which provides no

[1]Ghent University - imec, Department of Information Technology, Ghent, B-9052, Belgium. [2]University of California Berkeley, Berkeley Wireless Research Center, Department of Electrical Engineering and Computer Sciences, Berkeley, CA, 94704, USA. [3]Charles Sturt University, Medical Imaging, SDHS, Faculty of Science, Wagga Wagga, NSW, 2678, Australia. *email: arno.thielens@ugent.be

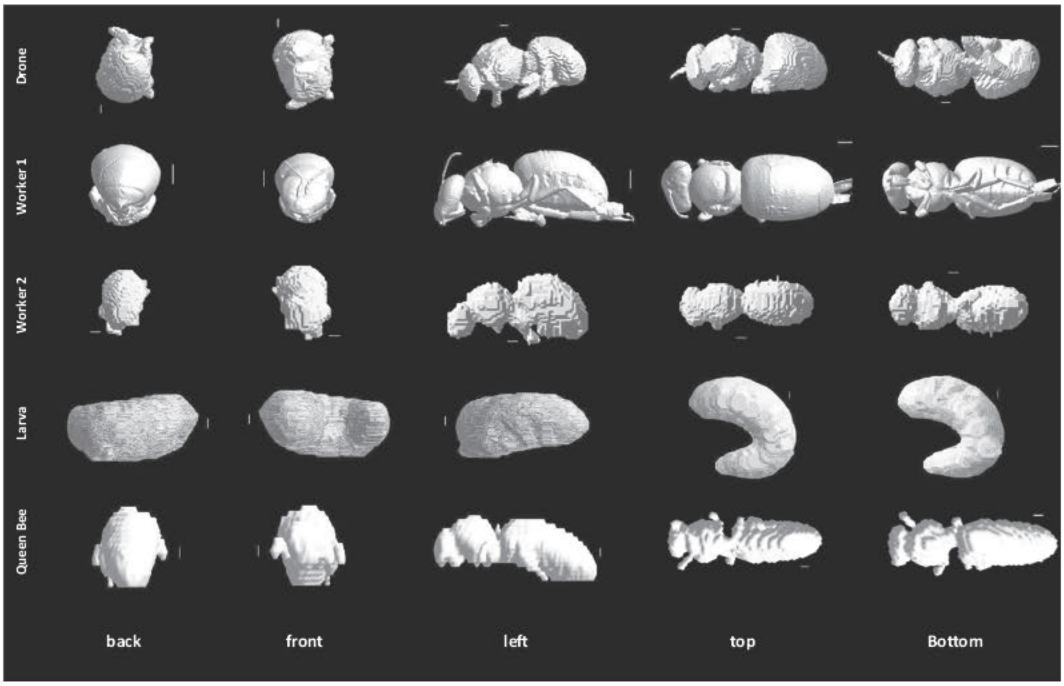

Figure 1. Studied Honey Bee Models, from top to bottom: Male Drone, Worker Bee 1, Worker Bee 2, Worker Larva and Queen Bee. Columns show different perspectives: back, front, left, top, and bottom view, respectively. The white lines show a 1 mm scale for reference.

information on the evolution of such absorption as a honey bee goes through different developmental stages. Nor is it clear whether this RF absorption is realistic for other castes, such as drones or queens, in a bee colony.

Therefore, the aims of this study were to numerically evaluate RF-EMF absorption in western honey bees and validate the frequency dependency of this absorption during various developmental stages and experimentally quantify real-life exposure of bees. To this aim, numerical simulations were executed to determine the absorption of RF-EMFs in five different honey bee models: a larva, a queen, two workers, and one drone, obtained using micro-CT imaging. These simulations were implemented as a function of frequency in a broad band, 0.6 GHz up to 120 GHz, that can be used to model both current and future telecommunication frequencies. In parallel, RF-EMF exposure measurements were executed near five bee hives in Belgium, in order to quantify the real exposure of such honey bees. Finally, these measured values were used to rescale the numerical simulations in order to quantify real honey bee absorption and assess a potential change in absorption in case a shift in operation frequencies in future telecommunication networks would occur.

Methods

Studied honey bees, imaging technique, and model development. Images of the studied insects are shown in Fig. 1. All studied insects are western honey bees (*Apis mellifera*), which is the most commonly used honey bee worldwide. Honey bees within a colony are subdivided into different castes. An active viable honeybee colony contains only one queen bee who spends most of her time laying 2,000 to 3,000 eggs per day. The queen is the only reproductive female within the colony and her health is vitally important to the survival of her colony. Damage to her ovaries has the potential to effect the function and survival of her progeny. A queen typically lives between approximately three and five years. From early spring time to mid-summer the queen lays unfertilized "haploid" eggs which develop into drone bees. All drones are males. Their specific role is to mate with a virgin queen so that she can initiate the propagation of a new colony. During this mating season, there are approximately 3,000 to 5,000 drones within any given colony. Drones typically live between one to two months.

A healthy honey bee colony can contain approximately 50,000 individuals. Most of these are sterile, female, worker bees. Worker bees perform all the tasks within a colony to keep it full of provisions and free from disease. This involves feeding and nursing larvae, foraging for nectar and pollen, storing nectar and pollen, guarding the entrance, tending to the hygiene of the queen-workers-drones and maintaining a clean hive environment. Workers live for three to four weeks during the active seasons (spring-summer-autumn) and approximately three months during the colder inactive season (winter). There are approximately 3,000 (winter) to 10,000 (summer) larvae present at any given time.

We chose representatives from all three castes within a honeybee colony, one queen bee, two worker bees, one drone bee and one worker larva. All honey bees were scanned at the Western Sydney University National Imaging Facility (Sydney, Australia) using a bench-top MicroCT scanner (Quantum GX MicroCT Imaging System, PerkinElmer, Hopkinton, MA, USA). The parameters used during this scanning depended on the scanned bee. Such scans are made using different projections, at different time intervals on the scanners settings.

The rotation between projections also depends on the scanner's settings and the studied honey bee (see below for full description).

Worker 1. The insect named 'Worker 1' is the same bee studied in[11], which had a full body length of approximately 11.0 mm long, is 5.0 mm wide, and had a mass of approximately 900 mg. During the scanning of Worker 1, the Micro-CT scanner was operated using the following parameters: 50 kVp, 80 mA, and a 2048 × 2048 pixels image matrix. This resulted in scans with a 20 μm isotropic voxel size. Each projection had a scanning time of 3.0 s, with 3.0 s rotation time in between projections. The total scan time for Worker 1 was approximately 18 min.

Worker 2. The second honey bee worker (Worker 2) has a full body length of 13 mm with cross sectional dimensions of 6.8 mm and 5.4 mm and a mass of approximately 900 mg. For Worker 2, the scanner was operated using the following parameters: 40 kVp, 70 mA, and a 2048 × 2048 pixels image matrix. The isotropic voxel size was 100 μm. Each projection had a scanning time of 1.5 s. There was a 3.0 s rotation time in between each projection. The total scan time for the whole bee was approximately 10 min.

Larva. Larvae of this age (three weeks) are typically approximately 16 mm long with an approximate mass of 900 mg. The scanned larva was curled up, which made estimating its full body dimensions difficult, but the sample fitted within a $14 \times 7 \times 15$ mm^3 box. This scanning of the larva was done using the following parameters: 50 kVp, 80 mA, and a 2048 × 2048 pixels image matrix. This resulted in scans with a 20 μm isotropic voxel size. Each projection had a scanning time of 3.0 s. and with a 3.0 s rotation time this resulted in a total scan time for the larva of 18 min.

Male drone. The drone has a full body length of 18 mm with cross sectional dimensions of 7.2 mm and 9.4 mm and an approximate mass of 1 g. During the scanning of the drone, the Micro-CT scanner was operated using the following parameters: 40 kVp, 70 mA, and a 2048 × 2048 pixels image matrix. The isotropic voxel size was 100 μm. Each projection had a scanning time of 1.5 s. The full scan took 180 projections and there was a 3.0 s rotation time in between each projection. The total scan time for the whole bee was approximately 10 min.

Queen bee. The QB has a full body length of 19 mm and cross sectional dimensions of 7.5 times 7.1 mm^2 and an approximate mass of 1100 mg. The queen was scanned was using the following parameters: 40 kVp, 70 mA, and a 2048 × 2048 pixels image matrix. The isotropic voxel size was 250 μm. Each projection had a scanning time of 1.5 s. There was a 1.5 s rotation time in between each projection. The total scan time for the queen bee was approximately 10 min.

Development of 3D models. The software running on the Quantum GX, bench-top MicroCT scanner was used for all honey bees to reconstruct the 180 projection images. Those were then converted into a 2D rendered image stack of 512, 16 bit bitmap images. Finally, the BeeView volume rendering software (DISECT Systems Ltd, Suffolk, UK) was used to acquire Bee volume data from the image stack. All 3D models of the insects were created using the software TomoMask (www.tomomask.com). We used the same approach as in[11]. The image stack for each honey bee was imported into TomoMask, which also required the pixel and slice spacing. The software generated a 3D model using a marching cubes algorithm[21]. This model was then exported as an STL (STereo Lithography)[22] file. This is a commonly used format to describe surface geometry. The models were also smoothed using the Taubin λ/μ smoothing scheme[23] implemented in MeshLab[24]. The dimensions of the models and mesh integrity were checked (and corrected if necessary) before simulations using Netfabb (Autodesk, San Rafael, CA, USA).

Numerical simulations and RF EMF exposure conditions. Electromagnetic, numerical simulations were executed to estimate electromagnetic fields in and around the honey bees under far-field exposure. Far-field exposure is in this manuscript defined as RF-EMF sources being more than $2D^2/\lambda$ away from the insects, with D the largest dimension of the RF source and λ the wavelength of the RF-EMFs. This is often referred to as the Fraunhofer far-field limit[25]. In general, far-field RF-EMF sources can be located in any direction from the honey bees. Therefore, different approaches exist to model such far-field exposure to RF-EMFs: a stochastic method where far-field exposure is decomposed in sets of plane waves according to certain statistics is used in[26,27], while a more limited set of plane-wave exposures coming from six predefined directions along the main axis of the exposed subject or animal are considered in[11,28]. In this study, we have chosen to work with the latter method. We have modeled exposure of the studied honey bees by a set of 12 incident plane waves traveling along six directions defined by a Cartesian coordinate system, see Fig. 2. For each direction, two orthogonal incident electric field polarizations were chosen, since any other free-space E-field polarization can be obtained using a linear combination of both. All incident plane waves have a root-mean squared electric field strength of 1 V/m. This value is chosen to facilitate renormalization to any potential value of incident field strenght.

Numerical simulations were executed using the Finite-Difference Time-Domain (FDTD) method implemented in Sim4life (ZMT, Zurich, Switzerland). This is a common technique used to determine RF-EMF in and near homogeneous and heterogeneous dielectric objects[11,26,28], such as the honey bees studied in this paper. In this method, the simulation domain is divided in cubes using a three-dimensional rectilinear grid. Depending on the wavelength, feature sizes of the objects in the simulations, and the desired spatial accuracy, a different spatial step is used to discretize the simulation. The FDTD algorithm requires a grid step smaller than one tenth of the smallest wavelength in the simulation domain in order to return stable solutions[29]. Since this is a time-domain technique, it requires a predefined simulation time in order to reach a steady-state solution, which will again depend on the chosen spatial resolution, the wavelength, and the size of the simulation domain.

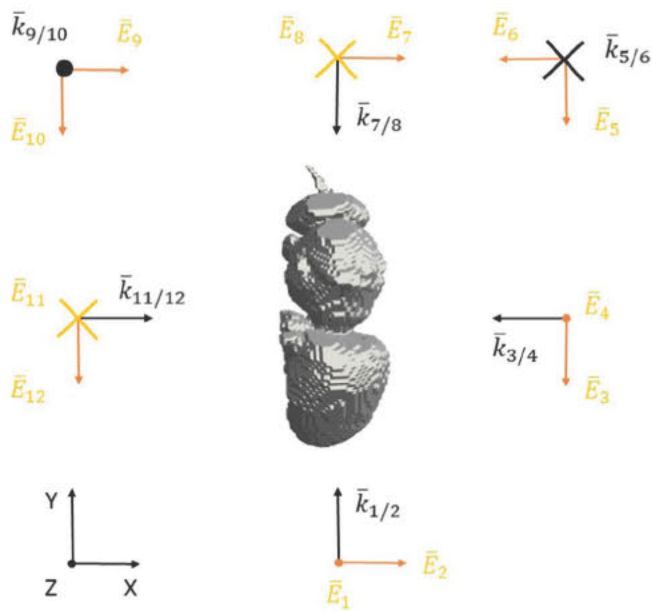

Figure 2. Configuration of the RF-EMF plane-wave simulations. Twelve potential RF plane waves incident from six directions are incident on the insect (honey bee drone shown here in grey, top view). Orange arrows indicate the electric field $\overline{E}_i$ polarizations, while the black arrows indicate the direction of propagation with wave vector $\overline{k}_{i/j}$ of the plane waves. *i* and *j* indicate the simulations' configuration number, from 1 to 12.

	0.6 GHz	1.2 GHz	2 GHz	3 GHz	6 GHz	12 GHz	24 GHz	60 GHz	120 GHz
Maximal grid step (mm)									
Larva	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Others	0.1	0.1	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Simulated Periods									
Worker Bee 1	20	30	60	30	30	30	30	40	40
Others	10	20	20	30	30	30	30	30	30
ε_r	45.6	44.2	39.9	38.8	38.0	28.6	14.9	7.018	5.46
σ (S/m)	0.688	0.924	1.35	2.05	5.05	12.0	21.1	27.9	29.2

Table 1. Simulations Settings and Dielectric Properties of the Honey Bees.

We executed numerical simulations at nine harmonic frequencies from 0.6–120 GHz (sinusoidal waves at a single frequency). The lower and upper frequency limits were chosen because they correspond to the current limits in terms of simulation size and length that can realistically be supported by our simulation hardware. The simulated frequencies are listed in Table 1 alongside the chosen grid steps in the simulation domain and the number of periods used for every simulation. These settings were the same for each of the five studied honey bee models. The studied insects have certain dielectric properties, quantified using the relative permittivity (ε_r) and conductivity (σ). We did not measure the dielectric properties of the studied insects. Instead, we assigned dielectric parameters obtained from[11]. The value at 1 GHz is obtained using the same literature database and interpolation presented in[11]. Table 1 lists these properties. All insects were modeled as homogeneous objects. These configurations resulted in 12 (plane waves) × 9 (frequencies) × 5 (honey bees) = 540 simulation results.

After each simulation, the internal electric field in the insect model was extracted and used to calculate the total absorbed RF-EMF power (P_{abs}) in the honey bee. P_{abs} is calculated as the integrated product of the conductivity and the squared internal electric field strenght ($\overline{E}_{int}$) over the total volume (V) of the insect:

$$P_{abs} = \int_V \sigma \times |\overline{E}_{int}|^2 .\ dV \tag{1}$$

We report P_{abs} rather than specific absorption rate (SAR) values since we did not measure the mass and density of all the simulated honey bees. P_{abs} is an important quantity since dielectric heating of an insect is proportional to absorbed RF-EMF power[2].

In order to validate our simulations we tested the influence of four simulation settings on the RF-EMF P_{abs}: grid step size, dielectric parameters, angle of incidence, and number of simulated periods. The influence of the grid step is expected to be the most significant at the highest simulated frequency (120 GHz), since the chosen maximal grid step of 0.05 mm is closest to the smallest wavelength in the simulation domain at that frequency in the tissue ($0.05\,mm = 0.045\,\lambda$). Therefore the maximal grid step was set to $25\,\mu m$ for exposure configuration number 2 in Fig. 2 for both the Larva and Worker 2 phantoms. In[11], it was demonstrated that the maximal uncertainty on the dielectric parameters occurs between 2 and 3 GHz, with maximal relative deviations of 40%. In order to test the dependency of our simulation results on the chosen dielectric parameters, we executed four additional FDTD simulations in exposure configuration number 2 shown in Fig. 2 using the Worker 2 phantom. In these simulations the dielectric parameters (ε,σ) were changed to: ($1.5.\varepsilon$, $1.5.\sigma$), ($0.5.\varepsilon$, $1.5.\sigma$), ($1.5.\varepsilon$, $0.5.\sigma$), and ($0.5.\varepsilon$, $0.5.\sigma$), respectively, allowing for a potential 50% deviation on the dielectric parameters, which should be larger than the uncertainty on the chosen dielectric parameters. We chose to model RF-EMF exposure of the studied honey bees using plane waves incident from 6 directions. However, it is uncertain whether this set of plane waves provides a complete overview of the full range in P_{abs} as function of the angle of incidence. In order to validate our exposure set up, we have executed 20 additional FDTD simulations at 6 GHz using the Worker 2 phantom, where the elevation, azimuth, and polarization angles were generated according to uniform distributions between $[0, \pi]$, $[0, 2\pi]$, and $[0, 2\pi]$, respectively. The settings of these FDTD simulations were the same as those shown in Table 1. Finally, the number of simulated periods was tested at 120 GHz for the Worker 2 phantom in exposure configuration number 2 shown in Fig. 2 by increasing the number of simulated periods to 120 instead of 30, see Table 1. After each of these validation simulations, the P_{abs} was extracted and compared to the one obtained in the original simulation set.

RF-EMF field measurements. In order to quantify current RF-EMF exposure of honey bees in real exposure scenarios, we executed RF-EMF exposure measurements at five sets of bee hives in Belgium at: Aalter, Merelbeke, Eeklo, Zomergem, and Drongen, see Fig. 3(a). At each measurement site, three different measurements were executed in order to quantify RF-EMF exposure.

First, a spectrum analyzer of the type FSL6 (R&S Belgium, Excelsiorlaan 31 1930 Zaventem Belgium) connected to a triaxial isotropic antenna was used to perform a broad-band RF overview measurement from 80 MHz to 6 GHz. These measurements were executed in two steps: first spectral overview measurements were executed from 0.08–3 GHz using a tri-axial antenna TS-EMF (Rhode and Schwartz, dynamic range of 1 mV/m–100 V/m for the frequency range of 80 MHz–3 GHz), followed by measurements from 3–6 GHz using a Clampco AT6000 antenna. At one out of five measurement sites, Drongen, a conical dipole antenna PCD 8250 (Seibersdorf Laboratories, Seibersdorf, Austria) was used for the 80 MHz - 3 GHz measurements. This antenna was rotated to obtain three orthogonal polarizations of the electric field. During these overview measurements, the spectrum analyzer measured in maximum-hold modus during 17 and 9 minutes in the lower and higher frequency bands, respectively. The antennas were supported by a plastic tripod and were placed at 1 m in front of the bee hive at a height of 1.5 m from the ground level. Figure 3 shows the studied bee hives and the measurement set up in the field. The 1.5 m height is a typical height at which such EM field measurements[30]. Additionally, this height is mentioned in the ECC(02)04 standard[31]. The purpose of these measurements was to get an overview of which frequency bands were in use at the respective sites. These frequency bands were then investigated further in the second measurements.

Second, the same spectrum analyzer was connected to the tri-axial antenna TS-EMF which was again supported by the same tripod at a height of 1.5 m. The tripod was placed at two distances of 1 and 2 m from the central bee hive. The spectrum analyzer performed root-mean square electric field strength (E_{RMS}) measurements over a measurement period of 6 minutes[2] in each of the telecommunication frequency bands identified using the first measurement. Each of the three electric field components (E_x, E_y, E_z) were measured individually. E_{RMS} was then obtained as the square root of the sum of squares of the individual components.

$$E_{RMS} = \sqrt{E_x^2 + E_y^2 + E_z^2} \qquad (2)$$

The spectrum analyzer measurements in terms of received power on the antenna were then recalculated using the known antenna factor of the tri-axial antenna to incident root-mean-squared electric field strength. The $E_{RMS,i}$ values in each frequency band (i) were then summed quadratically and the square root of that sum is listed as the total instantaneous electric field strength ($E_{RMS,tot}$).

$$E_{RMS,tot} = \sqrt{\sum_i E_{RMS,i}^2} \qquad (3)$$

The measurement procedure and measurement settings for these RF-EMF exposure measurements are presented in[32]. The expanded measurement uncertainty (95% confidence interval) for electric field strength measurements using this set up is $\pm 3\,dB$[30].This measurement setup enables the most accurate assessment of *in situ* exposure from various RF-EMF sources[30].

Third, a broadband exposure measurement was executed using a Narda NBM-550 probe (Narda, Hauppauge,NY, USA) connected to an EF 0691 broad-band probe (Narda, Hauppauge, NY, USA) which has a frequency span from 100 kHz to 6 GHz, thus including so-called intermediate frequencies (IF). These IF fields are not considered in our numerical simulations. However, we measured those to provide a complete overview of the exposure to electromagnetic field below 6 GHz. The NMB probe was placed on top of the central bee hive and was left there during both RF measurements. The device measured and registered root-mean-squared electric field strengths with a period of 1 s. From those time series of measurements, we obtained the time average and the maximal value.

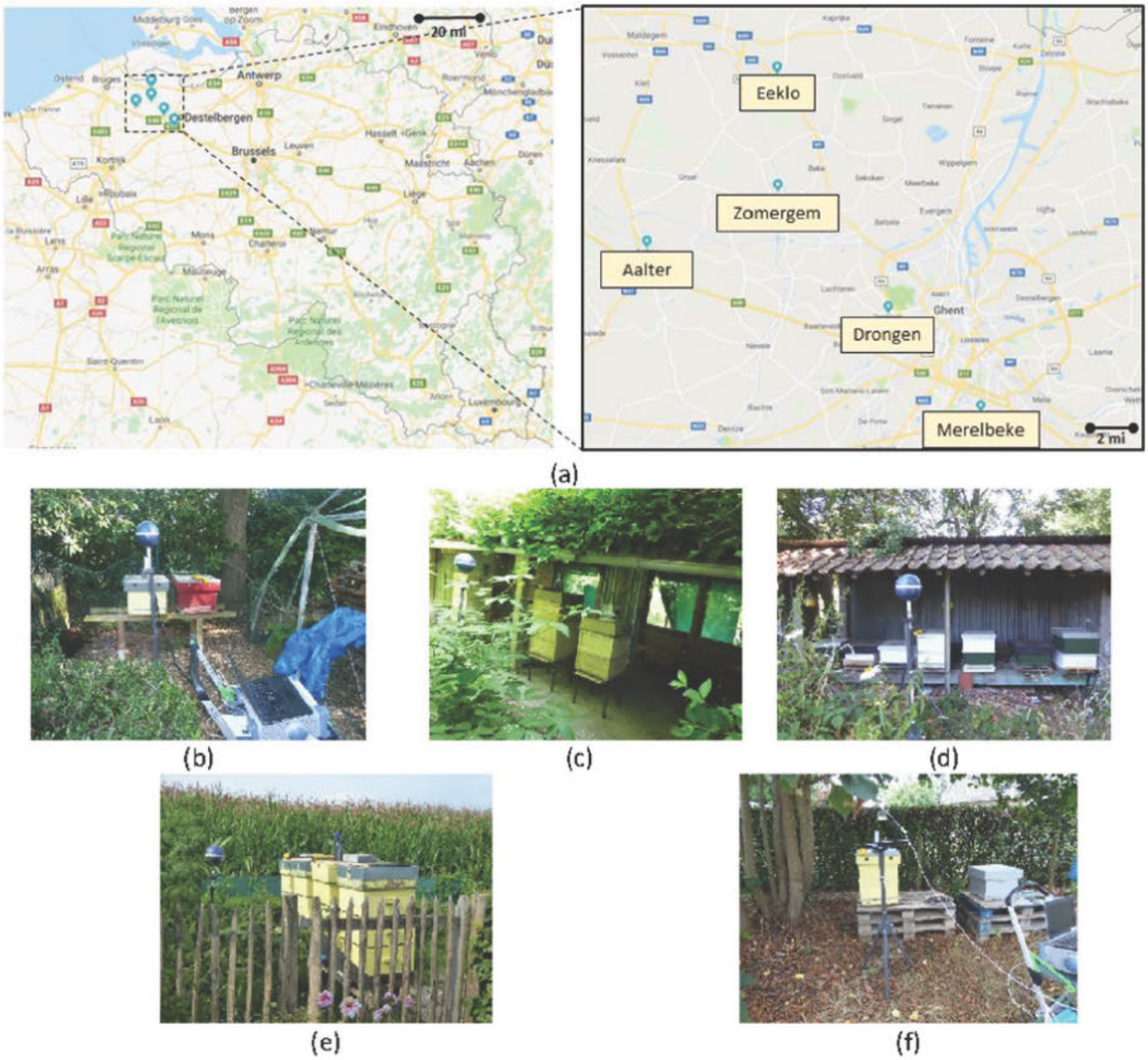

Figure 3. Five measurement locations near bee hives in Belgium: (**a**) Overview of the measrurement locations (source: https://www.google.com/maps, Google Maps, Google, Alphabet inc., Mountain View, CA, USA) Map data: Google, GeoBasis-DE/BKG (**b**) Aalter, (**c**) Merelbeke, (**d**) Eeklo, (**e**) Zomergem, and (**f**) Drongen.

The researchers that executed the RF-EMF field measurements did not use personal devices during the measurements. All wireless devices brought to the measurement site by the researchers were operated in flight mode, i.e. any wireless transmissions by those devices were not allowed.

Estimation of realistic RF-EMF absorbed power in honey bees. Realistic P_{abs} absorbed in honey bees can be obtained by rescaling the simulated P_{abs} values using the measured incident field strengths. Therefore, we linearly averaged the total E_{RMS} values measured near the five bee hives at two different positions to obtain an average $E_{RMS,avg}$ value. In order to estimate exposure of honey bees in current wireless networks, we averaged the P_{abs} values using:

$$P_{abs,av}(f < 3\ GHz) = \frac{1}{4}\sum_{i=1}^{4} P_{abs}(f_i) \tag{4}$$

with $f_i = 0.6, 1.2, 2, 3\ GHz$. We only considered P_{abs} values < 3 GHz, since our measurements will show that there are only incident RF-EMFs below 3 GHz in the current environment of honey bees in Belgium. This value is then rescaled using:

$$P_{abs,real}(f < 3\ GHz) = \frac{E^2_{RMS,avg}}{1\ V^2/m^2} \times P_{abs,av}(f < 3\ GHz) \tag{5}$$

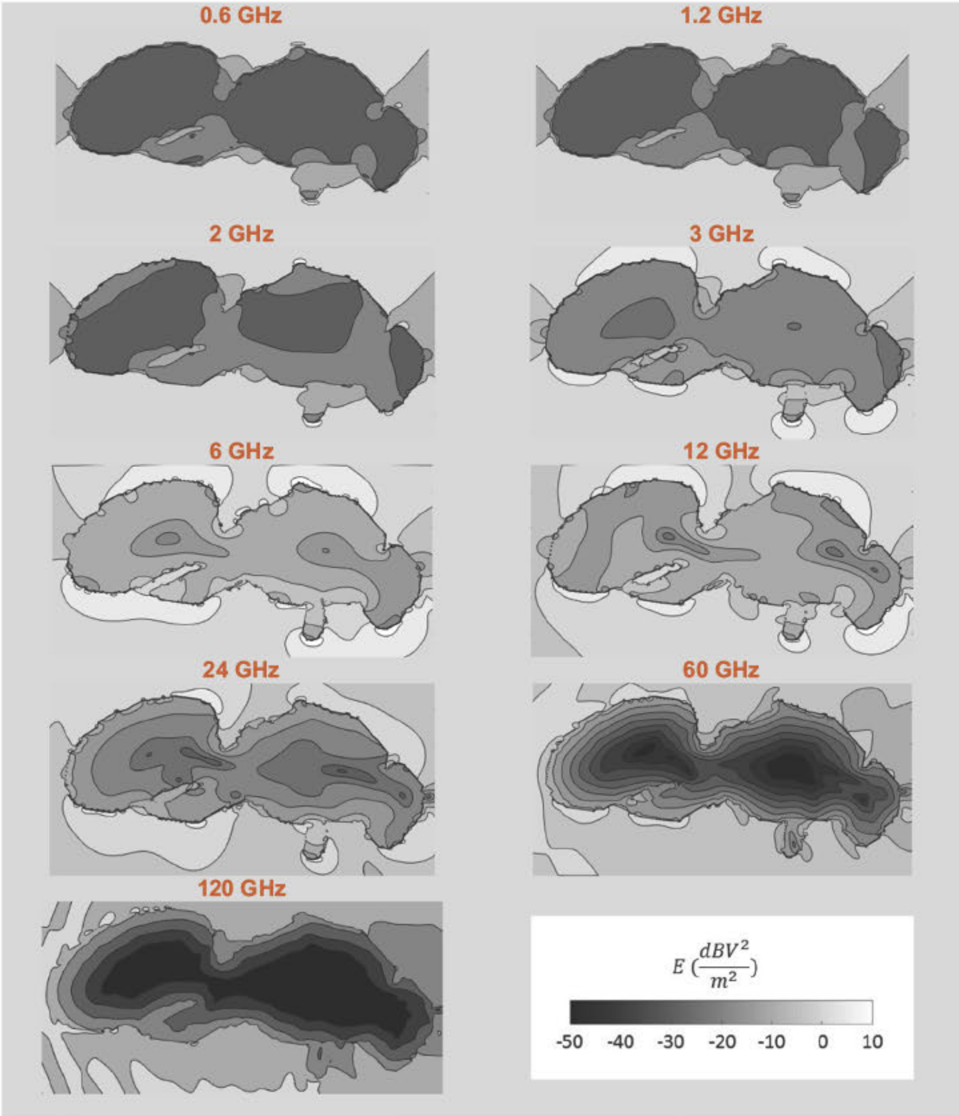

Figure 4. Relative electric field strength in and around a mid-sagittal plane of the Honey Bee Drone at the nine studied frequencies. Grey scale shows the electric field strengths relative to 1 V/m electric field strength.

In order to estimate the effect of a fraction ($p \in [0, 1]$) of the RF-EMF incident fields shifting to frequencies higher than 3 GHz we also determine the average P_{abs} for frequencies higher than 3 GHz, using:

$$P_{abs,av}(f > 3\ GHz) = \frac{1}{5}\sum_{j=1}^{5} P_{abs}(f_j) \tag{6}$$

with $f_j = 6, 12, 24, 60, 120\ GHz$. The realistic $P_{abs,real}(p)$ for a fraction p of the power shifted to frequencies higher than 3 GHz is then calculated as:

$$P_{abs,real}(p) = p \times \frac{E^2_{RMS,avg}}{1\ V^2/m^2} \times P_{abs,av}(f > 3\ GHz) + (1-p) \times \frac{E^2_{RMS,avg}}{1\ V^2/m^2} \times P_{abs,av}(f < 3\ GHz) \tag{7}$$

Results

Numerical simulations. Figure 4 shows the relative electric field strength (electric field strength divided by the maximum electric field strength in the simulation domain) in and around the studied drone in a mid-sagital plane as function of frequency for exposure configuration number 1 shown in Fig. 2. The internal electric fields increase up to 12 GHz and shift towards the outside of the phantom at higher frequencies. At 120 GHz the electric

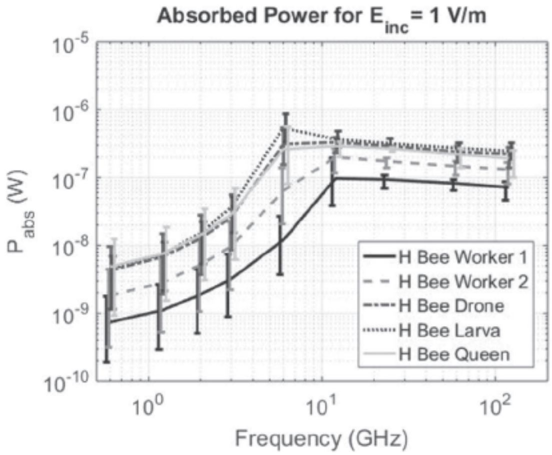

Figure 5. Total absorbed power (P_{abs}) in the five studied honey bees as function of frequency, normalized to an incident plane-wave field strength of 1 V/m at each frequency. The curves indicate the mean values over the twelve plane wave simulations, while the whiskers indicate the maximum and minimum values found at each frequency. The whiskers are slightly offset in order to avoid visual overlap but are all determined at the simulated frequencies described in the Methods Section.

field strengths decreases very rapidly within the phantom and electric fields are basically only present in the outer layers of the insect. This is caused by a decrease in skin depth that is driven by the increase in conductivity at higher frequencies, see Table 1. Note that the total RF-EMF absorbed power in the insect scales both with the internal electric field strength and the conductivity.

Figure 5 shows the normalized RF-EMF P_{abs} as a function of frequency for the five studied insects from 0.6 GHz up to 120 GHz. The curves connect the linear averages of the 12 P_{abs} values obtained for each honey bee at each simulated frequency, while the whiskers indicate the minimum and maximum P_{abs} values found at those frequencies. All P_{abs} values are normalized to an incident field strength of 1 V/m. Figure 5 shows an increase of P_{abs} over frequency for all studied phantoms up to 6 GHz. When comparing the average P_{abs} at 0.6 GHz and 6 GHz, we found relative increases of factors of 16, 35, 72, 121, and 54 for the Worker Bee 1, Worker Bee 2, Drone, Larva, and queen Bee, respectively. The P_{abs} slightly decreases over frequency beyond 12 GHz for all the studied honey bees. When comparing P_{abs} at 12 GHz and 120 GHz, we found relative decreases of 26%, 34%, 33%, 32%, and 34% for the Worker Bee 1, Worker Bee 2, Drone, Larva, and Queen Bee, respectively. The spread on the P_{abs} values obtained at each individual frequency reduces from up to a factor of 13 below 12 GHz to smaller than a factor 2.5 beyond 12 GHz. Figure 5 shows a general increase of P_{abs} with increasing volume and surface area of the studied insects. Previous studies on whole-body averaged absorbed RF power and specific absorption rate of humans have shown a dependency of these quantities on the absorption cross section, a quantity that scales with volume and/or surface area of an exposed subject. When the diagonals of the smallest rectangular brick that contain the insect phantoms are considered, the honey bee with the smallest diagonal, Worker Bee 1 with a diagonal of 13 mm has the overall lowest average P_{abs}. The Larva, Queen Bee, and Drone all have associated diagonals of 22 mm and have similar average P_{abs} values as function of frequency. The Worker Bee 2 has a diagonal that falls in between Worker 1 and the other insects of 16 mm and also has an average P_{abs} that falls in between the curve for the smaller worker and the other honey bee models, see Fig. 5. We attribute he differences between the two Worker Bee phantoms mainly to the difference in size of both phantoms. The larger Worker Bee 2 phantom has a larger diagonal, surface area, and volume. This leads to a higher absorption cross section[33] and higher P_{abs}.

The maximal P_{abs} for the five studied insect models occurs at those wavelengths that are close to the double of this diagonal, which suggests an absorption peak around half a wavelength. The maximum P_{abs} for the Larva model lies in between 3 and 12 GHz, i.e. in between 25 and 100 mm in terms of λ, while the diagonal of said bounding box is 22 mm for the phantom. For the other studied insect models the maximum P_{abs} lies in between 6 and 24 GHz, i.e. in between 23 and 50 mm in terms of λ, with associated phantom diagonals ranging from 16 mm to 22 mm.

As mentioned in the Methods section, the influence of dielectric parameters was studied with simulations using Worker 2 at 2 GHz with altered dielectric parameters. These resulted in P_{abs} values of 6.3×10^{-10} W, 6.3×10^{-9} W, 3.1×10^{-9} W, and 1.8×10^{-9} W, in comparison to 2.0×10^{-9} W for an incident field strength of 1 V/m. This corresponds to relative deviations of −69%, +210%, +50%, and −10%. These deviations are significant but smaller than the full range of a factor of 5 we observed for the larva at 2 GHz as a function of changing incident angle and polarization. These relative differences are small in comparison to the differences we observe over frequency for the same phantom: a factor of 121 over frequency from 0.6 to 6 GHz.

At 120 GHz we find a deviation on P_{abs} smaller than 0.1% when 120 simulation periods are executed in comparison to 30 simulation periods in configuration number 2 shown in Fig. 2 for the Worker 2 phantom. Indicating that the number of simulated periods is sufficient for these simulations. At the same frequency and in the same simulation configuration, a reduction of the grid step with a factor of 2 resulted in a P_{abs} of 8.6×10^{-8} W and 3.1×10^{-7} W for the Worker 2 and Larva phantoms, respectively, while the regular simulations with 0.1 mm

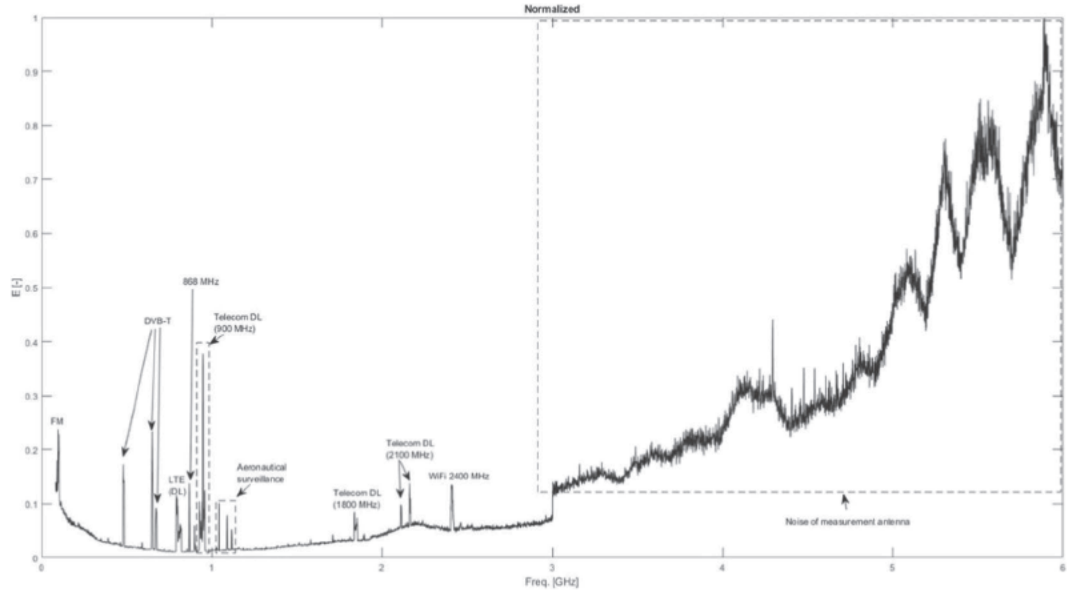

Figure 6. Overview measurement of electric field strength (normalized to maximally measured electric field strength), between 0.8 and 6 GHz, in Aalter. The wireless technologies associated with the different peaks are indicated in the figure as well.

and 0.05 mm grid steps, respectively, resulted in P_{abs} values of 8.4×10^{-8} W and 3.1×10^{-7} W for an incident field strength of 1 V/m. This corresponds to relative deviations of 0.3% and 0.5% for the Worker 2 and the Larva phantoms, respectively, indicating that the chosen grid step was small enough to result in stable numerical results.

The set of 20 incident plane waves with randomized angles of incidence and polarization at 6 GHz using the Worker 2 phantom resulted in an average P_{abs} of $4.5 \times 10^{-8} \pm 1.6 \times 10^{-8}$ W for an incident field strength of 1 V/m, while the set of 12 incident plane waves used to model far-field exposure results in an average P_{abs} of $6.5 \times 10^{-8} \pm 5.3 \times 10^{-8}$ W at the same frequency. The value are fairly close, which indicates that the set of 12 incident plane waves along the main axes is a good proxy for average exposure under a randomized angle of incidence and polarization. The set of twelve plane waves does seem to overestimate exposure at the higher percentiles, since they are significantly higher than those obtained using the random set of plane waves.

RF-EMF field measurements. Figure 6 shows an example of an RF-EMF overview measurement at one of the five studied bee hives (Aalter). Figure 6 shows the relative electric field strength, normalized to the maximally measured electric field strength. The different peaks correspond to several individual frequency bands that are used for telecommunication and broadcasting signals. These frequency bands were then measured individually using the same set-up with triaxial antenna and spectrum analyzer at two positions relative to the bee hive on each measurement site using the measurement procedure described in[32].

Table 2 lists the measured E_{RMS} values at the five studied bee hives shown in Fig. 3. As all these measurement sites were rural, private areas, there were no uplink (emissions from a user device to the network) transmissions found. Downlink (DL, this is network to user communication) signals were found at all measurement sites. These signals were generated by three different mobile telecommunications providers in fourteen different frequency bands. The wireless technologies used by the telecommunication operators were: Long Term Evolution (LTE) in frequency bands close to 800 MHz and 1800 MHz, Global System for Mobile telecommunications (GSM) in frequency bands close to 900 MHz, and Universal Mobile Telecommunications Service (UMTS) in frequency bands close to 900 MHz and 2100 MHz. Four other telecommunication bands were identified: TETRA (Terrestrial Trunked Radio, 390–395 MHz) which is a technology used by public services (police, firefighters, etc.), an Industrial, Scientifical, and/or Medical (ISM) application around 870 MHz, Digital Enhanced Cordless Telecommunications (DECT) close to 1900 MHz, and Wireless Fidelity (WiFi) at 2400 MHz. Additionally, several frequency bands with RF signals for broadcasting were measured: Frequency Modulated (FM) Radio around 100 MHz, Digital Audio Broadcasting (DAB) around 200 MHz, Digital Video Broadcasting (DVB) at 480–680 MHz. We found one unidentified RF wireless transmission at 592 MHz on two measurement sites: Merelbeke and Eeklo. The total E_{RMS} values ranged from 0.016 V/m on both positions in Merelbeke up to 0.226 V/m on position 1 in Drongen. The average E_{RMS} over the ten studied measurement sites was 0.06 V/m. FM Radio was the dominant source of RF exposure on 7/10 measurement positions. In Drongen and in Aalter, GSM 900 DL was the dominant contributor to the RF-EMF exposure. The field strength of WiFi signals depends strongly on the duty cycle used by the wireless technology[34]. The measured E_{RMS} values can be extrapolated to peak values under the assumption of 100% duty cycle. In the case of Aalter, this would result in 0.027 V/m and 0.032 V/m on positions 1 and 2, respectively. In the case of Zomergem, this extrapolation would result in peak E_{RMS} values of 0.059 V/m and 0.016 V/m on positions 1 and 2, respectively. On both measurement sites, a theoretically maximal 90% duty cycle would make WiFi the dominant source of exposure. However, such a network load is unlikely in a rural

$E_{RMS}(V/m)$	Aalter		Merelbeke		Eeklo		Zomergem		Drongen	
Frequency Band	Pos 1	Pos 2	Pos 1	Pos 2	Pos 1	Pos 2	Pos 1	Pos 2	Pos 1	Pos 2
FM[a] radio	0.019	0.021	0.009	0.009	0.018	0.014	0.011	0.011	0.009	0.008
T-DAB	—[b]	—	—	—	—	—	0.004	0.005	0.005	0.004
TETRA (390 MHz-395 MHz)	0.001	0.001	0.002	0.001	0.001	0.001	—	—	0.001	0.002
DVB-T 482 MHz	0.009	0.006	—	—	0.003	0.003	0.008	0.006	0.004	0.002
Freq. 592 MHz	—	—	0.001	0.002	0.002	0.002	—	—	—	—
DVB-T 650 MHz	0.008	0.008	0.003	0.003	0.002	0.003	0.006	0.006	0.006	0.004
DVB-T 674 MHz	0.004	0.008	0.004	0.004	0.002	0.002	0.006	0.005	0.004	0.004
ISM 868 MHz (869.5 MHz)	0.001	0.001	—	—	—	—	—	—	—	—
LTE 800 DL Prov. 1[c]	0.003	0.004	0.001	0.001	0.006	0.004	0.002	0.002	0.002	0.002
LTE 800 DL Prov. 2	0.002	0.002	0.004	0.004	0.002	0.002	0.002	0.002	0.047	0.031
LTE 800 DL Prov. 3	0.003	0.002	0.001	0.001	0.002	0.002	0.002	0.002	0.087	0.073
GSM 900 DL Prov. 1	0.005	0.004	0.001	0.002	0.005	0.007	0.003	0.004	0.004	0.004
GSM 900 DL Prov. 2	0.019	0.036	0.008	0.009	0.002	0.003	0.003	0.004	0.065	0.083
GSM 900 DL Prov. 3	0.004	0.004	0.003	0.002	0.002	0.003	0.003	0.004	0.180	0.137
UMTS 900 DL Prov. 1	0.001	0.002	0.001	0.001	0.003	0.003	0.002	0.002	0.002	0.001
UMTS 900 DL Prov. 2	0.001	0.001	0.005	0.006	0.001	0.001	0.001	0.001	—	—
UMTS 900 DL Prov. 3	0.002	0.002	0.001	0.001	0.001	0.001	0.002	0.001	0.055	0.055
LTE 1800 DL Prov. 1	—	—	—	—	0.004	0.005	—	—	—	—
LTE 1800 DL Prov. 3	0.004	0.004	—	—	—	—	—	—	—	—
DECT 1880 MHz	—	—	—	—	—	—	0.002	0.003	0.002	0.001
UMTS 2100 Prov. 1	—	—	—	—	0.006	0.007	—	—	—	—
UMTS 2100 DL Prov. 2	0.003	0.003	0.004	0.004	—	—	—	—	0.039	0.026
UMTS 2100 Prov. 3	0.005	0.006	—	—	—	—	—	—	—	—
WiFi 2400 MHz instantaneous[d]	0.007[e]	0.008[e]	—	—	—	—	0.006[f]	0.002[f]	—	—
Total instantaneous	**0.032**	**0.046**	**0.016**	**0.016**	**0.022**	**0.020**	**0.019**	**0.018**	**0.226**	**0.189**

Table 2. Measured root-mean squared electric field strengths (E_{RMS}) in the $80\ MHz - 6\ GHz$ frequency band in V/m. [a]'FM' = Frequency Modulated,'TETRA' = Terrestrial Trunked Radio, 'DVB-T' = Digital Video Broadcasting - Terrestrial, 'ISM' = Industrial, Scientifical, and Medical'LTE' = Long Term Evolution, 'GSM' = Global System for Mobile Communication, 'UMTS' = Universal Mobile Telecommunications System, 'DECT' = Digital Enhanced Cordless Telecommunications, 'WiFi' = Wireless Fidelity. [b]'—' indicates that the frequency band was not present at the measurement site. [c]Three identified Providers are denoted as Prov. 1, 2, and 3. [d]E_{RMS} values for Wireless Fidelity (WiFi)depend on the used duty-cycle, which depends on the use of the network. [e]Duty cycle of 7%. [f]Duty cycle of 1%.

Location	Maximum E-field (1 s interval) (V/m)	Avg E-field (1 s interval) (V/m)
Aalter	0.430	0.272
Merelbeke	0.233	0.1675
Eeklo	0.652	0.532
Zomergem	0.665	0.346
Drongen	0.397	0.297
Average	0.503	0.344

Table 3. Measured maximum and time-averaged broadband incident electric field strengths ($100\ kHz - 6\ GHz$).

area. WiFi was not measured at three out of five measurement sites. Additionally, at all measurement sites, RF EMFs emitted by a pulsed radar or other wireless technologies used in aeronautical surveillance were observed. The E_{RMS} value of RF EMFs emitted by a radar cannot be accurately measured without having the specifications of the radar. Therefore, we can only measure the peak value over the 6 min measurement interval. These fields were the highest in Merelbeke, where at position 1 peak E-field values of 0.017 V/m and 2.2 V/m were measured at 1.09 GHz and 1.3 GHz, respectively, while at position 2 peak E-field values of 0.02 V/m and 2.9 V/m were measured at at 1.09 GHz and 1.3 GHz, respectively.

In order to provide the readers with a complete overview of the exposure to EMF fields below 6 GHz at the chosen measurement sites, Table 3 lists measured values in the 100 kHz to 6 GHz range using a broadband field

Fraction $< 3\,GHz$ $(1-p)$ (%)	Fraction $> 3\,GHz$ p(%)	$P_{abs,real}(p)(nW)$					$\frac{P_{abs,real}(p)}{P_{abs,real}(100\% < 3\,GHz)}(.)$				
		Drone	Worker 1	Worker 2	Larva	Queen Bee	Drone	Worker 1	Worker 2	Larva	Queen Bee
100	0	0.63	0.010	0.26	0.73	0.71	1	1	1	1	1
90	10	2.5	0.57	1.2	3.0	2.3	3.9	5.7	4.6	4.2	3.3
80	20	4.3	1.0	2.1	5.3	3.9	6.8	10	8.2	7.4	5.6
70	30	6.2	1.5	3.1	7.6	5.6	9.7	15	12	11	7.8
60	40	8.0	2.0	4.0	9.9	7.2	13	20	15	14	10
50	50	9.8	2.4	5.0	12	8.8	16	25	19	17	12
40	60	12	2.9	5.9	15	10	18	29	23	20	15
30	70	14	3.4	6.9	17	12	21	34	26	23	17
20	80	15	3.9	7.8	19	14	24	39	30	26	19
10	90	17	4.3	8.8	22	15	27	43	33	30	21
0	100	19	4.8	9.7	24	17	30	48	37	33	24

Table 4. Absorbed power in the four studied insects for an incident electric field strength of 0.06 V/m, distributed uniformly over frequencies lower and higher than 3 GHz for different relative fractions.

probe. All the average values are higher than what is obtained from the frequency-selective measurements presented in Table 2, as should be the case since a broader band is considered.

Estimation of realistic RF-EMF absorbed power in honey bees. Using the results presented in Table 2, one can rescale the P_{abs} values shown in Fig. 5 in order to obtain a realistic estimate of the absorbed RF-EMF power in honey bees $P_{abs,real}$. The third to eight columns of the top row of Table 4 list $P_{abs,real}$ assuming that all incident $E_{rms} = 0.06\,V/m$ is uniformly distributed over the simulated P_{abs} values lower than 3 GHz. These values range from 0.1 nW for Worker 1 until 0.7 nW for the Larva and Queen Bee. In each subsequent row, 10% of the incident power density is transferred to frequencies higher than 3 GHz. This causes an increase in the estimated $P_{abs,real}(p)$. In order to quantify this increase, the five columns to the right show the relative increase in $P_{abs,real}(p)$ as p increases from 0 to 1. A full shift of all RF-EMF power to frequencies higher than 3 GHz - without changing the incident field strength - would result in relative increases in absorbed power between a factors 24–48 for the studied honey bee models. Even a relatively small shift of 10% of the incident power density to higher frequencies will lead to a relative increase in P_{abs} of a factor higher than 3, see Table 4.

Discussion

This study investigates RF-EMF absorption in Western Honey Bees as a function of frequency in the 0.6 to 120 GHz range. To this aim, we used five different models of different honey bees: two workers, a drone, a larva, and a queen. These models were obtained using micro-CT imaging and used for FDTD simulations. These were used to evaluate far-field exposure of honey bees. This far-field exposure is modeled as a set of plane waves at harmonic frequencies between 0.6 and 120 GHz. The numerical simulations resulted in P_{abs} as a function of frequency for the different studied honey bees. These simulations were combined with real RF-EMF exposure measurements near bee hives in Belgium in order to estimate realistic exposure values for honey bees.

Micro-CT imaging is a technique that has previously been shown to accurately scan insects[35,36]. The models used in this study have resolutions between 0.02 mm and 0.25 mm, which is larger than the resolution of the micro-CT models using in[11]. Since the smallest grid step used in our simulations is 0.05 mm, the ideal resolution of the insect models would be smaller than that. The larger resolution of the scanning is not a problem for the stability of the FDTD algorithm, but more spatial resolution could be obtained with the same simulation settings. It is expected that the micro-CT models used in this study lead to a better estimation of P_{abs} and the spatial distribution of the electric fields than approximate models such as ellipsoids or cylinders[37].

The results of our numerical simulations, see Fig. 5, show an increase of P_{abs} with frequency up to 6–12 GHz. Figure 4 illustrates the mechanism behind this increase: as the frequency increases the EMFs are less likely to diffract around the honey bees, that are relatively small in comparison to the wavelengths $< 6\,GHz$, and can penetrate further in the models, generating higher internal electric fields and consequently higher P_{abs} values. Figure 4 also shows why the whole-body averaged P_{abs} does not increase beyond 12 GHz. As the conductivity increases, see Table 1, the electric fields will decay faster within the honey-bee phantoms, which leads to larger relative volumes within the insect with lower fields, see Fig. 4, which will also contribute to the whole-body averaged P_{abs}. This effect also causes the P_{abs} to have a smaller dependency (variation) on incident angle and polarization, see Fig. 5. We also observe that both the frequency-dependency of the P_{abs}, i.e. the transition point between sharp increase in P_{abs} over frequency and slight decrease over frequency, and the magnitude of the P_{abs}, i.e. the offset of the P_{abs} curve, depend on the honey bee's size. This effect was previously observed in[11]. In general, the results presented in this manuscript are in excellent agreement with those presented in[11]. The results in terms of P_{abs} obtained for the honey bees in this study fall right in between those obtained in[11] for the smaller Australian Stingless Bee and the larger Desert Locust, which confirms again the dependency of P_{abs} on phantom size. The same size-related effect was described for humans in[28,33,38] and comparable frequency trends were observed in humans that have larger full-body sizes at MHz frequencies[28,38]. It should be noted that this manuscript focused on exposure of individual insects in free space. In reality, honey bees might cluster, creating a larger absorption cross section and potentially higher absorption at lower frequencies.

The FDTD simulations presented in this manuscript use dielectric properties that were obtained from the literature survey executed in[11]. Ideally, these dielectric parameters would be obtained for the honey bees studied in this manuscript. However, as shown in[11], most studies on dielectric properties of insects in literature[3,39–41] show similar frequency dependencies of those dielectric parameters. We have executed additional numerical simulations to test for the uncertainty on the dielectric parameters and found deviations up to 210% on P_{abs}, which is significant but still smaller than the variations that exist due to changing angle of incidence and polarization at a fixed frequency, or changes in frequency. We modeled the insects as homogeneous dielectric objects, while in reality they have heterogeneous dielectric parameters. Even though the FDTD algorithm will always require an averaging of dielectric parameters over the cube size, further developments in honey bee and insect phantoms should be focused on the inclusion of multiple tissues in order to refine these models.

In-situ RF-EMF measurements were executed using a measurement set up consisting out of a spectrum analyzer connected to an isotropic, triaxial antenna according to the measurement procedure listed in[32]. We measured total incident E_{RMS} between 0.016 V/m and 0.226 V/m in five rural environments with a linear average of 0.06 V/m and a quadratic average of 0.1 V/m. Joseph *et al.*[32] measured a median total E_{RMS} value of 0.09 V/m over several rural locations in Belgium, the Netherlands, and Sweden. Bhatt *et al.*[1] measured an average E_{RMS} value of $0.07 \pm 0.04\ V/m$ in rural environments in Belgium. Both previous studies of rural RF-EMF exposure are close to what we found in this manuscript and certainly within the measurement uncertainty of 3 dB on our measurements.

As our RF-EMF exposure measurements near bee hives demonstrate, see Table 2, most of the current RF-EMF exposure is located at frequencies $\leq 1\ GHz$. Additionally, Fig. 5 demonstrates that the P_{abs} in all studied Honey bee models is lowest at frequencies $\leq 1\ GHz$. This implies that in reality, potential shifts in telecommunication frequencies to higher frequencies might induce even larger increases that the ones estimated in Table 4 since in that analysis an average value over all P_{abs} values $\leq 3\ GHz$ is assumed.

Strengths and limitations. This manuscript presents several contributions to the state of the art in the field of RF-EMF exposure assessment of insects. First, to the best of the authors' knowledge, this is the only paper where a numerical RF dosimetry is presented for different developmental stages of honey bees. Second, this is the only study that combined real, *in-situ* exposure measurements with numerical simulations of RF-EMF exposure of insects in order to estimate a realistic exposure of honey bees. In comparison to our previous study[11], we considered a broader frequency range from 0.6 GHz up to 120 GHz, which is more in line with the frequencies used in the current telecommunication networks (3 G and 4 G). Finally, this study presents a unique quantification of real-life exposure of honey bees and estimations of how this might change if future frequency shifts in that exposure might occur. A disadvantage of this study is that we did not executed dielectric and thermal measurements in order to obtain dielectric and thermal properties of the studied honey bees. We obtained dielectric properties from literature and were able to execute electromagnetic simulations. We did not perform thermal simulations in this study. Another disadvantage is that we modeled far-field exposure by a limited number of plane waves, while previous studies have shown that a large set of plane waves is necessary to properly model far-field exposure[26]. We did executed a validation of our exposure set up by comparing it with a set of random plane wave exposures and found good correspondence, certainly close to the mean/median. Finally, we used FDTD simulations that are faced with uncertainties[29] and used models that have a limited spatial resolution. This is a disadvantage of any RF-EMF simulation study in comparison to a study that relies on measurements of real insects.

Future research. Our future research will focus on executing exposure measurements of insects in order to validate the RF-EMF P_{abs} values and the dielectric parameters. Additionally, we would like to execute thermal simulations of honey bees and other insects under RF-EMF exposure. Finally, we aim to work on the development of more insect phantoms, with more spatial accuracy and potentially several independently identified tissues.

Conclusions

Exposure of Western Honey Bees (*apis mellifera*) to radio-frequency (RF) electromagnetic fields was studied using a combination of *in-situ* exposure measurements near bee hives in Belgium and numerical simulations. The simulations use the finite-difference time-domain technique to determine the electromagnetic fields in and around five honey bee models exposed to plane waves at frequencies from 0.6 GHz up to 120 GHz. These simulations lead to a quantification of the whole-body averaged absorbed radio-frequency power (P_{abs}) as a function of frequency. The average P_{abs} increases by factors 16 to 121, depending on the considered phantom, when the frequency is increased from 0.6 GHz to 6 GHz for a fixed incident electric field strength. A relatively small decrease in P_{abs} is observed for all studied honey bees between 12 and 120 GHz. RF exposure measurements were executed on ten sites near five different locations with bee hives in Belgium. These measurements resulted in an average total incident RF field strength of 0.06 V/m, which was in excellent agreement with literature. This value was used to assess P_{abs} for those honey bees at those measurement sites. A realistic P_{abs} is estimated to be between 0.1 and 0.7 nW for the studied honey bee models. Assuming that 10% of the incident power density would shift to frequencies higher than 3 GHz would lead to an increase of this absorption between 390–570%. Such a shift in frequencies is expected in future networks.

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Author contributions

A.T. conducted the numerical simulations, analyzed the results, and drafted the manuscript. L.V. conducted the measurements. M.K.G. conducted the imaging and post processing of the imaging. W.J and L.M. contributed to analyzing the methodology and results. All authors reviewed the manuscript and provided input to the different sections.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to A.T.

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Tree damage caused by mobile phone base stations

An observation guide

By Helmut Breunig

Photos and RF measurements by Cornelia Waldmann-Selsam
Additional photos by Alfonso Balmori, Helmut Breunig, Örjan Hallberg, Volker Schorpp and Monika Schuberth-Brehm

March 2017

Why an observation guide?

Since the rollout of GSM mobile phone networks in the 1990s, scientists have criticized that the effects of radiofrequency or RF radiation (microwaves) on living organisms and the environment have not been sufficiently studied. In the setting of exposure limits for mobile phone base stations, RF radiation effects on plants have not been considered. In view of the explosive proliferation of the diverse wireless communication technologies across the entire environment and almost all areas of life, this represents an uncovered risk. This is why available studies and documentations on how RF radiation affects and damages trees engage our particular attention. They contain important evidence that justifies the urgent call for further thorough investigations. No research, however, has been initiated by the established science community and official radiation protection agencies to date.

The observation guide presented here is meant to encourage independent observations and documentations of trees and any damage they may sustain through exposure to radiofrequency radiation. It builds on the work and foundational findings of BERNATZKY, BALMORI, SCHORPP, HALLBERG, WALDMANN-SELSAM, and others.

In light of the increasingly visible consequences of climate change, the continuation of their work is an important step toward forming an independent judgment. This is all the more important since the observations described here will take extra efforts – especially in view of the massive climatic changes – to ensure that this issue is not denied the scientific recognition by the established research community it deserves.

This call for research is based on the reasonable suspicion suggesting an association between health symptoms in humans and damage in trees at locations in the line of sight of mobile phone base stations, which was pointed out by EGER and WALDMANN-SELSAM.

Why observe trees?

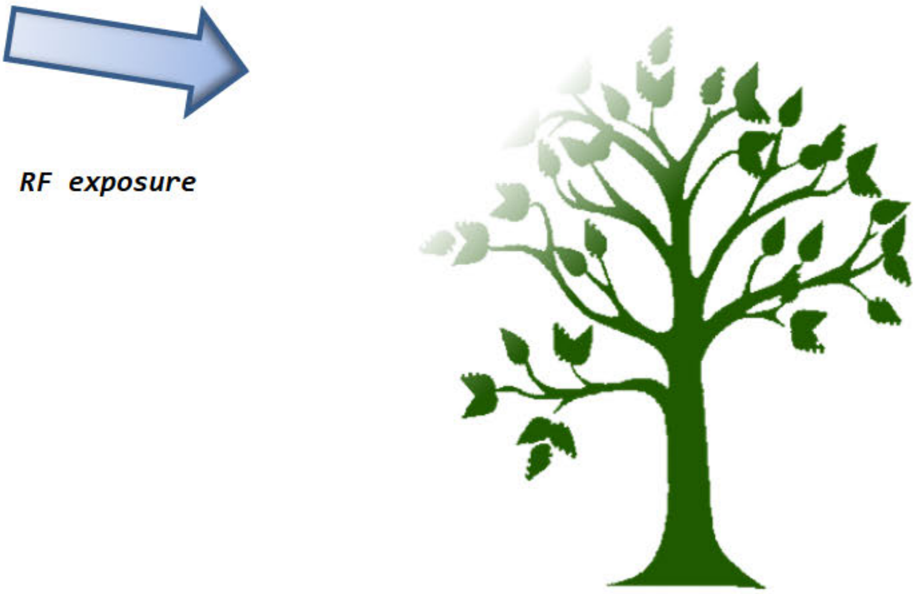
As stationary and perennial living organisms, trees are well suited for studying the question as to whether radiofrequency emissions from phone masts may cause damage in plants. The observation guide is designed to help *observers recognize visible crown damage in free-standing trees exposed to radiofrequency radiation. The photos show typical damage patterns and thus can sharpen the observer's eye. Based on this observation guide, scientists and laypersons alike can systematically observe trees in their immediate living environment or in other regions when they travel.*

In urban areas, it is not uncommon that trees are located within the exposure area of different phone masts from multiple directions. In crowns of free-standing (solitary) trees, which are exposed to RF radiation from one side only, it is rather easy to show the signs that may indicate a possible exposure to RF radiation. Advanced stages of sustained damage are best suited for describing the typical characteristics. This is also how the examples for this observation guide have been selected. The majority of the examples are deciduous trees.

Based on the analysis of advanced patterns of damage and their development, general characteristics for the crown damage in exposure areas of RF transmitters can be derived, which, in turn, can help recognize damage in trees with a less advanced stage and under conditions where the exposure occurs from multiple directions.

Observation of one-sided crown damage in trees in the line of sight of mobile phone base stations

Visual signs include irregular leaf coloration, leaf wilt, leaf loss, temporal and spatial irregularities in the seasonal leaf color change and leaf loss, fewer shoots, greatly elongated shoots with foliage at the tip and bare patches farther down the shoot, changes in branching patterns, and dead limbs and branches. The damage is most prominent at the edge on one side of the crown. This area is referred to as the starting point of damage. From there, the damage decreases in its intensity toward the opposite side of the crown that may be less affected or not at all. The crown volume, which is damaged within this geometric space, is referred to as the damage area. It will continue to develop further over the course of several growing seasons.



The geometry of the crown damage points to an abiotic, atmospheric, exposure-related factor of influence.

If, in the case of a free-standing tree, the starting point of damage is in line of sight of an RF transmitter, it is reasonable to suspect that the damage pattern may be caused by the exposure to the RF radiation of the RF transmitter.

The RF measurements, as stated for selected photos below, were taken by WALDMANN-SELSAM, using the EMF-broadband analyzer HF59B (27–3300 MHz) with the horizontal-isotrope antenna UBB27_G3 (Gigahertz Solutions), in some cases in conjunction with a 6 m (ca. 20 ft) long telescopic rod. It is not the intention of the RF measurements to provide a detailed RF radiation exposure analysis for a given location. This basic measurement method, however, is sufficient in demonstrating that a given crown may only be exposed from one side, that the worst damage occurs at the side of the tree with the highest RF exposure levels facing the RF transmitter, and that the damage patterns described in the observation guide occur at exposure levels well below currently valid exposure limits.

The presented agreement of the measurement results with the visual observations makes existing associations more transparent and thus demonstrates that the observation method described here is well suited to

generate meaningful documentations, even without measuring the actual RF exposure levels.
In conjunction with heat, cold, drought, soil composition, soil compaction and sealing, salting, air pollutants, soil contaminants, and pests, different types of crown damage can occur. By observing negative effects on the foliage, spatial orientation and crown damage development over time described here, specific characteristics of the exposure pattern due to radiofrequency radiation become apparent.

Linden tree, July 2015
Well-developed tree crown in the city
No RF transmitter in the line of sight

Norway maple tree, August 2012
Badly damaged tree crown on the side facing an RF transmitter

At both locations, soil sealing is a concomitant adverse factor. The difference in the crown pattern, therefore, is most likely not a result of soil sealing.

At the location of the red oak tree shown here, none of the known stress factors are obvious. Still, the crown is damaged in a way that corresponds to the above-shown graph. The tree is in the line of sight of a nearby mobile phone base station.

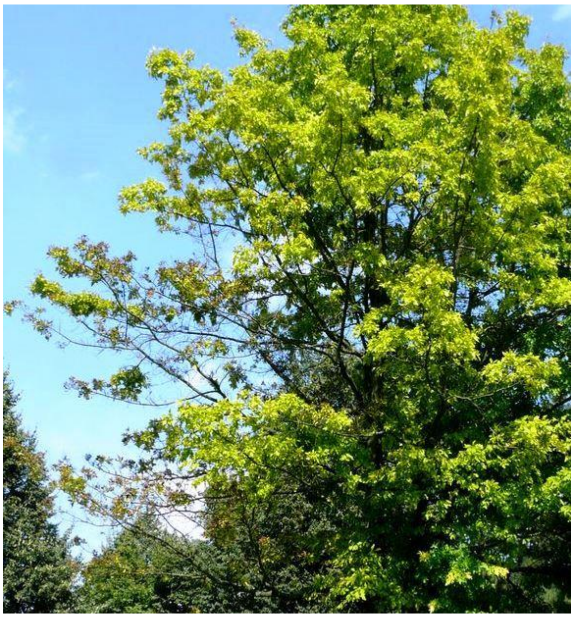
Exposure ->

Red oak tree, August 2013

The direction of the RF emission source and the location of the starting point of damage on the side of the tree facing the mobile phone base station coincide with each other.

Red oak tree, August 2013

Red oak tree, August 2015



Section of red oak tree, August 2013

Section of red oak tree, August 2015

The damage area spreads across the crown over the course of the coming years. At the individual branches, the sight is similar to drought damage. The spatial and temporal development of the damage area as a whole, however, is not typical for drought damage that occurs as a result of a lack of water at the roots.

The loss and discoloration of the leaves is most prominent where the tree faces the RF transmitter. The spread of the damage area follows a pattern independent of the branch architecture of the tree.
The location of the damage area is independent of the natural environment and the sky direction.

Tree damage in the line of sight of RF transmitters has already been extensively documented. The damage in these documentations shows diverse patterns and developmental stages (see Documentations).

The photos presented here place a special emphasis on the unique damage pattern due to RF radiation exposure from one side.

Some of the photos also show the location of the tree crown in relation to the associated RF transmitter within sight. If the RF transmitter is not shown, the distance to the RF transmitter is given.

Examples of different spruce trees show that similar damage patterns can also be observed in conifers to various degrees.

Exposure from the right side,
260 m (ca. 850 ft)

Spruce, October 2010

Exposure from the right side,
190 m (ca. 620 ft)

Spruce, March 2012

Exposure from the left side,
200 m (ca. 660 ft)

Spruce, June 2003

Exposure from the left side,
310 m (ca. 1000 ft)

Spruce, October 2008

The damage decreases on the side of the crown facing away from the RF transmitter (damage gradient), which can be explained by the attenuation effect of the foliage. Due to the absorption and scattering of the RF radiation along its path through the foliage, the power flux density of the RF radiation decreases (used measurement unit: microwatt per square meter = µW/m²). Comparison measurements between the side of the tree crown facing the RF transmitter and the side facing away from it confirm this.

Exposure from upper left ->

Norway maple tree, June 2015

Measurement:	*Side facing the RF transmitter:*	*Opposite side:*
14 July 2015	*2,100 µW/m²*	*290 µW/m²*

The agreement between the spatial orientation of the damage gradient and the gradient of the RF measurements suggests that the damage is associated with the RF radiation exposure from the RF transmitter.

According to the Twenty-sixth Ordinance Implementing the Federal Immission Control Act, *German exposure limits for mobile phone base stations range from 4,500,000 to 10,000,000 µW/m², depending on the respective mobile phone network.*

May 2013

July 2016

The damage increases over the years and spreads from the direction of the RF transmitter across the crown. No regeneration can be seen. This is a sign of chronic exposure to a damaging factor. The RF exposure from the mobile phone base station within sight began between 2006 and 2008.

Observing the development of the damage over the long term provides insight into the unique characteristics of the damage.

May 2013

June 2014

June 2015

The tree is located at a strip of greenery, running in a north-south direction. To the east (foreground), the root area is sealed by a traffic area. The damage area points toward south where the RF transmitter is located. Despite the less than favorable climate conditions at this side, the crown on the north side has expanded.

At the upper left – where the RF radiation hits the crown – the dieback at the edge is the most severe.

The annual increase in leaf loss most likely can be traced back to an impairment of the buds in the year before. The resulting decreased level of shoots for leaves and branches causes the closed crown to open at those points, whereby one quarter of the crown outline starts breaking up.

With increasing leaf dieback, the attenuation effect of the foliage decreases, starting at the edge of the crown.

Inside the crown, there are naturally less leaves because of shadow

July 2016

effects. This is why – after the more dense foliage at the crown edge has receded – it is easier for the RF radiation to cross over to the other side of the crown. As a result of the increasing RF exposure level, the crown then also starts to lose leaves in this opposite area and thus the tree's inherent attenuation also decreases. In this way, the damage area spreads from the inside to the outside of the side of the crown edge facing away from the RF transmitter.

April 2015
In bloom

The more the branches and buds are protected by the attenuation inherent to the crown, the higher the density of the flowering shoots will be.

Due to the crown dieback at the side facing the RF transmitter, more light reached the inside of the crown, resulting in shorter shoots with buds on branches closer to the trunk compared to the right side.

February 2017

After renewal pruning

Because the right side of the crown had denser foliage, the inside of the crown experienced more shade. Consequently, the shoots are more elongated, trying to reach the edge with more light exposure, resulting in less branching along the way. After pruning, the crown then has less buds for renewal at this side.

The renewal of pruned crowns, which are exposed to radiofrequency radiation, should be included in observations.

If trees, which are lined up in a row, show all damage on the same side, this may also be a sign of RF radiation causing damage to the crowns.

June 2016

<-Exposure from upper right

Distance 730 m (ca. 2400 ft)

July 2008

Month not known 2010

Sycamore maple tree

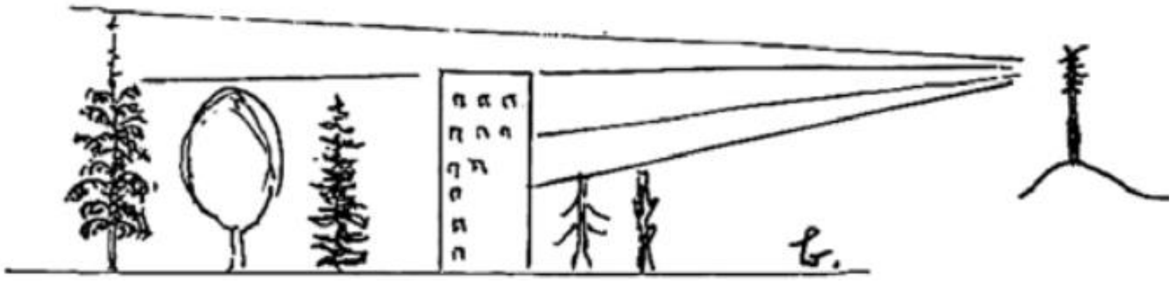
Starting point of damage and damage gradient coincide with the direction of the RF emission source. The damage increases over the years.

If the RF radiation exposure comes from above, the damage is particularly prominent at the top of the tree.

Gleditsia tree
September 2011

Beech trees,
June 2009

Crowns can show damage when a tree stands in front of a building that faces an RF transmitter and also when a tree stands behind such a building if the treetop reaches above the rooftop.



(Figure taken from BERNATZKY 1994)

The following example shows a situation similar to the tree in the above graphic in the upper left.

Exposure from the right above the rooftop

Cherry tree, September 2012

Distance to multiple RF transmitters 150-500 m (ca. 500-1600 ft)

June 2015

Trees of the same species planted along a roadside are especially well suited for comparing RF radiation exposure patterns. The trees in the radio shadow of the building show a different pattern compared to those exposed directly to RF radiation.

RF radiation exposure ->

Tree-lined road Turkish hazel trees,

June 2008

Tree-lined road Turkish hazel trees,

August 2013

The Turkish hazel trees on the left are mostly in the radio shadow of the buildings. The line of trees on the right side of the road are more exposed; both directly and indirectly (reflection from buildings). The bare shoots and dead twig tips of the transparent crowns of the trees on the right side of the road reveal the level of stress caused by the RF radiation.

The shielding effect of buildings can be demonstrated with measurements of the RF exposure levels. In the radio shadow, the tree crowns are only marginally affected.

Distance to RF transmitter 130 m (ca. 430 ft)

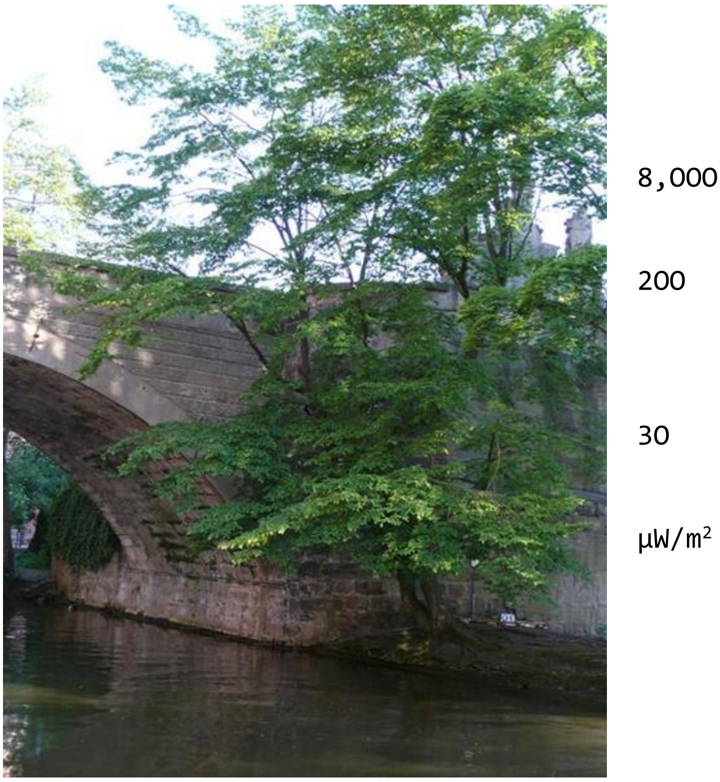
Exposure and view from south — *Maple tree*, *Hornbeam tree*

View from north — *Hornbeam tree*, *Maple tree*

October 2009

In spring, dead branches were removed

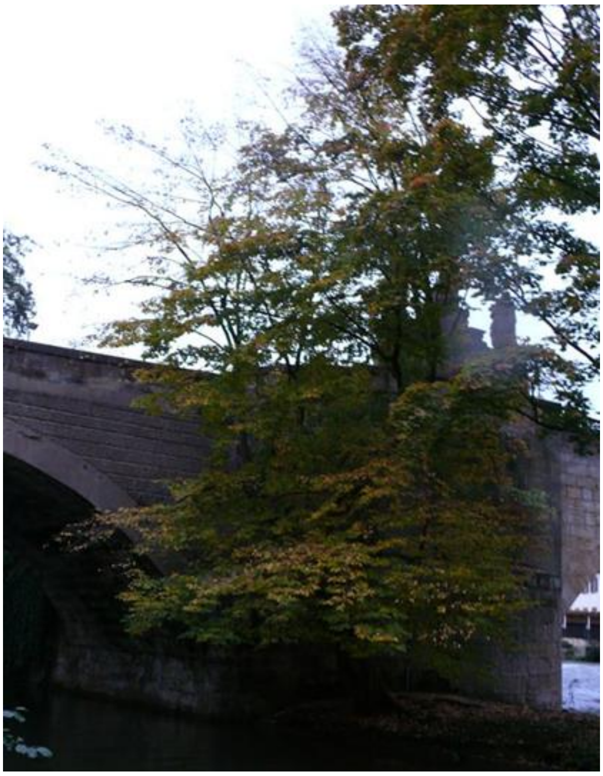
July 2012



RF measurements, May 2012

Maple tree Hornbeam tree

October 2014



Hornbeam tree Maple tree

The upper part of the crown that reaches above the bridge structure is exposed by an RF transmitter. Despite excellent light conditions and a good water supply, leaf loss occurs at this location. The lower part of the foliage is dense and healthy because it is protected by the bridge structure.

Microwave exposure from a traffic radar <-

Viburnum hedge in a strip of greenery

The damage area in the foliage of the hedge clearly delineates the focused exposure area of the radar.

A disparate fall coloration inside the crown with regard to its timing can be conspicuous. The one-sided discoloration of the foliage occurs on the side facing the RF transmitter.

RF exposure from the upper left ->

Distance to RF transmitter 60 m (ca. 200 ft)

Hornbeam tree, October 2010

At the edge facing the RF transmitter, the leaf loss and the coloration differences within the crown show the damage gradient from the starting point of damage to the damage area.

Ash trees naturally lose their leaves in fall without major discoloration. If the leaves of one tree start falling in different areas of the crown at different times, this can be the result of a one-sided RF exposure. This characteristic requires observing the tree over several years. Thus it would be possible to distinguish the damage from the acute effects of frost, which can be caused by cold air that blows in from the side.

Ash tree, October 2016

Tree site at a slope

<- Exposure from the right from RF transmitter a the same height, distance 500 m (ca. 1600 ft)

In winter, bare crowns of deciduous trees will reveal differences in their sides, if applicable, which would indicate an exposure to RF radiation.

RF exposure from the left from a distance of 320 m (ca. 1050 ft)

->

Sycamore maple tree, February 2017

The branching differs between the left and the right side.
On the side of the crown facing the RF transmitter, less branching of branches and shoots occurs. The closed crown starts opening from the left and above.

*At the side **facing the RF transmitter,** the closed crown starts opening and areas of dieback become visible as a result of less branching.*

*At the side of the crown **facing away from the RF transmitter,** branching is clearly much denser. The edge of the crown looks smoother and closed.*

Characteristics of damage to the foliage of free-standing trees in the case of one-sided radiofrequency exposure from mobile phone base stations over a longer period:

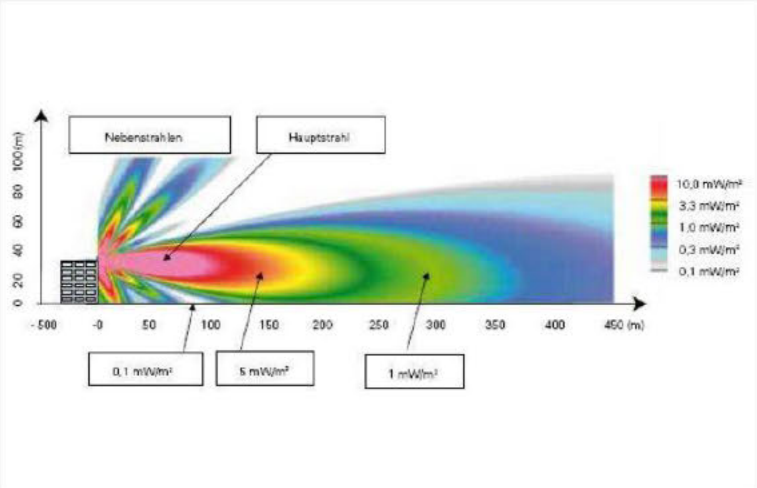
- ***The decrease in foliage starts at the edge of the crown (starting point of damage).***
- ***Over the following growing seasons, the process of receding foliage will spread from the starting point of damage across the crown to other areas (damage area).***
- ***The gradual spread of the damaged area follows the spatial pattern of decreasing attenuation provided by the foliage.***
- ***At all sites, the tree crown is in the line of sight of a RF transmitter.***
- ***This type of damage occurs at sites where conditions vary in their suitability for tree growth.***

The damage patterns described here, which are suspected of being caused by adverse effects of RF radiation, require observations over several years. It is possible then to follow the characteristic development of the damage area over time to distinguish it from the damaging effects of other factors.

You can sharpen your observational eye to detect the typical damage patterns by observing trees over longer periods that have mobile phone base stations installed nearby or have been newly planted next to RF transmitters. When older trees are cut or pruned, checking if the tree is in the line of sight of RF transmitters can be revealing.

Evaluation of observations

Conventional antennas of mobile phone base stations emit RF radiation either in all directions (omnidirectional antennas) or in a particular direction with main and side lobes, focused vertically and horizontally (directional or sector antennas). A sector antenna commonly covers a horizontal area of 120°.



The simulation shows how the transmit output of a sector antenna propagates through space. In addition to the main lobe, which covers the far-field area, there are also side lobes at certain angles.
Source: LfU

Haupstrahl = main lobe

Nebenstrahlen = side lobes

(Figure taken from Bayerisches Landesamt für Umwelt*)*

The incident RF radiation is reflected, scattered, and diffracted at buildings and the landscape. As a result, the spatial distribution and intensity of the RF electromagnetic field is rather inhomogeneous. In turn, the RF exposure levels at trees in the same location, which are standing in the line of sight of an RF transmitter, can vary greatly. Even the area of the crown that sustains the highest exposure can be at different heights. For example, the pictures of the red oak tree (p. 5-6) clearly show how the opening up of the closed crown can occur midway up the crown.

Both in general and in the vicinity of mobile phone base stations, damage to tree crowns can occur in different locations for various reasons.
If, in a line-of-sight exposure area of RF transmitters, there are trees with clear patterns of damage and trees with little or no obvious damage, the best practice approach in epidemiology (BRADFORD-HILL) does not allow for the conclusion that the existing damage could not have been caused by the exposure to the RF radiation from the RF transmitters as long as this has not been verified by an in-depth investigation of the matter.
Therefore, the exposure to RF radiation should always be considered by the environment and parks agencies when assessing damaged trees.

Typical city view with trees in the vicinity of mobile phone sites
July 2015

The linden trees to the left in the blind spot near the antennas (marked) don't seem to be adversely affected. Other trees in the background along the road and the newly planted tree in front of the building all are in the line of sight of the RF transmitters on the rooftop. Here we can recognize damage to the shape of the top of those trees and to the density of their foliage.

Due to the limited knowledge in this research area, it cannot be ruled out at this time that differences among trees in the line of sight of a given RF transmitter may also be traced back to characteristics of the tree species and their provenances.
The expectation that trees within the exposure area of a given mobile phone base station should respond in the same way is therefore unfounded as long as this matter has not been studied in depth.
Furthermore, crown damage can be caused by different factors that overlap with each other. In laboratory studies, it could be demonstrated that RF radiation is capable of triggering physiological stress responses in plants. This finding suggests that we should focus our observations on whether the damaging effect of a possible additional stress factor tends to be more prominent on the side of the crown exposed to RF radiation. For example, it should be noted if the point from which the damage spreads and the incidence and degree of infestations with e.g. fungi, viruses, worms, and insects are associated in any way with the side of the tree facing an RF transmitter.

The same basically also applies to other common natural and technical factors, which may only affect one side of the tree such as wind direction, solar exposure, traffic exhausts, road salt, root and trunk damage.

The initial stages of damage development caused by heat, drought due to a lack of water in the soil, root damage, damage to the water pathways in the tree, and limited frost damage may at first sight look like a crown damaged by the exposure to radiofrequency radiation.

The more the damage of the crown advances, as can be observed as the result of the chronic exposure to radiofrequency radiation over several growing seasons, the clearer the distinguishing characteristics become. "The damage follows a path along the direction of the RF radiation" (see the documentation by SCHORPP, 2007).

At any location without RF radiation exposure, it should be rather unlikely to find a damage pattern as shown here.

Maple tree, September 2006

SCHORPP points out that the inhomogeneous emissions of the antennas as well as the reflection, diffraction, and scattering effects at buildings may lead to well-defined, small-area differences in power density levels.

These types of crown dieback are new and only occur around built environments.

In this case, an explanation that only refers to known damaging factors does not cut it.

The above presentation regarding one-sided crown damage – describing the characteristics of temporal and spatial patterns in shape and color, while considering various site factors – demonstrates that no other damaging factor is known at this time that could regularly cause the above-described damage patterns in crowns of free-standing trees.

In this observation guide, the selection of damage patterns is limited to the ones presented for didactic reasons. There are many additional types and developmental stages of visible crown damage caused by radiofrequency radiation (see Documentations). We lack comprehensive documentations on the hazard assessment to date. To justify the lack of a systematic investigation into this type of crown damage with the notion that only a few such observations have been made so far bears the risk of overlooking a new threat to the environment and humanity.

In times of climate change, to what extent will efforts to maintain trees in urban areas for their balancing effect be challenged if we do not consider the consequences of chronic RF radiation exposure?

Tree crowns in a strip of greenery become damaged through the exposure to ***radiofrequency radiation***
July 2008

In an urban green space, healthy tree crowns in the radio shadow
August 2015

Scientific application of the observation method

Owing to the new and unique type of damage pattern, an in-depth investigation into its causes seems indicated and can be carried out with relatively little effort. The above-described observation method can serve as a guide for locating and assessing crown damage in trees. By applying the knowledge of the developmental characteristics of the above-described type of crown damage, it is possible to also include less advanced levels of damage.

For the study **Radiofrequency radiation injures trees around mobile phone base stations,** *60 trees with the above-described damage pattern were located in the cities of Bamberg and Hallstadt, some of which have been documented over the course of several years.*

The visual inspections at each location revealed that, in the case of one-sided crown damage, it was exclusively the damaged side facing an RF transmitter. The RF exposure level measurements on the damaged side were on average about 2,000 µW/m² and on the opposite side about 200 µW/m².

Another group of 30 trees was randomly selected. Thirteen trees of this group had crown damage. The visual inspections revealed that six of the trees had crown damage only on one side of the tree, which was facing an RF transmitter; five of the trees had damage on more than one side all of which were facing RF transmitters on the respective damaged sides. One tree (spruce) with a damaged top also was in the line of sight of an RF transmitter, as was another tree that had dead parts of the crown removed. The RF radiation exposure levels for the trees of this group were on average about 1,600 µW/m² on the side facing an RF transmitter and about 600 µW/m² on the opposite side.

The crown damage occurred regardless of different soil characteristics of the tree locations such as sealing, strips of greenery, gardens, parks, in the vicinity of water bodies, etc.

The RF radiation exposure levels for the 17 trees of the randomly selected group that were not in the line of sight of any RF transmitter ranged from about 8 to 50 µW/m², both on the side with the highest reading and the opposite side.

In addition, a third group of 30 trees was located in an area with lower RF background levels where the trees were not in the line of sight of any RF transmitter. In those areas, the RF radiation exposure levels ranged from 3 to 40 µW/m². The difference in the RF radiation exposure levels between the two sides of a given tree was negligibly small, max. 10 µW/m². All 30 tree crowns did not show any signs of damage.

At all locations of the 47 trees with no line-of-sight connection to an RF transmitter and an overall low RF background level, no crown impairments as described above were visible.

The assumption that the type of crown damage described in this guide is caused by the exposure to radiofrequency radiation proves to be justified because

- ***this particular crown damage occurs at exposed locations in the line of sight of mobile phone base stations, and***
- ***at unexposed locations outside the line-of-sight exposure areas of RF transmitters, however, this crown damage does not occur.***

Documentations *(selection)*

- *SCHORPP, V., http://www.puls-schlag.org/dr-volker-schorpp.htm*
  2007: Baumschäden durch chronische Hochfrequenz-Belastungen?
  (Tree damage from chronic radiofrequency radiation?)
  2011: Tree damage from chronic high frequency exposure, The effect of electromagnetic radiation on trees, First symposium February 18, 2011, Lecture, Baan, Netherlands
  http://www.puls-schlag.org/download/Schorpp-2011-02-18.pdf
- *WALDMANN-SELSAM, C., 2016: Trees in Bamberg*
  http://kompetenzinitiative.net/KIT/wp-content/uploads/2016/09/Trees-in-Bamberg-and-Hallstadt-Documentation-2006-2016.pdf

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BRADFORD-HILL, A., 1965: The Environment and Disease: Association or Causation? https://www.edwardtufte.com/tufte/hill

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- *Waldmann-Selsam, C., Balmori-de la Puente, A., Breunig, H., Balmori, A., 2016: Radiofrequency radiation injures trees around mobile phone base stations* *https://www.researchgate.net/publication/306435017_Radiofrequency_radiation_injures_trees_around_mobile_phone_base_stations*

Contact:

This private manuscript was written by Diplom-Forstwirt Helmut Breunig (Diplom degree in forestry).

You can download the Observation Guide at:
Competence Initiative for the Protection of Humanity, the Environment and Democracy e.V.

http://kompetenzinitiative.net/KIT/KIT/new-observation-guide-tree-damage/

German version: http://kompetenzinitiative.net/KIT/KIT/beobachtungsleitfaden-baumschaeden-durch-mobilfunkstrahlung/

If citing this work, please provide the author's name and the Internet link of the document.

If you would like to contact the author regarding the contents of the Observation Guide, please send an e-mail to
Baeume.beobachten@gmail.com

Feedback and suggestions are always welcome. If you wish to send me photos, please contact me by e-mail before sending any photos.

Review Article

B. Blake Levitt*, Henry C. Lai and Albert M. Manville II

Effects of non-ionizing electromagnetic fields on flora and fauna, Part 3. Exposure standards, public policy, laws, and future directions

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Abstract: Due to the continuous rising ambient levels of nonionizing electromagnetic fields (EMFs) used in modern societies—primarily from wireless technologies—that have now become a ubiquitous biologically active environmental pollutant, a new vision on how to regulate such exposures for non-human species at the ecosystem level is needed. Government standards adopted for human exposures are examined for applicability to wildlife. Existing environmental laws, such as the National Environmental Policy Act and the Migratory Bird Treaty Act in the U.S. and others used in Canada and throughout Europe, should be strengthened and enforced. New laws should be written to accommodate the ever-increasing EMF exposures. Radiofrequency radiation exposure standards that have been adopted by worldwide agencies and governments warrant more stringent controls given the new and unusual signaling characteristics used in 5G technology. No such standards take wildlife into consideration. Many species of flora and fauna, because of distinctive physiologies, have been found sensitive to exogenous EMF in ways that surpass human reactivity. Such exposures may now be capable of affecting endogenous bioelectric states in some species. Numerous studies across all frequencies and taxa indicate that low-level EMF exposures have numerous adverse effects, including on orientation, migration, food finding, reproduction, mating, nest and den building, territorial maintenance, defense, vitality, longevity, and survivorship. Cyto- and geno-toxic effects have long been observed. It is time to recognize ambient EMF as a novel form of pollution and develop rules at regulatory agencies that designate air as 'habitat' so EMF can be regulated like other pollutants. Wildlife loss is often unseen and undocumented until tipping points are reached. A robust dialog regarding technology's high-impact role in the nascent field of electroecology needs to commence. Long-term chronic low-level EMF exposure standards should be set accordingly for wildlife, including, but not limited to, the redesign of wireless devices, as well as infrastructure, in order to reduce the rising ambient levels (explored in Part 1). Possible environmental approaches are discussed. This is Part 3 of a three-part series.

Keywords: aeroecology; electroecology; International Council on Non-ionizing Radiation Protection (ICNIRP); Migratory Bird Treaty Act (MBTA); National Environmental Policy Act (NEPA); non-ionizing electromagnetic fields (EMFs); radiofrequency radiation (RFR); rising ambient levels; U.S. Federal Communications Commission (FCC).

***Corresponding author: B. Blake Levitt,** P.O. Box 2014, New Preston, CT 06777, USA, E-mail: blakelevitt2@gmail.com, blakelevit@cs.com
Henry C. Lai, Department of Bioengineering, University of Washington, Seattle, WA, USA, E-mail: hlai@uw.edu
Albert M. Manville II, Advanced Academic Programs, Krieger School of Arts and Sciences, Environmental Sciences and Policy, Johns Hopkins University, Baltimore, USA, E-mail: amanvil1@jhu.edu

Introduction

This is Part 3 and concludes a three-part series on electromagnetic field (EMF) effects to wildlife.

Part 1 focused on measurements of rising background levels in urban, suburban, rural, and deep forested areas as well as from satellites. Discussed were different physics models used to determine safety and their appropriateness to current exposures. The unusual signaling characteristics and unique potential biological effects from 5G were explored. The online edition of Part 1 contains a Supplement Table of measured global ambient levels.

Part 2 is an in-depth review of species extinctions, exceptional non-human magnetoreception capabilities, and other species' known reactions to anthropogenic EMF exposures as studied in laboratories and in the field. All animal kingdoms are included and clear vulnerabilities are seen. Part 2 contains four Supplement Tables of extensive low-level studies across all taxa, including ELF/RFR genotoxic effects.

Part 3 discusses current exposure standards, existing federal, and international laws that should be enforced but often are not, and concludes with a detailed discussion of aeroecology—the concept of defining air as habitat that would serve to protect many, though not all, vulnerable species today.

Government exposure standards

Extremely Low Frequency (ELF)

In the U.S., there are no federal government exposure standards for humans, much less wildlife, for the extremely low frequency (ELF) bands between 0 and 300 Hz. Within this range are the 50–60 Hz exposures common to powerlines and electric utility wiring that continue to rise due to our increasing energy demands, as well as electric utility grounding practices that use the Earth itself as the return neutral for excess current back to substations. Today in many regions, rather than run additional neutral lines (at significant expense) on utility poles along roadways to handle the extra harmonic load that all of our new electronic and wireless devices place on the lines, utilities siphon off excess voltage every few poles apart directly into the ground. Earth itself becomes the neutral line, sometimes with significant accumulations near substations that can elevate contact currents in nearby homes and outdoor environments, affecting pets and urban wildlife, as well as on underground metal gas pipelines that can form dangerous corrosion and hotspots [1]. In addition, new technologies like "wireless electricity"—called wireless power transfer (WPT)—to charge electric vehicles, batteries, computers, and chargers are coming on the market, creating novel ambient wireless and DC power exposures that we have never seen before, spanning from ELF through the 9 kHz to 40 GHz frequency bands. The technology is in nascent stages but involves transmission of power via RFR, most likely in the microwave bands at 2.45 GHz, to a special receiver called a rectenna that then converts it back to DC power for use in an ELF ambient capacity. The goal is to get rid of wires. This is a completely new exposure to which many species of flora and fauna are sensitive (see Part 2). Such industrial-scale grounding practices and wireless ELF/RFR have never been studied as environmental factors for air, land-based, or underground wildlife. This includes potential damage to flora with vulnerable root systems in the ground while their primary growth is above ground level (AGL), making flora susceptible to both ELF and radiofrequency radiation (RFR) exposures. Standards-setting groups may soon turn attention to ELF in light of WPT that is coming on the market with virtually no environmental review.

The U.S. Federal Communications Commission

In the U.S., the Federal Communications Commission (U.S. FCC) has jurisdiction over the licensing of electromagnetic spectrum use between 100 kilohertz (kHz) and 100 gigahertz (GHz), which includes cable TV/Internet, amateur radio, AM/FM commercial broadcast stations, wireless cellular facilities, satellite communications, and all other communications devices/services (See Figure 1). There are adopted and enforceable exposure standards in the radiofrequency bands between 300 kHz and 100 GHz under FCC—a non-health agency that relies on other agencies and outside expert groups for advice regarding human exposures ([2, 3], and see Part 1). FCC's 1997 standards were reviewed and reaffirmed in 2020 with minimal changes [4].

The model for the FCC standards are human-centric, based on short-term, acute high-intensity exposures to RFR that are capable of heating tissue the way a microwave oven cooks food. Thermal heating effects were well-quantified decades ago and are reasonably easy to regulate while allowing technology to flourish. It is the ubiquitous lower intensity exposures that are problematic and unregulated (see Part 2, Supplement 3 for effects at very low intensity exposures).

It is important to understand that the FCC standards (and other similar models) are exposure limits, not emissions allowances from generating sources although the two are intricately linked. As such, the standards are distance related with accessibility to a generating source being the most important factor, and they are relevant only to locations that are accessible to workers and/or members of the public [2, 5, 6]. This means that despite safety factors built in to such standards, ambient levels are largely unregulated outside of built environments.

However, while standards by any group are derived with only humans in mind, all measurement factors are potentially relevant metrics to species in the wild. Thus the large body of research intended to help set exposure limits for humans are germane to determining new standards to protect wildlife, at least in some very broad ways. But in regulating for wildlife, factors involving rising ambient levels (see Part 1) must include both exposure and emission considerations, due to the increased sensitivity to EMF/RFR of many species (see Part 2) based on taxonomy, size, physiology, habitat, magnetoreception, seasonal

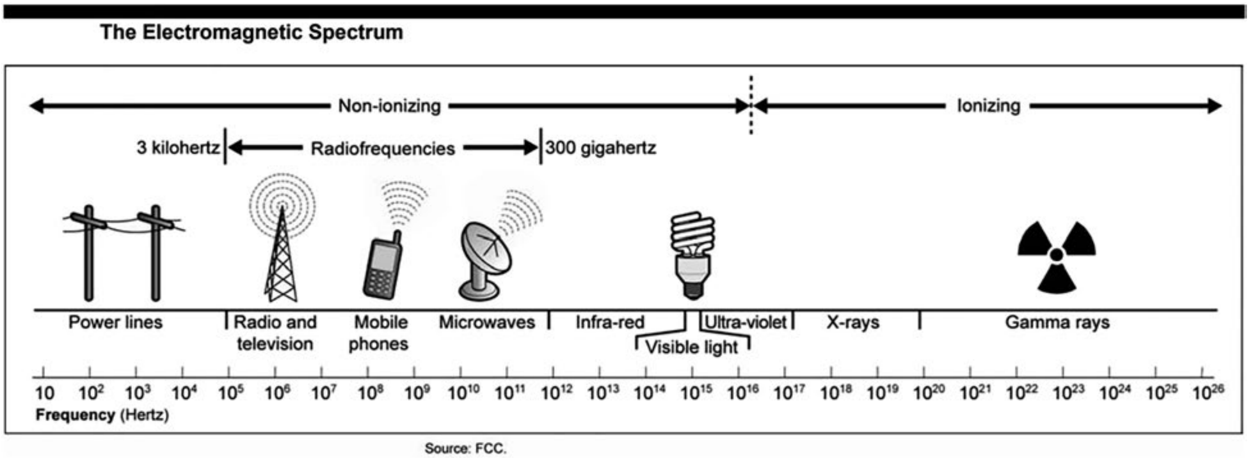

Figure 1: Illustration shows FCC area of regulatory responsibility between 100 kilohertz (kHz) up to the far microwave bands in the non-ionizing section of the spectrum. The frequency range for FCC limits cover from 300 kHz to 100 GHz. ([5] p. 3).

migration, and many other factors. Many airborne species, for example, have the ability to reach close proximities to antennas mounted on towers or buildings and routinely reach areas with detrimental levels of RFR even at some distance from transmitters. And several bird species fly at altitudes high enough to experience exposures from satellite systems that humans would never encounter. In essence, other species can experience both near-and-far-field exposures that humans rarely, if ever, experience and likely move in and out of such fields on a routine and/or seasonal basis.

Below is information on how governments regulate this subject regarding human exposures that point to possibilities for wildlife protection.

The U.S. FCC exposure standards are a two-tiered model based on recommendations from key regulatory agencies and two expert organizations: the National Council on Radiation Protection and Measurements (NCRP) report in 1986 [7, 8] and a subcommittee recommendation from 1992 to the American National Standards Institute (ANSI) by the International Electronics and Electrical Engineers (IEEE; [9]). The NCRP is a non-profit corporation chartered by the U.S. Congress to develop information and recommendations across many public and private sectors on radiation protection. The ANSI is a non-profit, privately funded, membership organization that coordinates the development of voluntary U.S. national standards used across all industry sectors. The IEEE is a non-profit, privately funded, technical, and professional/industry group that widely represents the technology sector with a membership of over 300,000 engineers and scientists worldwide; they have almost no biologists or members with medical backgrounds. ANSI, IEEE, and FCC are not health or environment-related entities, yet they play pivotal roles in non-ionizing radiation exposure regulation. NCRP does include human health expertise on their review panels. These various groups issue exposure guidelines. Once a government entity with enabling authority adopts such guidelines, they become enforceable and the government entity can require the private sector to abide by them as well as impose fines when they transgress. The FCC was given authority over RFR exposure standards adoption and enforcement by The Telecommunications (TCA) Act of 1996 [10].

At the impetus of the U.S. Environmental Protection Agency (U.S. EPA), the multi-agency Radiofrequency Interagency Working Group (RFIAWG) was formed in the 1990s. EPA, which has primacy over environmental radiation effects, was specifically defunded for non-ionizing radiation research and oversight in 1996 [11] just as the TCA was coming into effect. In lieu of EPA writing its own RFR exposure standards at the time—something they were poised to do and took criticism for not completing—EPA instead recommended a two-tiered exposure standard (see below) be adopted at FCC taken from recommendations by both NCRP and ANSI/IEEE, which FCC did in 1996. Subsequent to that, the RFIAWG also sent a letter in 1999 to the IEEE committee responsible for developing RF standards that listed 14 major topics and/or areas of concern related to any future revision of the IEEE standard [12]. Those concerns have yet to be addressed. The RFIAWG was comprised of key bioelectromagnetics scientists from seven or more U.S. federal regulatory agencies, representing health, the environment, and professional exposures (One of the authors of this paper was on RFIAWG representing the U.S. Fish and Wildlife Service). Although RFIAWG still exists on paper, it rarely meets, if at all, and is no longer the analytical advisory authority it once was to FCC. Consequently FCC regulates and issues rule-makings in an environmental vacuum, other than minimal comments provided by the Food and Drug Administration (U.S. FDA) which advises on devices like cell phones over which it has authority.

FCC is often now seen as an agency that is captured by the industries it is supposed to regulate [13] and because of cutbacks at key advisory agencies like EPA, FCC lacks the wider expertise upon which it relies to conduct thorough assessments regarding exposure safety [11].

What today's exposure standards measure

Most of the current guidelines used in Western countries are based on the specific absorption rate (SAR)—the rate of energy absorbed per unit mass of biological tissue with units expressed in watts per kilogram (W/kg) or milliwatts per kilogram (mW/kg) of tissue. Harmful effects from which the SAR was originally derived were based upon relatively few animal studies in the 1980s [14, 15] in which behavioral disruption was observed at approximately 4 W/kg when test animal body temperatures rose by about 1°C. Safety factors were built in to allow for unknown/unidentified effects and are reflected in the allowances noted below, but it is important to know that these additional margins are purely hypothetical. SARs are also studied on fluid-filled phantom laboratory models in the shape of human body parts, as well as cadavers which can never reflect the complexities of whole living electrodynamic organisms. SARs are extremely difficult, if not impossible, to measure in living models.

The FCC standards divide exposure allowances (based on the baseline or 4 W/kg) into two tiers legally defined as:

- **Occupational/controlled limits based on ANSI/IEEE:** Applies when people are exposed due to employment, provided they are fully aware of exposures and can exercise control over them. SAR is 0.4 W/kg, reflecting a safety factor of 10.
- **General population/uncontrolled limits based on NCRP:** Applies to when the general public may be exposed, or when people who are exposed as a consequence of employment may not be fully aware of potential exposure, or cannot exercise control over the exposure. SAR is 0.08 W/kg, reflecting a safety factor of 50.
- Limits are different for cell phone exposures when partial body exposure would be experienced and is derived by complicated methods of scaling from the whole body exposure. The SAR for partial body exposure is 1.6 W/kg measured over 1.0 g cube of tissue—a limit that all cell phones must meet in the U.S., and which is stricter than what is used in Europe as recommended by the ICNIRP guidelines (see below) at 2.0 W/kg averaged over 10 g of tissue. SAR evaluation continues to be required as the only acceptable compliance metric for portable devices below 6 GHz.
- In addition, there are whole-body SAR limits at 0.08 W/kg related to various factors including size, shape, and orientation toward a generating source, among other things. There are also higher SAR allowances for the body's extremities defined as hands, wrists, feet, and ankles, where the limit is 4 W/kg as averaged over any 10 g of tissue and where some peak allowances can be up to 8 W/kg over 1 g of tissue (it is assumed that extremities can absorb more energy without tissue heating [the ear—or pinna—was included as an extremity in 2013 – see discussion below]). There are also resonant SAR peaks for humans (maximum absorption rates) reflected in the illustration below. For whole-body human irradiation of a 6′ male, peak resonant SARs are reached in the bands between 70 and 100 Megahertz (MHz)—the middle of the FM radio band, where exposures are therefore most stringent (see Figure 2).

The frequency range for FCC limits covers from 300 kHz to 100 GHz and is dependent on frequency as defined in maximum permissible exposures (MPE). MPE's are given in terms of power density—milliwatts per centimeter squared (mW/cm^2)—or in field strength as volts per meter (V/m) or amperes per meter (A/m). Often far-field exposures from infrastructure are given in mW/cm^2 and MPE. (For a table of FCC MPE limits for occupational and general populations see reference [5], p. 15).

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) compared to the FCC

Countries throughout Europe and Canada have adopted standards based on recommendations by The International Commission on Non-Ionizing Radiation Protection (ICNIRP), a self-selecting group chartered in Germany in 1992 that functions as a collaborating non-state entity with the World Health Organization [16– 18]. ICNIRP is a

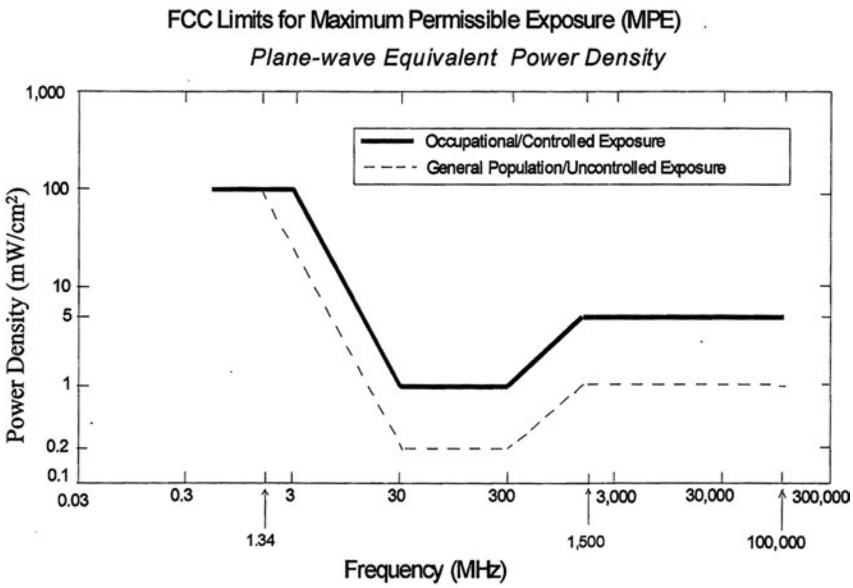

Figure 2: Worker limit is the solid line; general public is the dotted line.
Note that the strictest limit is in the 30–300 MHz range where human whole body resonance occurs. Standards-setting organizations have all made limits strictest in that region. Also note that higher limits are allowed on both sides of that area ([2] p. 69).

relatively new entity in standards setting, given that the ANSI-IEEE basic thermal exposure framework was first delineated and published in 1968 (at higher allowances) and the U.S. NCRP's basic reports on RF were published in 1986 and 1993 ([7, 8], respectively).

The FCC standards remain more stringent than ICNIRP's although in 2020 ICNIRP published an update of their 1998 allowances and adopted a few of FCC's measurements. Both remain two-tiered, human-centric, thermal-based models. ICNIRP differs in some exposure levels and averaging times, as well as allowances in some lower as well as upper frequency ranges that are more lenient than FCC. There is variation between countries that have adopted other standards, i.e., Italy and Switzerland use standards far below FCC and ICNIRP (see below).

By way of comparison: For power density (MPE) the U.S. standards are between 0.2 and 1.0 mW/cm^2 and for SAR between 0.08 and 0.40 W/kg of human tissue. For cell phones and uncontrolled environments, FCC SAR levels require hand-held devices to be at or below 1.6 W/kg averaged over 1.0 g cube of tissue. For whole body exposures in uncontrolled environments, the limit is 0.08 W/kg. Canada, which previously had used the ICNIRP standard, now uses the FCC's 1.6 W/kg averaged over any 1.0 g of tissue and for whole body exposures, the limit is 0.08 W/kg. The peak spatially-averaged SAR in the limbs, averaged over any 10 g of tissue, is 4 W/kg. In European countries and elsewhere where the ICNIRP standard is used, the SAR limit for hand-held devices is higher than FCC at 2.0 W/kg averaged over 10 g cube tissue mass (than measurement, which changed in 2020, used to be over any contiguous tissue). Whole body exposure limits are the same at 0.08 W/kg but until recently were averaged differently: in the FCC standards they are averaged over 30 min; ICNIRP used to be averaged over 6 min but has now gone to 30 min for whole body exposures too [19]. ICNIRP's local body-area SARs are still averaged over 6 min.

The 2020 ICNIRP revision made some other critical changes that many find troubling (see below). Hardell et al. [20] published a recent thorough review and analysis of why these standards are not as protective of public health as many assume.

Longstanding criticism of FCC and ICNIRP standards

The longstanding primary criticism of both the FCC and ICNIRP standards is that they are based on short-term acute exposures for tissue heating—unlike today's more realistic long-term chronic low-level exposures—and that the safety factors of 10 and 50 below that acute heating threshold are purely suppositional [21]. There are other flaws with how these standards are written, for instance the effect of time averaging diminishes the biological significance of peak intensity short-term exposures. And because real-life exposures can be quite organ-specific, such as a cell phone held against the head or carried in a pocket, partial body exposure guidelines for specific organs may not be accurate, especially after the FCC ruled in 2013 that the human ear (pinna) can be classified as an appendage like arms or legs [22, 23], thereby allowing cell phones to transmit at higher levels with higher SAR limits.

This reclassification only changes exposures to the ear. FCC standards are still 1.6 W/kg as averaged over 1 g of tissue, except for extremities where the limit is 4 W/kg as averaged over 10 g of tissue (For occupational exposures, the localized SAR limit is 8 W/kg as averaged over 1 g of tissue, except for within the extremities where it is limited to 20 W/kg as averaged over 10 g of tissue). The ear now fits that higher allowance even though the auricle is simply not an 'extremity.' The auricle is histologically very different from arms or legs and lacks bone, tendon, and skeletal muscle. It is also very close to the human brain and eyes. In addition auricle nerves are innervated by the vagus nerve which in turn innervates many other vital organs in the body, including the heart, GI-tract, and reproductive organs. The higher allowance may also affect the eyes as many now text and look directly into a cell phone screen. This entire new classification should be reconsidered. The eye is a highly conductive aqueous saline organ—the exact opposite of cartilage. The reclassification is inviting adverse effects to the ear, the brain, the eyes, and potentially other systems in the body [23]. It also exponentially increases ambient RFR levels with the number of active cell phones in operation at any given location. Health concerns over human eyes directly translate to species with eye structures similar to humans which includes most mammals. But in other species, effects are potentially more dire. Many insect species, for instance, have compound eye structures with sometimes thousands of lenses in addition to which insects do not dissipate heat efficiently. Their smaller size also makes them a resonant match with RFR's higher frequencies.

Given the scale of human cell phone use today, that technology's contribution alone to ambient levels is not insignificant (see Part 1). Yet people rarely understand that their cell phone may cause downstream effects to other species. Raising the power density output of cell phones may be an environmental factor in and of itself. In fact many of the fundamental criticisms of the human exposure standards may have consequences at the ecosystem level to wildlife species (see Part 2 and below).

In addition, no current exposure standards at FCC or ICNIRP take into consideration signal modulation, wave form, or cumulative exposures from multiple low-power devices transmitting simultaneously—all biologically important factors that have been found in numerous studies to be independent of frequency alone (see Parts 1 and 2). And both FCC and ICNIRP categorically exclude whole classes of low-power devices from review if they adhere to a certain transmission level around 1 mW effective radiated power (ERP).

In other words, there are multiple problems and significant deficits with the most widely adopted exposure standards as originally conceived, formulated, written, and defended. Both major entities have recently reinforced and justified their exposure parameters despite decades of recent research pointing to adverse effects from exposures far below heating thresholds. Both FCC and ICNIRP are actually dosimetry-based models—meaning a defined minimum exposure that will allow technology to function without causing gross short-term adverse heating effects—rather than true biological models based on thresholds where effects are seen [12].

Today a growing number of people, domestic pets, and urban and suburban wildlife are exposed to 24 h EMFs from individual devices, products, and infrastructure [21, 24–27]. Popular wireless devices such as baby monitors, smart grid/meters, home and industrial appliances, WiFi routers, remote controls, security systems, personal "assistants" like Amazon's Alexa and Apple's Siri, and some wireless laptop computers fall at, or below, the power density level of 1 mW ERP which qualifies them for categorical exclusion (CE, or CatEx) from licensing review. This can include CatEx for small cell infrastructure too but there is complex overlap in some situations.

There is a distinction between "no license required" for low-power individual consumer devices vs. "no environmental review pursuant to a CatEx" for low power infrastructure. Small cell networks do require FCC licensing because they use the spectrum, even though individual antennas can be categorically excluded as low-powered. And because issuing a license is a major federal action, NEPA should apply, even though under some circumstances, a CatEx can satisfy NEPA compliance—see below. Today, FCC CatExs include most consumer wireless products and the infrastructure for hundreds of thousands of individual 4G and 5G small cells. Exclusion criteria are based on such factors as type of service, antenna height, and operating power. CatExs are not exclusions from compliance itself, but rather exclusions from performing routine evaluations to demonstrate such compliance and therein lay problems because no one is monitoring. Qualifying for CatEx is based on manufacturer's declarations. According to FCC OET Bulletin 65 (2 p. 12), "… the exclusion itself from performing routine evaluation will be a sufficient basis for assuming compliance, unless an applicant or licensee is otherwise notified by the FCC or has reason to believe that the excluded transmitter or facility encompasses exceptional characteristics that could cause non-compliance …" In other words, much of this semi-regulated area is based on the honor system.

CatEx does not mean that significant exposures are unrealistic or unlikely, especially from cumulative exposures from many devices working simultaneously as is the case in most homes and workplaces today. Although infrastructure is the dominant contributor to outdoor pollution (see Part 1), cell phones and some domestic WiFi systems can be significant contributors to ambient exposures in indoor as well as outdoor environments at levels known to affect wildlife (see Part 2, Supplement 3). What are widely thought to be local indoor transmitters such as personal WiFi and home signal boosters, can and do penetrate walls to become outdoor exposures too. Every new application, though functioning within its own categorically excluded parameter, adds that much more to the aggregate, in essence creating a synergistic effect with the sum of exposures being greater than the individual effects of each component part. Although aggregate RFR levels are not supposed to exceed the FCC or ICNIRP regulations, no regulatory entity today measures, enforces, or attempts to mitigate for this [23] unless complaints are filed over interference issues with other systems. Each CatEx exists within its own technical realm, considered safe if kept under 1 mW ERP. Most such excluded devices and/or networks have considerable overlap, creating multiple exposures, and possible elevated effects. This is not a realistic, scientifically sound, or safe way to determine actual exposures to humans, domestic animals, or wildlife from aggregate, ambient radiation.

5G: changes at FCC and ICNIRP

5G is poised to bring radical changes to the ambient landscape from individual devices and especially infrastructure exposures, yet the major standards-setting groups have recently reinforced and justified their existing exposure allowances [3, 18, 19]. They continue to adhere to acute dosimetry-based frameworks rather than true biological models based on more sensitive thresholds where effects are seen. Plus, a most urgent area in need of clarification concerns how traditional standards have been written from the outset, which may, in fact, be based on a fundamental theoretical flaw. We may not even be using the correct physics model in today's standards setting (see Part 1) in light of actual exposures. The entire justification for adhering to thermoregulatory models rests on the classic physics theory of non-ionizing radiation not having enough energy to knock electrons off cellular orbits and thereby cause DNA damage. This may not be the most accurate model regarding biological reactions/interactions with low-level energy found in current exposures [28–32]. The classic theory is based on a mathematical calculation best suited to ionizing radiation and a narrow definition of a one-cell, one-photon concept whereas today's exposures are many simultaneous and often-overlapping streaming photons arriving at multiple cells from multiple angles at the same time in what behave more like photon wave "packets" rather than single photons [33–39] Our entire regulatory concept needs further attention if we are to truly understand and trust where we are headed with 5G's new technology.

To better accommodate 5G's buildout, all exposure limits at FCC and INCIRP may soon become more lenient. FCC has opened a new docket (Docket #19-226) to target the need for different regulations for 5G [40], even as they have stated their current regulations are adequate for 5G exposures [3]. The new FCC docket covers a wider frequency range from 3 kHz to 3 THz for permissible human exposures and has allocated certain applications in the millimeter (MMW) bands from 57.05 to 64 GHz for unlicensed use, meaning CatEx for some devices and infrastructure. FCC is also seeking comments on applying localized exposure limits above 6 GHz in parallel to the localized exposure limits already established below 6 GHz, as well as specifying new conditions and methods for averaging RFR for both time and exposure area. They are also seeking comment on new issues raised by WPT devices [3].

There have been numerous comments submitted to FCC regarding Docket 19-226 by citizens, organizations, and professional groups like the American Public Power Association (APPA) urging FCC not to further expand unlicensed operations in the 6 GHz bandwidth due to possible interference with present licensed systems, among many other issues. Numerous comments also center on health/environmental concerns [41].

There has been significant discussion at FCC and ICNIRP about changing SAR exposure categories that are now used for cell phones and other mobile/portable devices to a mW/cm^2 power density exposure measurement (MPE) for devices above 6 GHz, which 5G phones will be. FCC states that for portable devices operating at frequencies above 6 GHz, 'special frequency' considerations are necessary [2]. The localized SAR criteria used by the FCC only apply at operating frequencies between 100 kHz and 6 GHz. For portable devices that operate above 6 GHz (e.g., 5G millimeter-wave devices) they say that localized SAR is not an appropriate means for evaluating exposure; that at the higher frequencies, exposure from portable devices should be evaluated in terms of power density MPE limits instead of SAR, adding that power density values can be either calculated or measured, as appropriate, at a minimum distance of 5 cm from the radiator of a portable device to show compliance with FCC standards (2 p. 43–44). They do not elaborate on their reasons but it may have to do with the assumption that MMW do not penetrate skin deeply, which has been proven false (see Part 1 and below).

With 5G in mind, ICNIRP (2020) also addressed the subject of special "transition frequency" [19]—the frequency at which the measurement quantity changes—regarding local RF restrictions. Prior to 2020, the ICNIRP SAR was used up to 10 GHz (vs. FCC's 6 GHz), while power density was used above 10 GHz. They noted that the different quantities are used because SAR may underestimate superficial exposures at higher frequencies, whereas power density may underestimate deeper exposures at lower frequencies. As a pragmatic approach, ICNIRP reduced the transition frequency from 10 to 6 GHz to "… provide the most accurate account of exposure overall" [19].

ICNIRP's 2020 update [16–19] includes new allowances for 5G that many find disturbing [20, 42–45]. The new guidelines allow higher power densities above 6 GHz that replaced the SAR values, larger temperature increases in localized areas that may exceed thermal thresholds for both short and long periods of time, and divide skin into different types with different allowances (Type-1 tissue includes all tissues in the upper arm, forearm, hand, thigh, leg, foot, pinna and the cornea, anterior chamber and iris of the eye, epidermal, dermal, fat, muscle, and bone tissue. Type-2 tissue includes all tissues in the head, eye, abdomen, back, thorax, and pelvis, excluding those defined as Type-1 tissue). ICNIRP adheres to a thermal-effects-only model and now indicates assumed safety with increases to 5 °C in skin, the cornea and iris, and bones, as well as a 2 °C increase in brain temperatures on an indefinite basis. Their 1998 guidelines only allowed a 1 °C maximum increase for localized tissue and overall body temperature. Their rationale for the increased 2020 allowances stated that the 1998 safety margins were too conservative. For comparisons between ICNIRP's 1998 and 2020 allowances, see ICNIRP [19], and charts in Leszczynski [46] as well as Hardell et al. [20].

In the U.S., there has been significant longstanding pressure from industry over the years to harmonize FCC standards with ICNIRP—an action that FCC has resisted. As of this writing, which excludes any new standards pertinent to 5G being adopted, the current FCC standards are still more stringent in some frequency bands, exposures, and time allowances than ICNIRP's [47].

Other countries have adopted more stringent standards than FCC or ICNIRP based on different health criteria orientation—some more precautionary than others [25, 48]. There are calls to disband ICNIRP [49] as well as numerous lawsuits in various states of deposition against the U.S. FCC regarding NEPA enforcement (see below), federal preemptions in favor of industry over local/state infrastructure review and siting [50], and the adequacy of FCC's exposure standards [51]. A 2021 court ruling found that the FCC's decision terminating its inquiry into the adequacy of the RF health standards was unlawful [51]. There are other significant issues—such as the defunding of the U.S. EPA for nonionizing EMF research and oversight—that are mentioned in this 2021 case [11].

What wildlife may be experiencing

At a 100–200 ft (30.5–61 m) distance from a cell phone tower/base station (i.e., antennas or antenna arrays), a person or animal moving through the area can be exposed to a power density of 0.001 mW/cm^2 (i.e., 1.0 μW/cm^2). The SAR at such a distance can be 0.001 W/kg (i.e., 1.0 mW/kg) for a standing man. Throughout this three-part series, we defined low-intensity exposure where effects are seen to RFR for power density at 1 μW/cm^2 and a SAR of 0.001 W/kg. The reason for using such a very low level is to show that biological effects have been widely observed much lower than at the 4 W/kg used in standards setting. (For extensive tables of studies that match these low levels, see Part 2, Supplement Tables 1–4).

Many biological effects have been documented at low intensities comparable to what the population—and therefore wildlife—experience within 200–500 ft (61–152 m) of a cell tower [21]. These can include effects seen in *in vitro* studies of cell cultures and *in vivo* studies of animals after exposures to low-intensity RFR. Reported effects include: genetic, growth, and reproductive alterations; increases in permeability of the blood brain barrier; stress protein increases; behavioral changes; molecular, cellular, and metabolic alterations; and increases in cancer risk (see Part 2 Supplement 3 for broad animal effects and Supplement 4 for flora effects).

Unlike field research, *in vitro* and *in vivo* laboratory studies are conducted under highly controlled circumstances, often with immobilized test animals, typically at near-field exposure, for set durations, at specific frequencies and intensities. Extrapolations from laboratory research to species in the wild are difficult to make regarding uncontrolled far-field exposures, other than, for example, to seek possible correlations with laboratory-observed DNA, behavioral, or reproductive damage. In the wild, there is more genetic variation and mobility, as well as variables that confound precise data assessment. There are also numerous variables like orientation toward the generating source, exposure duration, animal size, species-specific physical characteristics, and genetic variation that also come into play. Assessments for wildlife may vary considerably depending on abundant factors.

It is highly likely that the majority of wildlife species are constantly moving in and out of varying artificial fields. Although precise exposure data are difficult to estimate, there is a growing body of evidence that finds damage to various wildlife species near communications structures, especially where extrapolations to, or measurements of, radiation exposure have been made [52–63].

The introduction of 5G broadband using frequencies in the mid-MHz through mid-GHz millimeter wave (MMW) bands—radiating from both land and satellite-based transmitters in urban, suburban, and rural/forested areas—has the ability to impact numerous species at very low intensities based on several mechanisms. These involve a plethora of unique magnetoreception factors in non-human species, depending on taxonomy, size, season, and habitat (see Part 2). Some of these include resonance factors and intense heating effects for some insect species as insects do not dissipate heat and therefore have no thermoregulatory compensatory responses; interference with orientation in some insect and bird species based on the presence of natural magnetite and cryptochrome in their physiologies that enable complex interactions with the Earth's geomagnetic fields and sunlight for all their life's activities; and adverse die-off effects in flora such as trees in close proximity to infrastructure like small cells, to name but a few (see Parts 1 and 2 and their Supplements for a more thorough analysis). 5G's effects on insects alone have the ability to create holes in critical food webs affecting all other species, and ultimately humans.

The exposure allowances used by FCC and ICNIRP are already higher in the MMW bands to be used in 5G. This is based on whole human body resonance factors and partly on efficient skin absorption—estimated at 90–95% MMW incident energy absorbed in human skin [64]. But this simplistic assessment does not factor in that skin tissue—human and some non-human species alike—contains critical structures like blood and lymphatic vessels, nerve endings, collagen, elastin fibers, and hair follicles, as well as sweat, sebaceous, and apocrine glands. MMW effects to skin have been found to be considerable in glandular tissue with multiple cascading effects throughout the human body even without deep penetration [65]. One study by Cosentino et al. [66] found effects to unilamellar vesicles made of phospholipid—or lipid vesicles—with decreased cell membrane water permeability and partial dehydration of the cell membrane, as well as cell membrane thickening/rigidity seen at 52–72 GHz at incident power densities of 0.0035–0.010 mW/cm^2. Human sweat ducts in particular may act as coiled helical antennas and propagate MMW energy as a waveguide deep into the body at these higher frequency exposures causing uniquely higher SARs [67] not reflected in today's standards. Where there are similar physical characteristics in other species, the above information would also apply.

Because of sub-millimeter depths of penetration in skin tissue with MMW, "superficial" SARs as high as 65–357 W/kg are possible. Eyes are of particular concern in all species. MMW frequencies penetrate less than 1/64 of an inch (0.4 mm)—about the thickness of three sheets of paper. That is thick enough to penetrate deeply into thin-skinned amphibian frog and salamander species, for instance, as well as most flora, and is more than half the depth of some small insects that are primary food sources for other species. The wavelength of MMWs is shorter (about 1/8th inch or 3.2–5 mm long) than microwaves used in cell phone/WiFi technology at 2.4 GHz (6.3 inch or 12.5 cm). The shorter the wavelength, the higher the energy density per wavelength unit. In this case, with MMWs it is about 25 times higher than with cell technology microwaves [68]. This means MMW are capable of resulting in significant damage throughout the biome, including possibly to all flora and fauna present, but effects are not due to wavelength alone. The multiple biological effects from intense energy absorption at very short wavelengths—e.g., in human skin cells or any thin-skinned species, and especially in insects that lack efficient heat dissipation—may cause intense heating with concomitant cellular destruction and organism death. Many of these effects are independent of power density, and therefore not covered by current regulations which are power-density and/or SAR-based. In other words, thermal exposure standards that may protect humans against heating have the ability to cause thermal damage to other species with more extreme consequences.

There are other interesting environmental characteristics regarding MMW. For instance, Betskii et al. [69] pointed out that MMW radiation, unlike other frequencies, is virtually absent from the natural environment due to strong absorption by the atmosphere. The authors hypothesized that low-intensity MMW may have broad nonspecific effects on biological organisms and that vital cell functions may be governed by coherent electromagnetic EHF waves. Their study results found alternating EHF/MMWs were used for interaction between adjacent cells, thereby interrelating and controlling intercellular processes in the entire organism. Other authors [70–73] expounded on the idea that because MMW are absent in the environment, living cells may make specific and dedicated use of them. While these ideas are theoretical, they may plausibly explain the high MMW sensitivity observed in biological subjects (see Part 1), especially in human therapeutic applications which have long been popular in Russia.

MMW below 100 GHz are maximally absorbed by water vapor (H_2O) at 24 GHz, and by oxygen (O_2) at 60 GHz [74–76], raising the possibility that 5G could destabilize the climate even more than current trends, especially from satellite transmission. Rain, foliage, and other things easily attenuate MMW signals so 5G must operate at higher power density, as well as utilize different modulation characteristics such as phasing to enhance signal propagation's penetration through physical objects like building walls. At 60 GHz, 98% of transmitted energy is absorbed by atmospheric oxygen. As far back as 1997, the FCC issued a report [74] on MMW propagation characteristics, noting that between 200 MHz and 95 GHz, there was significant signal loss at 40 GHz due to foliage (see Part 1), as well as resonant matches for atmospheric water vapor at 24 GHz and oxygen at 60 GHz.

Despite this, the FCC has already licensed the buildout of 5G in the 24, 28, 37, 39, and 47 GHz ranges thus far with higher bands extending above 95 GHz allocated for future use. FCC has also allocated MMW from 57.05 to 64 GHz for unlicensed use; ICNIRP may follow. Concerns include both land-based networks as well as satellite transmissions. By the time satellite transmissions reach the Earth's surface, the power density is low (see Part 1) but with 5G's phased array signals, the biologically active component is in the waveform, not power density alone. There is no research to predict how this will affect wildlife in remote areas but given what is known about extreme sensitivity to EMFs in many species, it is likely that effects will occur and likely go undetected. Even weak signals from satellites using phased array characteristics may be a significant contributor to species effects in remote regions (see Part 1 and Part 2, Supplement 3).

Much of the research on MMW and phased array with accompanying unusual biological effects—e.g., precursor formation capable of causing deep nonlinear body penetration (see Part 1)—has been done in lossy materials like water. We therefore have models to suggest that 5G may have particular effects not only on insect populations (due to resonance factors) and amphibians (due to thin membranes and deep body penetration) but also in some aqueous species since water is a highly conductive medium. Both aqueous environments and the high water content in living organisms may make MMW exposures particularly unique due to the way MMWs propagate though water with virtually no impedance [77–82].

In addition, Betskii and Lebedeva [83] described the complex hypothetical mechanism that stochastic resonance (see Part 2) may play in very sensitive water-containing biological species to very-low intensity EMF (in μm ranges) based on the generation of intrinsic resonance frequencies by water clusters that fall between about 50 and 70 GHz. When biological species are exposed to extremely weak EMF at these frequencies, their water-molecule oscillators can lock on to the external signal frequency and amplify the signal by means of synchronized oscillation or regenerative amplification. Since MMWs pass through aqueous media almost without loss but also with high absorption, in the process they are capable of deep penetration involving internal tissue and organ structures. The researchers summarized a long list of MMW effects that included EHF strong absorption by water and aqueous solutions of organic and inorganic substances; effects to the immune system; changes in microbial metabolism; stimulation of ATP (adenosine 5′-triphosphate) synthesis in green-leaf cells; increases in crop capacity (e.g., pre-sowing-seed treatment); changes in certain properties of blood capillaries; stimulation of central nervous system receptors; and the induction of bioelectric responses in the cerebral cortex. Biological effects were dependent on exposure site, power flux density, and wavelength in very specific ways. In addition, low-intensity MMWs were detected by 80% of healthy people, but perception was asymmetrical. Peripheral applications were found to affect the spatiotemporal organization of brain biopotentials, resulting in cerebral cortex nonspecific activation reactions. MMW-induced effects are perceived primarily by the somatosensory system with links to almost all regions of the brain. The authors also discussed water and aqueous environments' unique role on MMW effects, which induce convective motion in the bulk and thin fluid layers and may create compound convective motion in intra and intercellular fluid. This can result in transmembrane mass transfer and charge transport can become more active. EHF can also increase protein molecule hydration. The theory of stochastic resonance playing a mechanistic role in the effects noted in the above study deserves further investigation given its known function in non-human species perception abilities that are used for survival (see Part 2).

And then there's the role of unique wildlife magnetoreceptor cells. Akoev et al. [84] studied MMW effects to the specialized electroreceptor cells called Ampullae of Lorinzini in anesthetized rays (an elasmobranch fish) and found that the spontaneous firing in the afferent nerve fiber from the cells could be enhanced or inhibited by MMWs at 33–55 GHz continuous wave (CW). The most sensitive receptors increased firing rates at intensities of 1–4 mW/cm^2, which produced less than a 0.1 °C temperature increase. The authors emphasized they were not observing just a MMW bioeffect but rather a specific response to that frequency range by a unique electro-receptor cell. This one study points out the inadequacy of assuming that MMW's superficial skin penetration is enough to base exposure-standard extrapolations to nonhuman species (For an extensive reviews of other MMW studies pertinent to wildlife, see Parts 1 and 2).

In wildlife, especially small thin-membrane amphibians like frogs and salamanders, even at penetration less than 1/64 of an inch (0.4 mm), deep body penetration would result. In some insect species that would equal deadly whole body resonance exposure [85]. In a study, Thielens et al. [86], modeled three insect populations and found that a shift of just 10% of the incident power density to frequencies above 6 GHz would lead to an increase in absorbed power between 3 and 370% in some bee species, possibly leading to behavior, physiology, and morphology changes over time, ultimately affecting their survival. Insects smaller than 1 cm showed peak absorption at frequencies above 6 GHz. In a 2020 follow-up study of RFR, Thielens et al. [87] used *in-situ* exposure measurements near 10 bee hives in Belgium and numerical simulations in honey bee (*Apis mellifera*) models exposed to plane waves at frequencies from 0.6 to 120 GHz—frequencies carved out for 5G. They concluded that with an assumed 10% incident power density shift to frequencies higher than 3 GHz, this would lead to an RFR absorption increase in honey bees between 390 and 570%—resulting in possible catastrophic consequences for bee survival.

In birds, hollow feathers have piezoelectric properties that would allow MMWs to penetrate deep within the avian body cavity [88, 89]. 5G's complex phased MMWs may also be capable of disrupting crucial biological function in other species and critical ecosystems with broad effects throughout their entire food webs. In addition, the top end of these ranges reach infrared (IR) frequencies, some of which are actually visible to other species, especially birds, and could impede their ability to sense natural magnetic fields necessary for migration [90] as well as other crucial aspects of avian life.

Any assumed wildlife protection in exposure standards for humans is purely hypothetical at the ecosystem level. Chronic long-term, low-level ambient exposures to MMWs are yet to be studied but some extrapolations can be made based on the extensive database that does exist (see Parts 1 and 2, plus Supplements). FCC rules do not require an Environmental Assessment (EA) for new towers, for example, unless a proposed structure can be proven to negatively affect birds or other species federally listed as threatened or endangered (see below). EAs as currently applied can include effects from physical tower placement itself, but not typically RFR exposures. As a result, no one is required to assess ambient environmental EMF effects, let alone answer questions about impacts to other species from such technologies (see the Section "Discussion: synthesis of linear and nonlinear disciplines needed" below for some reasons why this situation exists at the federal level). There is a critical hole in our regulatory environmental apparatus when it comes to electroecology.

Regulations and laws pertinent to EMF

There are several significant U.S. federal environmental statutes and their implementing regulations intended to protect wildlife and their habitats. All potentially apply directly or indirectly to the impacts created by EMF if we choose to use these statutes in that capacity. In some cases, treaty protocols and international laws also extend to Canada, Mexico, Russia, and elsewhere. Some states, provinces, counties, and cities also have similar laws in place but space precludes detailed listing here. The focus of the sections below is on key U.S. federal laws and those of Canada and Europe that could incorporate EMF into assessment considerations.

The Endangered Species Act of 1973

While the Migratory Bird Treaty Act of 1918 (MBTA)—discussed in detail below—is the oldest U.S. environmental wildlife protection law, having been enacted over 100 years ago, the Endangered Species Act (ESA) of 1973 (16 U.S.C. 1531 et seq). [91] is considered the key U.S. environmental statute. The ESA is intended to recover plant and animal species from extinction, preventing further extinctions or extirpations, and provides subsequent protections including at ecosystem levels. ESA has been amended many times over the years[1] [92]. Somewhat like the MBTA, ESA was designed to implement an international protocol called the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) [93], which

1 To view the entire contents of each section of the Endangered Species Act of 1973 as amended and to click on a section title below that cor responds with your interest see: https://www.fws.gov/endangered/laws policies/esa.html. Many section pages include audio or slideshow summaries that provide a more general overview of that section. Or to download the entire Act or individual sections in PDF format from US FWS's document library, go to: https://www.fws.gov/endangered/esa library/index.html.

itself was designed to protect plant and animal species worldwide through restrictions on such trade.

ESA was implemented to protect all plant and animal species listed as threatened or endangered, and to protect habitats designated as critical. ESA also contains provisions for designating species as *candidates* under Section 4(b)3(A) [94] for possible future threatened or endangered status—i.e., listings that may have been warranted but precluded for one reason or another, or are in need of additional population assessment before determinations can be made. While the process is supposed to be based strictly on sound scientific review and findings, politics have often impacted listing decisions. Nevertheless, since its passage in 1973, some 1,400 plant and animal species have been afforded protections, with many on the path to recovery (e.g., grizzly bears and gray wolves) or fully recovered (e.g., Bald Eagles and Peregrine Falcons). ESA is a longstanding highly successful environmental law.

The ESA is administered by two agencies: The U.S. Fish and Wildlife Service [95] and the U.S. National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) [96]. U.S. FWS maintains a worldwide ESA list of threatened and endangered species and is responsible for overseeing terrestrial and freshwater organisms, including four species of marine mammals—i.e., manatees, polar bears, walrus, and sea otters. The NMFS oversees all ESA listed marine wildlife, including large and small cetaceans, sea turtles, and anadromous and steelhead salmon, as well as some flora critical to marine wildlife survival such as Johnson's sea grass which is important for shelter and sea bottom nursery habitat.

All oversight agencies use the ESA as part of their enforcement toolkit.

The ESA regulations make it illegal to kill, harm or otherwise "take" a listed species. ESA definitions include:

- **"Take":** A "taking" under ESA is defined as to "… harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct."
- **Endangered:** A species is listed as: endangered if it faces a significant risk of extinction in the near foreseeable future throughout all or a significant portion of its range.
- **Threatened:** A threatened species is defined as at risk of becoming endangered in the near future.

The ESA and its implementing regulations include a detailed consultation process. Under Sections 7 and 10 [97, 98] the regulations can authorize "incidental or accidental take." Under Section 7, a federal agency must consult with either U.S. FWS or NMFS (depending on the species and/or habitat affected) and specifically provides that, "… each federal agency shall, in consultation with and with the assistance of the U.S. FWS or NMFS, insure that any action authorized, funded, or carried out by such agency is not likely to jeopardize the continued existence of any endangered species or threatened species or result in the destruction or adverse modification of habitat of such species which is determined to be critical" [97]. Further, the "action agency," meaning the agency that retains discretionary federal control and is responsible for its actions on the environment, must determine at the earliest possible time whether any listed species or critical habitat may be affected in any manner by the proposed action. In the case of RFR, the FCC is the action agency whose licensing effects from EMFs on ESA-listed migratory birds, for example, must be addressed. That includes radiation from any communications tower, device, or whole communications networks. More specifically, the action agency must consider the *potential* risks/impacts from RFR emitted from towers or other sources. Unfortunately, such determinations have yet to occur for wildlife at FCC. (For an inventory of listed species, see reference [99]).

Under Section 10 of the ESA, private landowners can develop their own habitat conservation plans, which must be approved by U.S. FWS. These may also allow for some level of "take" of listed species [100]. Under Section 11 [101], citizens can file lawsuits against U.S. FWS or NMFS for actions they deem illegal under the statute and such suits may proceed if litigants prove they have legal standing (For some examples of legal suits brought by the Department of Justice, see reference [102]).

For decades, the ESA—a most significant law—has been challenged by politicians, numerous industries, and some public segments, including Congressional attempts to defund the programs altogether. But the ESA is vitally worth protecting and has stood the test of time thus far.

The Migratory Bird Treaty Act (MBTA) of 1918

The Migratory Bird Treaty Act of 1918 [103], as amended, is over 100 years old and still among the most effective laws protecting avian species [26]. Migratory birds—those that migrate across U.S., Canadian, Mexican, and/or Russian borders, of which 1,093 species are currently protected in the United States [104]—are a public trust resource that belong to every U.S. citizen. Almost all native North American continental birds are protected by the MBTA. Exceptions include the Wild Turkey, Asian Pheasant, Lesser and Greater Prairie Chicken, other grouse species, European Starlings, English Sparrows, and Monk Parakeets (among others) which have been accidentally or intentionally introduced to the U.S. The ESA also addresses birds [105].

The MBTA implements/regulates bilateral protocols with Canada, Mexico, Japan, and Russia regarding the shared migratory bird resources of the U.S. and its treaty partners [26]. It is a strict *prima facia* liability statute, meaning that proof of criminal *intent* in the injury or killing of birds is not required by U.S. FWS or the Department of Justice for cases to be made. The statute currently protects migratory birds, their parts, eggs, feathers, and nests, with migratory bird nests protected during the breeding season, while eagle nests are protected year-round. A federal permit is required to "possess" a migratory bird and its parts, but the MBTA contains no provisions for the accidental or incidental "take" (i.e., causing injury or death) of a protected migratory bird, even where normal, legal business practices or personal activities are involved. Bird death, injury, and crippling loss are the only "takings" that matter under the MBTA, not the circumstances under which they occur, although those circumstances can certainly come under investigation.

When the MBTA was enacted, Congress was serious and intended the "take" of even one protected migratory bird to be a violation of the statute, sometimes backed by extensive fines and criminal penalties [26]. Examples include: the 1999 Moon Lake Electric Cooperative fined $100,000 for electrocuting migratory birds; the 2009 criminal settlement with PacifiCorp for $10,500,000 for electrocuting birds (the final settlement resulted in $400,000 in fines, $200,000 restitution to the State of Wyoming, and $1,900,000 to the National Fish and Wildlife Foundation for eagle conservation); and the 2012 settlement agreement with Duke Energy Wind Facility for $1,000,000 for bird deaths from wind turbine blade collisions. All of these settlements involved several years of probation for company executives, and required significant improvements to facilities (an author of this paper was involved with these criminal cases while at the U.S. FWS) [26].

Unfortunately there were recent potentially serious erosions of the legal interpretations involving MBTA. Up until 2017, companies could be fined under criminal misdemeanor provisions when steps to avoid or minimize "take" of birds were not implemented—especially if U.S. FWS's Office of Law Enforcement had made requests to proponents to avoid/minimize dangers and such recommendations were ignored or minimally implemented. In late 2017, the former Trump Administration refused to enforce the MBTA for so-called "accidental or incidental take," while only enforcing provisions for poaching (illegal harvest) and illicit trade in birds and their parts in its then new legal opinion (M-37050). But on March 8, 2021, under a new Administration, the U.S. Department of the Interior withdrew M-37050 after a U.S. District Court invalidated the rollback of the MBTA [106] (One of the authors of this paper was involved in these court cases).

The MBTA has no consultation process like that under ESA's Section 7, and it does not authorize "incidental or accidental take" which ESA does under ESA Sections 7 and 10 [26, 97, 98]. Where "take" was likely to occur under MBTA, various agencies, entities, and individuals were working proactively with U.S. FWS (especially its Office of Law Enforcement, Ecological Service Field Offices, and Division of Migratory Bird Management) to implement all necessary and appropriate steps to avoid or minimize any future damage to birds. MBTA was intended to protect all migratory birds—no excuses accepted but solutions were appraised by U.S. FWS officials—while the ESA allowed some room to negotiate and remediate. But M-37050, as discussed above, until it was invalidated by the court and withdrawn by the Department of the Interior [106], completely upended that protective balance, demonstrating how fragile some of these longstanding effective laws can be due to political caprice. Both the ESA and MBTA could pertain to ambient EMF if applied that way.

Birds of Conservation Concern: how U.S. agencies track non-listed but imperiled migratory birds

There are two primary ways that U.S. federal agencies keep track of birds. In addition to ESA-listed birds, the U.S. FWS maintains the list of Birds of Conservation Concern (BCC) [107]. There are currently at least 147 species designated nationally of the 1,093 species now protected and the number grows with each BCC update [104]. When U.S. FWS regional lists are included in the overall tally, there are some 272 BCC species (>26% of all protected birds) designated in trouble [104]. BCC lists require periodic reviews/ updates under provisions of the Fish and Wildlife Conservation Act (16 U.S.C. 2901–2912) [108]. The overall objective of the U.S. FWS is to maintain bird populations at stable or increasing numbers—a daunting challenge due to both direct and indirect impacts, including EMFs discussed in detail in Part 2. The BCC list is designed to serve as an early warning system of birds in trouble but not yet candidates for listing under the ESA [26]. A species designation on the BCC list could impact both infrastructure siting as well as potentially measured or modeled/projected rising ambient EMF levels in some regions (see Part 1).

Federally listed bird species are those protected under the ESA. On the List of Threatened and Endangered Species, there are currently 77 endangered and 15 threatened birds [104]. An endangered species faces significant risk of extinction in the near foreseeable future throughout all or a significant portion of its range, while a threatened species is at risk of becoming endangered in the near future. Extinction is irreversible and permanent.

Collectively, migratory birds are in decline, some precipitously (see Part 2), with numbers of both listed and BCC species increasing [26, 107]. With 272 BCC-designated species and 92 Federally Endangered and Threatened migratory birds, out of 1,093 protected migratory birds, at least 364 (>33%) species are in trouble. Those numbers continue to increase at a sizable rate and once a bird population is in trouble, reversing its decline is extremely difficult [26, 109, 110]. The MBTA has no provisions for acquiring and protecting bird habitats although there have been bilateral discussions between the U.S., Canada, Mexico, Japan, and Russia that have resulted in some bird habitat protection efforts.

Other protections: presidential Executive Order 13186—Migratory birds, and The Bald and Golden Eagle Protection Act

In January 2001, the Migratory Bird Executive Order 13186 [111] was signed by President Clinton. It stipulates that, "… each Federal agency taking actions that have, or are likely to have, a measurable negative effect on migratory bird populations …" is to develop and implement a Memoranda of Understanding (MOU) "… to promote the conservation of migratory bird populations." Simply put, if the actions of a federal agency are now, or will in the near future, impact bird populations, that agency is to sign and implement an MOU with the U.S FWS in an effort to protect migratory birds and their habitats [26]. While many of the previous Executive Orders in place from the Clinton, Bush, and Obama administrations were rescinded by the Trump Administration, E.O. 13186 was not among them. An executive order from the White House does not have the full force of a law implemented by the U.S. Congress, but in this case E.O. 13186 does have the force of the MBTA clearly backing it. E.O. 13186 provides specific opportunities for habitat protection, land management, and conservation planning. U.S. FWS has the responsibility under the E.O. to protect migratory birds and their habitats.

In addition to protections under the MBTA, the U.S. FWS is also responsible for maintaining stable and/or increasing breeding populations of Bald (*Haliaeetus leucocephalus*) and Golden (*Aquila chrysaetos*) Eagles under The Bald and Golden Eagle Protection Act [112, 113]. The definition of "take" under BGEPA is broader than under MBTA, and includes provisions against pursuit, shooting, poisoning, capturing, killing, trapping, collecting, molesting, and disturbing both species (ref. [112], 50 C.F.R. 22.3). Permits are required from U.S. FWS for "disturbance take" and "take resulting in mortality" (ref. [112], 50 C.F.R. 22.26), and for "take of nests" (ref. [112], 50 C.F.R. 22.27). Disturbing, injuring or killing eagles without an "eagle take" permit under BGEPA could result in criminal culpability. Any infrastructure-related EMF effects to Bald or Golden Eagles would be actionable under these regulations.

The National Environmental Policy Act: how it applies to environmental EMF and categorical exclusions

The second most iconic U.S. environmental law, after the ESA, is the 50 year old National Environmental Policy Act [114, 115]. Among the most effective laws ever passed, it was signed by President Nixon in 1970 and has become an important means for protecting wildlife in the face of large government actions. As such it is a constant target for various industries regulated by the government, most recently the telecommunications industry seeking exemptions from the FCC for any effects from their operations, including RFR [50].

NEPA has been applied to any major federal, state, or local project where a federal regulatory nexus or action is involved, including actions taken by federal agencies themselves. This includes:

- Where federal funding had been, is, or will be used.
- Where a permit has been issued by a federal agency.
- Where work or action by a federal agency has been contracted for a project [26].

Courts have also expanded the purviews of NEPA. In addition, the NEPA legislation established the Council for Environmental Quality (CEQ) which is housed within the U.S. Executive Office of the President to advise the President on the state of the environment and environmental policy.

The primary role of NEPA rules is to establish national environmental policy and to determine the regulations that require all federal agencies to prepare EAs, and/or Environmental Impact Statements (EISs) that accompany official reports and/or recommendations whenever they are submitted to Congress for funding. A vast array of federal agencies is involved in NEPA review/compliance, including agencies like the Environmental Protection Agency (EPA) and U.S. FWS.

Unlike MBTA and BGEPA, which are both strict liability statutes (see above), NEPA regulations have no criminal or civil penalties or sanctions. As such, all enforcement of NEPA must go through the courts which may order a federal agency to require a proponent to perform NEPA-compliant analysis and performance. This would include, for instance, compliance with the previously described bird protection laws where migratory birds could be impacted by EMF and other radiation exposures.

To effectively apply NEPA, an evaluation is required of the relevant environmental effects of a federal project. For instance, in the case of environmental EMFs, assessing the impacts of 5G on wildlife (including insects and migratory birds), NEPA review should be performed by the FCC before instituting any rulings that would facilitate 5G buildout, or an evaluation of an action mandated by NEPA where the "nexus" conditions apply. This process begins when an agency or commission, such as the FCC or the Federal Energy Regulatory Commission, develops a proposal that addresses the need to take an action. If that action is covered under NEPA, three levels of analysis are required by the action agency (i.e., the agency with responsibility for its action on the environment) for that action to be in compliance with NEPA. These include where applicable:

- Preparation of a CatEx.
- Preparation of an EA.
- The determination of either a Finding of No Significant Impact (FONSI) or …
- The preparation/release of an EIS if there will likely be significant impact to species or habitats.

Because NEPA allows public review and comment on these documents and the process, this provides a venue for litigation and possible court action.

A CatEx [116] is a list of actions that an agency has determined do not individually or cumulatively significantly affect the quality of the human environment ([116], 40 C.F.R. §1508.4). A lot of things can slip through the cracks with such exclusions. The "quality of the human environment" represents a key phrase in interpreting NEPA. As such, if a proposed action such as the use of 5G and its impacts on wildlife were to be included in an agency's CatEx—say by FCC and U.S. FWS—the agency must ensure that no extraordinary circumstances might cause the proposed action to affect the environment (in this case, humans and wildlife). Extraordinary circumstances include negative effects/impacts on endangered species, protected cultural sites, and wetlands. If the proposed action is not included in the description provided in the CatEx, an EA must be prepared and can be published in the *Federal Register*, which allows the public to comment, and if necessary, to litigate. (Notice of all EISs must be published in the Federal Register; some, but not all, agencies choose to also publish notice of EAs—no absolute requirements to do so exist. The Council of Environmental Quality [CEQ] regulations also do not mandate notice of EAs—only EISs).

The release of an EA and a FONSI represent specific public documents which include information on the need for a proposal, a list of alternatives, and a list of agencies and persons consulted in the drafting of the proposal. "The purpose of an EA is to determine the significance of the proposal's environmental outcomes and to look at alternatives for achieving the agency's objectives. An EA is supposed to provide sufficient evidence and analysis for determining whether to prepare an EIS, aid an agency's compliance with NEPA when no EIS is necessary, and it facilitates preparing an EIS when one is necessary." [115, 116].

If it is determined that a proposed federal action does not fall within a designated CatEx or does not qualify for a FONSI, then the responsible agency—which in the case of 5G buildout would involve the FCC with significant input from U.S. FWS—must prepare an EIS. The purpose of an EIS is to help public officials make informed decisions based on the relevant environmental consequences and the alternatives available.

From the information presented in Parts 1 and 2 of this paper and elsewhere, the environmental consequences of 5G and rising background levels of RFR could be catastrophic to some species. The drafting of an EIS includes public parties, outside parties, and other federal agency input concerning its preparation. These groups subsequently comment on the draft EIS. However, the FCC has systematically categorically excluded many devices and current technologies that use RFR, as well as ruling that their exposure standards extend to 5G exposures [4, 117], thus allowing their use/buildout to proceed without full NEPA/EIS review.

Even when NEPA has been applied to an RFR exposure situation, there have been problems. Part 1 included discussion of a U.S. military training proposal throughout a protected wilderness area that involved a lengthy, but ultimately inadequate, NEPA review with the U.S. FWS (see Part 1 for further details). What that case revealed was the necessity for environmental agencies to have their own in-house bioelectromagnetics expertise with knowledge of nonionizing radiation effects to wildlife—something now lacking throughout regulatory agencies. In light of continuing new information, to do otherwise fosters large loopholes through which entire networks of low-power infrastructure can avoid larger environmental review.

It is important to note, as described above, that all small cells intended for 5G deployment, are categorically excluded by the FCC, thereby bypassing NEPA requirements despite significant studies (see Part 2) of adverse effects to all taxa that would apply for review under EAs, and EISs. Part 1 explored measured levels from the 1980s to today's measured rising background RFR that should also apply to NEPA review, given the expansion of a large new technology like 5G about to make its own significant contribution. Instead, FCC categorically excluded small cells from NEPA without any examination of the unique signaling characteristics of 5G that are new to broadband telecommunications technology in the built environment, or 5G's higher frequencies to be used widely at significant scale that may especially impact insects and birds (see above, "Government exposure standards"). Instead, FCC ruled that states and municipalities must streamline small cell network applications and buildouts without NEPA [117]—a position that was successfully challenged in U.S. courts [50].

At the moment, NEPA requirements still stand. But other suits challenging FCC's small cell streamlining without also updating their exposure standards were less successful [118]. Under the former Trump Administration, industry-friendly legislation was introduced [119] that would have excused the FCC from all NEPA review as a matter of course. No other federal agency with the ability to impact the environment had ever gotten such a pass. The bill did not succeed but such an attempt again demonstrates the fragility of these iconic environmental protections.

Canada's environmental laws and regulations: Species at Risk Act, and Migratory Birds Convention Act

In conjunction with U.S. laws that are observed across borders, Canada has some strong regulations of its own such as the Species at Risk Act and the Migratory Birds Convention Act (MBCA).

The Species at Risk Act, known as SARA [120], is similar in many respects to the U.S. ESA. SARA encourages the various government entities in Canada—e.g., Provincial, Federal, First Nations, territorial, county, city, town, and fort—to cooperate in protecting wildlife species in Canada. SARA also includes protocols for consultation and cooperation with Aboriginal/First Nations peoples which Canada views as essential to successfully implementing the statute.

Like the U.S. ESA, SARA can affect entities or individuals who own property or have a vested interest in land where a species at risk (designated in the List of Wildlife Species at Risk [121] is found at any time throughout the year. The statute also defines critical habitat, designated in the SARA Public Registry [122]. Like the purposes of the ESA, SARA is intended to prevent wildlife species in Canada from disappearing; to recover wildlife species extirpated (i.e., no longer found in the wild in Canada), endangered or threatened as a result of human activity; and to manage species of special concern so as to avoid threatened or endangered designation [123]. To accomplish these purposes and goals, SARA establishes how governments, organizations, and individuals in Canada should work together, and establishes guidelines for implementing a species assessment process to ensure the protection and recovery of species. Like the ESA, SARA incorporates penalties for violations; and like NGOs in the U.S. that support/publicize specific issues pertaining to threatened and endangered species, Canada also has NGOs doing the same thing [124].

Canada's Migratory Birds Convention Act (MBCA) of 1994

As with the U.S.'s MBTA, the vast majority of bird species in Canada are protected by the 1994 MBCA [125]. Passed in 1917 and updated in 1994 and 2005, MBCA implements the Migratory Birds Convention, a treaty signed with the United States in 1916. The Canadian Federal government is authorized to pass, implement, and enforce Migratory Bird Regulations [126] designed to protect the species included in the Convention. The lists of bird species protected by Canada and the U.S. may be different. Bird species that are not listed in Canada or the U.S., and/or defined under Article 1 of the MBCA, may or may not be protected by Provincial or territorial legislation, or by SARA, or the UN Convention on Biological Diversity [127] which is an international legal instrument for "… the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources" that has been ratified by 196 nations [128].

Persons, industries or other entities making any decisions (e.g., installing cell towers) that would impact the protected status of a bird species in Canada should also consult SARA. Environment and Climate Change Canada requires that three criteria be met to qualify for the list of bird species protected in Canada under the MBCA. They include:

(1) Birds designated in Article 1 of the MBCA as amended under the 1995 Protocol [128].
(2) Species native or naturally occurring in Canada noted under regulations.
(3) Species known to regularly occur in Canada. Although species that occur infrequently (i.e., "accidentals") and that meet criteria 1 and 2 are not included on this list, they continue to be considered as having protection under the MBCA any time they occur in Canadian territory.

While birds such as grouse, quail, pheasants, ptarmigan, and turkeys—which also in the U.S. are not migratory and/or have been introduced (e.g., pheasants)—are not protected under MBCA nor the MBTA, in Canada birds such as hawks, owls, eagles, falcons, cormorants, pelicans, crows, jays, kingfishers, and some species of blackbirds are also not protected under MBCA. This represents a significant difference between MBTA protection in the U.S., and eagle protection under the U.S. Bald and Golden Eagle Protection Act (discussed above) where all birds in the latter category are protected in the United States.

There are three introduced bird species that do not meet criterion 2 above, but continue to appear on the MBCA list. They include the Mute Swan (*Cygnus olor*), the Eurasian Collared-Dove (*Streptopelia decaocto*), and the Sky Lark (*Alauda arvensis*). Environment and Climate Change Canada [128] continues to consult with provincial and territorial governments, which share responsibility for the management of birds in Canada, regarding a proposal to remove these species from the list of MBCA birds. Until a decision is reached by the concerned parties, these three species will remain under MBCA protection. The list of birds protected under the MBCA follows the American Ornithologists' Union's Check-list of North American Birds, and its supplements to 2014, on matters of taxonomy, nomenclature, and sequence [129].

European environmental laws: European Union (EU) initiatives addressing endangered species and habitat protection

The EU, with its 27 member nations, has recently implemented a four-pronged approach to better address species protection, recovery, and restoration of imperiled plants and animals found on the continent [130, 131]. This includes:

– Species protection through a Birds Directive.
– Species protection under a Habitats Directive.
– Ensuring that plants and animals are not threatened by illegal and/or unsustainable international wildlife trade through stronger implementation of CITES—the Convention discussed above [93].
– Developing and implementing an EU pollinators initiative to reverse negative impacts to pollinators including effects from EMF/RFR [132].

The EU began an ambitious effort in 2011 to develop and implement a Biodiversity Strategy to institute the framework for this four-pronged approach above. The Strategy includes the following targets:

(1) Protect 100% more habitats and 50% more species above 2011 levels.
(2) Establish green infrastructure and restore at least 15% more ecosystems.
(3) Achieve more sustainable agriculture and forestry.
(4) Make fisheries more sustainable and the seas healthier.
(5) Combat invasive alien species.
(6) Help stop or reverse the global loss of biodiversity.

At this writing, the EU may still be on track to achieve their strategy, although progress calls for a much greater effort among all parties involved, and the transition from BREXIT is creating many difficulties, unknowns, and complexities [130–132].

It is clear that all industrialized Western countries are trying to address serious environmental issues with more and/or less success—depending on politics, funding, and the will to act. EMF as an environmental pollutant needs to be part of that effort.

Airspace as habitat: aeroecology

Birds, bats, insects, and other species that use airspace for critical life functions are of cornerstone significance to us all. Birds, for instance, provide key ecosystem functions that fuel multi-billion dollar industries through pollination and insect/weed/seed control in the agribusiness sector, as well as in the forestry industries. Without migratory birds, there would be untold problems and money spent globally for more pesticides, herbicides, and other chemicals. In addition, in the U.S. alone, feeding, photographing, and observing birds fuels a $32 billion annual recreation industry, representing 20% of the U.S. adult population engaging in these activities. Human/bird-related activities are reportedly more popular than golf [26, 133].

Birds also have spiritual significance to indigenous peoples. A number of migratory bird species—notably Bald and Golden Eagles, Common Ravens (*Corvus corax*), American Crows (*Corvus brachyrhynchos*), hawks, falcons, doves, owls, and hummingbirds—are revered and protected by the Tribal laws of several U.S. indigenous American Tribes and Canadian First Nation peoples. Some of these very species are at considerable risk from habitat disturbance/fragmentation, injury, and death, including from EMF and other radiation impacts which will undoubtedly increase exponentially without a change in human awareness.

We have a legal, moral, and ethical obligation to protect migratory species of every kind, the airborne included. Impacts from EMF may add to species declines and ultimately threaten their survival if we do not understand and respond appropriately because airspace is as critical a habitat as are water and soils for non-airborne species. Thus far we have failed to muster the macroscale vision of the air-as-habitat concept that also includes flora, which are exquisitely sensitive to the ELF of the Earth's geomagnetic fields with their root systems underground as well as to RFR with their primary stem and leaf growth in the air (see Part 2 and Part 2 Supplement 4). Humans have collectively done a poor job of addressing impacts to living organisms that use the airspace—most especially migratory birds, bats and beneficial insects—along with being negligent in protecting what is on, as well as below, the ground, and in aqueous environments. We need to understand EMF as a form of energetic air pollution, especially biologically active anthropogenic RFR that is endemic today in airspace.

Defining the habitat of airspace

The airspace used by plants and animals includes the space just above ground level (AGL) to ceilings in excess of 26,245 ft (8 km) AGL. These upper ranges are used, for example, by Demoiselle Cranes (*Grus virgo*) and other migratory bird species, as well as Golden Eagles which prey on the cranes and other quarry. But airspace should be considered as habitat for a variety of plants and animals too that use and depend on it during, and in some cases throughout, significant portions of their lives. These living organisms include, but are not limited to, flying insects, some arachnids, birds, bats, flying squirrels, flying fish, and some reptiles, as well as seeds, spores, vegetative plant parts, and forest canopies. Organisms use airspace for purposes of transport, dispersal, feeding, mating, territorial defense, escape, migration, daily movements, and for other reasons [134]. In most cases, unimpeded airspace is critical to mating, nesting, survival, food acquisition, territorial defense, daily movements, and migrations of birds and bats (including microchiropterans and megachiropterans) [27, 109, 110].

Impacts to species using airspace have been well documented, including of migratory birds and communication towers and their guy-wire support structures [135]—annual mortality now conservatively estimated at 6.8 million birds killed in the U.S. and Canada solely from collisions with communication structures [136–139]. However, the impacts to migratory birds, other wildlife, and plants generally do not include adequate cumulative effects analyses (cumulative biologically and under the legal mandates of NEPA). Cumulative effects under NEPA must consider and evaluate all impacts from all human-built structural sources including EMFs that they may emit and/or receive, where applicable.

Currently, environmental impacts from RFR on wildlife are not being assessed by the FCC, EPA, or the Department of Interior (DOI), nor is ELF-EMF being considered by the Department of Energy (DOE) regarding powerline exposures. However, it is important to note that precedent was set in 2014 when DOI publicly charged that the FCC's standards for RFR from cellular towers were outdated, based on narrow thermal heating effects, and inadequate to protect migratory birds and other wildlife [139]. A letter from DOI's Director of the Office of Environmental Policy and Compliance was sent in February 2014 to the National Telecommunications and Information Administration (NTIA), housed in the Department of Commerce [140]. The letter—and subsequent meetings with staff from the U.S. FWS—resulted in the initiation of an EIS process under NEPA by NTIA to begin an independent research study to address the impacts of radiation from cell towers on migratory birds using the airspace. Unfortunately, efforts languished and were completely suspended under the former Trump Administration with nothing similar initiated subsequent to that as of this writing. Under NEPA, cumulative effects must include impacts from all human-related sources that affect humans, wildlife, plants, and all living organisms that depend on/use airspace for survival. The effects of EMF on flora and fauna remain widely unassessed [27, 110].

Air as an actual habitat is a relatively new concept for many in the scientific community, including federal agencies such as U.S. FWS whose goal (including for wildlife that use the airspace) has been to "do no harm" [141]. Reducing harm to wildlife that use the airspace is a tall order because a lot of things occupy it—both permanently and on a temporary basis—but we do not generally think of it that way. Airspace interference and adverse effects to wildlife comes in many forms. For instance, in addition to the communication-tower bird-collision mortality estimates referenced by Longcore et al. [138] above, Manville [142] estimated that 440,000 protected migratory birds were killed annually by blade strikes at U.S. commercial wind energy facilities in 2008. Smallwood [143] increased that estimate to 573,000 bird fatalities per year (including 83,000 raptor deaths) based on increases in commercial wind turbines, and estimated that an additional 888,000 bats died in turbine blade collisions annually in the U.S. In addition, based on the variety of survey methods used, differences in survey detail, longevity of assessment, and robustness, as well as differences in infrastructures being investigated, Loss et al. [144] estimated between 8 and 57 million birds are killed annually by collisions with power distribution and transmission lines, and between 0.9 and 11.6 million birds die from wire and infrastructure electrocution each year in the U.S. This is not to mention the estimated 1.4–3.7 billion birds (median = 2.4 billion) killed annually in the U.S. by domestic and feral cats at ground level and/or near-ground while birds are in flight [145]; or the annual estimated 97.6–976 million U.S. bird deaths from building window collisions [146] which Klem and Saenger [147] later estimated was greater than any other source of human-associated bird mortality. Taken collectively, this is massive anthropogenic-caused avian mortality, all of which occurs within the airspace. There are reduction strategies for some of these—like keeping domestic cats indoors and/or placing bells on their collars, installing non-reflective window panes, and using vertical axis designs in wind turbines—but these do not substantially solve the problem. ELF and RFR problems can only be handled at the transmission source through use reduction. Approaches that use frequencies such as radar to repel birds only create an additional ambient source capable of affecting another species, such as insects, in a different way.

The staggering avian mortality rates noted above fail to include impacts from pesticides, contaminants, oil spills, disease, parasites, natural mortality, predators, entanglement, and other non-airspace related sources. Impacts to individual animal and plant species are cumulative. The potential role that EMF plays in adverse effects to animals that use the airspace should be added to the list as a growing concern based on evidence presented throughout this three-part series of papers, and elsewhere.

Aeroecology—a macrovision

The interdisciplinary field of aeroecology has evolved to encompass a variety of issues affecting airspace. The concept was founded around 2008 by Dr. T.H. Kunz, Professor of Biology and Director of the Center for Ecology and Conservation Biology at Boston University who sadly died from Covid-19 complications in April 2020. Kunz laid out an aeroecology vision that includes technological solutions for studying animals that use the aerosphere as well as the key questions that unite aeroecology. Frick et al. [148] wrote an excellent review of this emerging unifying discipline.

Aeroecology integrates domains that include atmospheric science, animal behavior, ecology, evolution, earth science, geography, computer science, computational biology, and engineering [134, 149, 150].

In 2008, Kunz and colleagues organized a symposium in San Antonio, Texas, entitled, “Aeroecology: Probing and Modeling the Aerosphere: the Next Frontier.” At that symposium and since, the concept evolved to define the field, including:

- The aerosphere comprises one of the three major components of our biosphere, yet it is one of the least understood substrata of the troposphere, especially in regard to how organisms interact with and are influenced by this highly variable and fluid environment [134].
- The biotic interactions and physical properties in the aerosphere provide significant selective pressures that influence the size and shape of organisms, as well as important influences affecting their behavioral, sensory, metabolic, and respiratory functions.
- While organisms that spend their entire lives on land or in the water tend to be less varied based on adaptive pressures, organisms that use the airspace can be immediately affected by the changing boundary layer conditions of the airspace.
- These conditions include winds, air density, oxygen concentrations, precipitation, air temperature, sunlight, polarized light, and moonlight, as well as geomagnetic and gravitational forces [134].

The authors of this paper would add to that growing list the impacts of ELF and RFR to organisms that use the airspace at varying durations and intensities.

The discipline of aeroecology allows us to better assess the impacts from anthropogenic factors affecting wildlife that use the airspace—ranging from nearly all, or significant portions of their lives, to minimal amounts of time. While no organism spends its entire life in the aerosphere, anthropogenic factors located within, or that directly or indirectly affect, the aerosphere can have significant impacts. These anthropogenic factors, for example, include skyscrapers, office buildings, homes, structural lighting, city/community lighting, power transmission and distribution wires and infrastructure, radio/television/cellular/emergency broadcast communication towers and structures, commercial wind turbines, industrial solar arrays (especially 'power' towers and large solar panel facilities), bridges, aircraft, air pollution, increases in greenhouse gases, climate change, and radiation emitted from communication structures and related devices, among others [26, 137]. Staff at U.S. FWS emphasized the importance of airspace as habitat, and garnered the attention of top service officials to respond through improved voluntary guidance addressing the various industries impacting airspace.

To study the impacts of communication structures on migratory birds (including from RFR), the U.S. Forest Service invited the Division of Migratory Bird Management at U.S. FWS, to design and develop a research protocol to study towers in several national forests in Arizona. While the protocol, which was written by one of the authors of this paper while at the U.S. FWS [151], would benefit from updating and peer-review, it nevertheless provides a framework for independent studies of EMF impacts to migratory birds, mammals, and other wildlife and plants in the field.

It is important that future studies be conducted by independent scientific sources without vested interests in the outcome. Such inquires clearly fall under the auspices of aeroecology. We first need the vision and will to move this forward.

Discussion: synthesis of linear and nonlinear disciplines needed

Nonionizing EMF is virtually uncontrolled as an environmental pollutant. This was observed as far back as the 1970s [152] and has only gotten progressively worse with each passing decade. There are several reasons for this, including the likelihood that in many regulatory agencies there is an assumption that the science is not robust or adequately developed upon which to base regulations, much less enforce them. There is also a pervasive attitude that risks to wildlife, if any, are minor compared to the human benefits of widespread wireless technology. Technology is seen as beneficial in many environmental circles for the information it can provide, for instance, via animal tracking devices (see Part 1), while potential adverse effects that create hidden variables from such devices rarely occur to environmental researchers. The need to study EMF effects is not obvious to many regulators or environmentalists. That may change once air is understood as 'habitat' and EMF is seen as an energetic pollution source.

Wildlife has also historically been considered resilient (despite much evidence to the contrary) and nonionizing radiation has been seen as relatively harmless beyond tissue heating and electric shock. If non-human species have been considered at all regarding EMF, broad but inaccurate assumptions have been made that protecting humans from the worst adverse effects also extend to other species. What has been lacking is the right government agency expertise with an understanding of how non-human species interact with exogenous EMFs, and at what intensities. There has never been funding in any agency to track or develop that area of interdisciplinary knowledge because the need was not obvious until recently. Other than at the FCC which is mostly staffed with engineers who lack knowledge of biology, civil scientists who are trained in bioelectromagnetics and/or biophysics are found throughout many regulatory agencies. Their work, however, is primarily focused on human health issues, not wildlife. Agencies tasked with wildlife protection have been completely defunded for such work—i.e., the U.S. FWS which does not have a bioelectromagnetics expert on staff, and most importantly the U.S. EPA which at one time had the world's foremost bioelectromagnetics basic research laboratory staffed with scientists who made groundbreaking discoveries (see Part 2, Mechanisms). Many agencies have simply not replaced what little bioelectromagnetics expertise they have had when those scientists retire and new ones have not been trained or hired. And it is only recently that environmental nonionizing radiation has increased to measurable levels high enough to warrant investigation to all living beings. Europe, for instance, is now taking an interest in potential 5G effects and developing standards that apply to wildlife protection [153].

One aspect of rising environmental EMF levels may, however, spur attention—the shadow role it could be playing in global climate change. Scientists know that what occurs in the ionosphere directly affects our weather patterns—of sudden importance given the dramatic increase in satellites being deployed globally for 5G telecommunications (see Part 1). Erratic weather and its consequences have grown to dangerous levels in most parts of the world. Thunderstorms increased 25% over

North America between 1930 and 1975, vs. between 1900 and 1930 [154]. That period directly parallels our first introduction of environmental EMFs along with other contaminants. As far back as 1975, a team of researchers at the Stanford University Radioscience Laboratories, then headed by Robert Helliwell, found evidence that powerline emissions are amplified within the magnetosphere [155], causing a veritable rain of electron precipitation into the ionosphere, which could theoretically lead to both highly localized as well as global changes in weather patterns. The technologies we have added since 1975—both ELF and RFR—which we assumed to be atmospherically benign, may not be as harmless as originally thought. The exponential growth planned for 5G broadband (including MMW) from satellites and millions of accompanying ground-based transmitters is certainly reason for caution. It is already well established that MMW bands at 60 GHz are maximally absorbed by atmospheric oxygen (O_2), as well as by H_2O at 24 GHz—ranges planned for 5G (see Part 1). Oxygen molecules readily absorb the 60 GHz frequency range and rain droplets easily attenuate signals [74–76, 156, 157]. In fact, at 60 GHz, 98% of transmitted energy is absorbed by atmospheric oxygen. This makes that frequency spectrum good for short-range transmission but no one understands how a large infusion of RFR in that band—or any other—may affect atmospherics. It could be highly destabilizing (see Part 1).

There is a need to re-integrate biology, which studies whole dynamic living systems, with the non-living sciences of physics and engineering that focus on how to create and make technology work. The latter have dominated EMF research and its applications in every way since the 1940s, including research protocols regarding human health and standards setting which are outside their areas of expertise. Today, physics and biology—although fundamentally very different disciplines with their own inherent cultures and biases—increasingly converge when it comes to environmental concerns. While we already understand how to make modern societies and accompanying technologies work, the most important questions now concern the potential effects to the living systems in the path of technology.

Electromagnetism is fundamental to life—indeed all living things function with biological microcurrent without which life would not exist. Technology, which also requires EMF to function, therefore speaks the same fundamental language as living cells. Yet biologists have consistently been left out of full participation in safety and environmental issues in anything other than cursory inclusion. If there is to be a better integration of physics and biology, it will need to be at the behest of the biology community. The physics/engineering disciplines have had the subject to themselves for decades and are somewhat territorial about it. Plus their inherent focus is on linear cause-effect dosimetry models in both technology design and exposure standards setting. They tend be less interested in the confounding complexities of biology which are mostly nonlinear and unpredictable.

The natural world typically demonstrates nonlinear dynamics, meaning that a small stimulus can result in a large, seemingly disproportionate outcome. The weather is nonlinear, for instance, as illustrated by the imagined "butterfly effect" in which a butterfly can theoretically flap its wings in Indonesia and cause a hurricane on the other side of the globe [158–160]. Some disease states are nonlinear, allergies being a prime example. A person with a severe peanut allergy can go into anaphylactic shock by merely being in the same room with the offending agent. Or someone with an allergy to bees, upon experiencing a sting, will react far out of proportion to the tiny amount of venom being injected by the insect. Physics and engineering, on the other hand, are highly linear—an exemplary asset in that realm. Humanity, after all, has no patience for machines or systems that don't work [161].

Until there is a synthesis between physics/engineering and biology, with an emphasis on nonlinear models, the potential environmental effects of our increasing EMF exposures will not be well understood. Each area has much to learn from the other. Biologists can benefit from the precision emphasized in physics and engineering while physicists and engineers can benefit for the savvy that biologists have acquired in environmental observation, measurement, quantification, hypothesis testing, and formulating policy in the face of scientific uncertainty.

Given the rising background levels in urban, rural, and some wilderness environments, EMF should be classified as an energetic air pollutant capable of adversely affecting wildlife and habitats as delineated throughout these papers. Cumulative effects should be taken into consideration from myriad sources, and continuing evidence should be evaluated by unbiased entities, including governments and NGO's. We can no longer presume that the status quo of ever-increasing EMF ambient levels is safe without much closer scrutiny.

Some solutions

Existing environmental laws in the U.S., Canada, and throughout Europe should be enforced. For example, in the U.S., NEPA and its EISs should be required each time a new broadly polluting EMF technology like 5G is introduced, not as the current policy is being interpreted through

"CatEx" or simple dismissal. EISs should be required for all new technologies that create pervasive ambient EMF such as 'smart' grid/metering, Distributed Antenna Systems (DAS), small cell networks, and the 5G "Internet of Things." Where wildlife species are affected, systems and networks that currently meet radiation levels for CatEx (and are therefore exempt from review) should be required to develop/implement NEPA and EIS reviews for cumulative exposures to wildlife from multi-transmission sources.

Efforts should begin to develop acceptable exposure and emissions standards for wildlife, which today do not exist. Setting actual exposure standards for wildlife will be an enormous challenge, and for some species there may be no safe thresholds, especially with 5G and MMW. We may simply need to back away from many wireless technologies altogether, especially the densification of infrastructure, and refocus on developing better dedicated wired systems in urban, suburban and rural areas. Environmentally sensitive wilderness areas should be considered off limits for wireless infrastructure. Once air is seen as 'habitat,' there may come a time when a cell phone call voluntarily *not made* will be understood as removing something detrimental from air's waste-stream, the way we now see plastic bags regarding terrestrial/aquatic pollution.

There are some reasonably simple things that can be done in the ELF ranges that would benefit insect, bird, and many wild mammal and ruminant species. For example, high-tension electric utility corridors can be built or changed to cancel magnetic fields with different wiring configurations. This is already widely done in the industry for other reasons but it also coincidentally eliminates at the source at least the magnetic field component for wildlife. There are other approaches too but further discussion is beyond the scope of this paper.

Research into the long-term, low-level ambient exposures to humans and wildlife is imperative given the picture that is emerging. There is a likelihood that low-level ambient EMF is a factor, or co-factor, in some of the adverse environmental effects we witness today—many previously discussed in this series of papers. There is currently no research in any industrialized country that looks to the broader implications to all flora and fauna from these rising background levels, even as effects to individual species are observed. This is an important, emerging environmental issue that must be addressed.

Conclusions

In this broad three-part review, we sought to clarify if rising ambient levels of EMF were within the range of effects observed in *in vitro, in vivo*, and field studies in all animal phyla thus far investigated. We further discussed mechanisms pertinent to different animal physiology, behavior, and unique environments. The intention was to determine if current levels have the ability to impact wildlife species according to current studies. The amount of papers that find effects at today's EMF levels to myriad species is robust. Some unusual patterns did emerge, including broadly in flora that react beneficially to static EMF but adversely to AC-ELF and especially to RFR.

There is a very large database supporting the hypothesis that effects occur in unpredictable ways in numerous species in all representative taxa from modern ambient exposures. Associations are strong enough to warrant caution. New enlightened public policies are needed, as well as existing laws enforced, reflecting a broader understanding of non-human species' interactions with environmental EMF. Emerging areas, such as aeroecology, help define airspace as habitat and bring better awareness of challenges faced by aerial species—including animals and plants. But we are in the nascent stages of understanding the full complexity and detailed components of electroecology—the larger category of how technology affects all biology and ecosystems.

Historically, control over the realm of nonionizing radiation has been the purview of the physics and engineering communities. It is time that the more appropriate branches of biological science, specializing in living systems, stepped up to fill in larger perspectives and more accurate knowledge. We need to task our technology sector engineers to create safer products and networks with an emphasis on wired systems, and to keep all EMF exposures as low as reasonably achievable.

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Review

Electromagnetic radiation as an emerging driver factor for the decline of insects

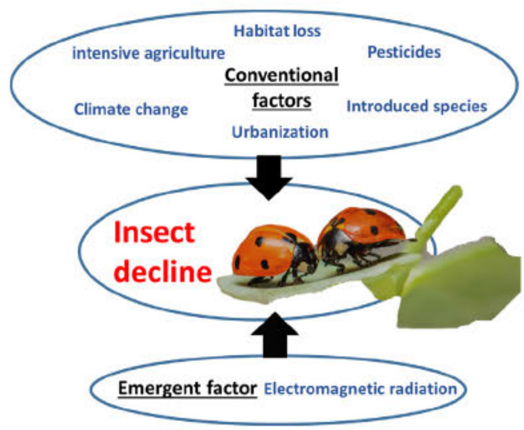
Alfonso Balmori

C/Navarra N°1 5° B, 47007 Valladolid, Spain

HIGHLIGHTS

- Biodiversity of insects is threatened worldwide.
- These reductions are mainly attributed to agricultural practice and pesticide use.
- There is sufficient evidence on the dam age caused by electromagnetic radiation.
- Electromagnetic radiation may be a com plementary driver in this decline.
- The precautionary principle should be applied before any new deployment (e.g. 5G).

GRAPHICAL ABSTRACT



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ABSTRACT

The biodiversity of insects is threatened worldwide. Numerous studies have reported the serious decline in in sects that has occurred in recent decades. The same is happening with the important group of pollinators, with an essential utility for pollination of crops. Loss of insect diversity and abundance is expected to provoke cascad ing effects on food webs and ecosystem services. Many authors point out that reductions in insect abundance must be attributed mainly to agricultural practices and pesticide use. On the other hand, evidence for the effects of non thermal microwave radiation on insects has been known for at least 50 years. The review carried out in this study shows that electromagnetic radiation should be considered seriously as a complementary driver for the dramatic decline in insects, acting in synergy with agricultural intensification, pesticides, invasive species and climate change. The extent that anthropogenic electromagnetic radiation represents a significant threat to insect pollinators is unresolved and plausible. For these reasons, and taking into account the benefits they provide to nature and humankind, the precautionary principle should be applied before any new deployment (such 5G) is considered.

Contents

E-mail address: abalmorimartinez@gmail.com.

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1. Insects and their importance in ecosystem services

There are numerous studies that show the fundamental importance of insects as key species in ecosystems (see for example: Noriega et al., 2018). Some of the most important ecosystem services they provide are climate regulation, crop pollination, pest control, decomposition and seed dispersal (Kremen and Chaplin Kramer, 2007; Schowalter, 2013). Insects are at the structural and functional base of many of the world's ecosystems (Sánchez Bayo and Wyckhuys, 2019), and numerous birds, lizards, frogs and bats feeds on insects (Nocera et al., 2012). The group of insect pollinators plays an important role in crop pollination, and insects provide an important contribution to crops as well as to wild plants (Powney et al., 2019).

2. The current decline of insects and causative drivers of this decline

Numerous studies have reported the serious decline in insects that has occurred in recent decades (Vogel, 2017). A study carried out in protected nature areas throughout Germany found a 76 82% decline in total flying insects between 1989 and 2016. The authors consider that agricultural intensification, with increased use of pesticide and fertilisers, may have aggravated the reduction in insect abundance over the last decades, whereas landscape modifications and climate change are unlikely explanatory factors (Hallmann et al., 2017).

A study of insects crashing into car windscreens in rural Denmark, based on data collected between 1997 and 2017, concluded that the number of insects had decreased by 80% in those 20 years, and the authors point out that reductions in insect abundance must mainly be attributed to agricultural practices and pesticide use (Møller, 2019). In a survey conducted in Kent (UK) in 2019, which examined the presence of crushed insects in the front grille above the licence plates of cars, a 50% reduction compared to 2004 was reported (Tinsley Marshall et al., 2019).

Some authors also point out climate change as a cause of insect decline (Baranov et al., 2020). In a tropical rainforest in Puerto Rico, one study found a 30 to 60 fold decline (a 97 98% decline) in total insects captured in sticky traps between 1976 and 2012. This decline may be attributed to climate change, since between 1976 and 2012, mean maximum temperatures have risen by 2.0 °C, and tropical arthropods are particularly vulnerable to climate warming (Lister and Garcia, 2018). However, in colder climes and the mountains of temperate zones, this factor affects only a minority of species (Sánchez Bayo and Wyckhuys, 2019).

After reviewing 73 historical reports of insect declines from across the globe, a recent study revealed that the biodiversity of insects is threatened worldwide (Sánchez Bayo and Wyckhuys, 2019). The rates of decline may lead to the extinction of 40% of the world's insect species, both specialists and generalists. Based on the results of this review, the most affected groups in terrestrial ecosystems are *Lepidoptera*, *Hymenoptera* and *Coleoptera*, whereas in terms of aquatic taxa, *Odonata*, *Plecoptera*, *Trichoptera* and *Ephemeroptera* are most affected. The authors conclude that the main plausible drivers are, in order of importance: i) habitat loss and conversion to intensive agriculture and urbanisation; ii) pollution, mainly by synthetic pesticides and fertilisers; iii) pathogens and introduced species; iv) climate change (Sánchez Bayo and Wyckhuys, 2019).

This same is happening with the important group of pollinators. A study has found evidence of declines across a large proportion of pollinator species in Britain between 1980 and 2013 (Powney et al., 2019). Another study strongly suggests a causal connection between local extinctions of functionally linked plant and pollinator species (Biesmeijer et al., 2006). Further, pollinator populations may collapse suddenly once drivers of pollinator decline reach a critical point (Lever et al., 2014). Key threats to pollinators include agricultural intensification (particularly habitat loss and pesticide use), climate change and the spread of alien species (Powney et al., 2019). The decline of pollinators may have important ecological and economic impacts that could significantly affect the maintenance of wild plant diversity, crop production and human welfare (Lázaro et al., 2016).

Loss of insect diversity and abundance is expected to provoke cascading effects on food webs and ecosystem services (Hallmann et al., 2017; Møller, 2019). For example, associated with the decline of insects, parallel decreases in insectivorous lizards, frogs and birds have been documented (Lister and Garcia, 2018). Pesticides have dramatically altered insect community structures and decimated populations, triggering nutritional consequences for aerially foraging insectivorous birds and bats (Nebel et al., 2010; Nocera et al., 2012). Agriculture is the largest contributor to insect and biodiversity loss, destroying biodiversity by converting natural habitats into intensely managed systems and by releasing pollutants, fertilisers and pesticides (Dudley and Alexander, 2017).

3. Scientific evidence for electromagnetic radiation as a factor contributing to insect decline

Insects are especially sensitive to electromagnetic radiation. An increasing number of reports indicate that flies and spiders, among other invertebrates, disappear from areas that receive the highest levels of radiation from mobile telephone antennas, and these observations are consistent with numerous laboratory studies showing the negative effects of electromagnetic radiation (EMR) on reproductive success, development and navigation (Balmori, 2009; Lázaro et al., 2016).

Evidence for the effects of non thermal microwave radiation on insects has been known for at least 50 years, e.g., the abnormal development of irradiated coleopteran pupae (Carpenter and Livstone, 1971). Radio frequency (RF) signals produced by mobile phones increased the numbers of offspring, elevated hsp70 levels by non thermal stress and caused other effects on reproduction and development of the fruit fly *Drosophila melanogaster* (Weisbrot et al., 2003). Another study showed that the reproductive capacity of fruit flies decreased by 50 60% after exposure to the RF signal of a mobile phone during the first 2 5 days of adult life (Panagopoulos et al., 2004). The same authors compared the biological activities of the two systems, GSM (900 MHz) and DCS (1800 MHz), and concluded that both types of radiation significantly decrease the reproductive capacity of fruit flies (Panagopoulos et al., 2007). This non thermal effect diminished with distance (decreasing intensity) and is provoked by induction of cell death (Panagopoulos et al., 2010).

Other authors have also worked with this species and have observed a statistically significant decrease in mean fecundity (Atli and Ünlü, 2006). Further, the mean pupation time was delayed linearly with an increasing period of exposure to an electromagnetic field (EMF), and the mean offspring number was significantly lower than that of the control (Atli and Ünlü, 2007). Pupae from another dipteran, the house fly *Musca domestica*, were exposed to an EMF (50 Hz), and the results showed that the field significantly slowed down metamorphosis (Stanojević et al., 2005).

Insects may be equipped with the same magnetoreception system as birds, and there is evidence that the geomagnetic field reception in the American cockroach is sensitive to a weak RF field (Vácha et al., 2009). Several laboratory studies have been carried out with ants, demonstrating the important effects of artificial EMFs on their orientation by geomagnetic fields (Camlitepe et al., 2005). Other authors demonstrate how changes of low intensity in the normal local magnetic field values affect the behaviour of workers of three magnetosensitive ant species, inducing significant changes in their foraging activities (Pereira et al., 2019). Belgian researchers experimentally demonstrated the effect of 900 MHz electromagnetic waves on ant olfactory and visual learning, revealing an impact on their physiology (Cammaerts et al., 2012). The ants' speed of movement was immediately altered by the presence of electromagnetic waves (Cammaerts and Johansson, 2014). These authors state that electromagnetic radiation affects the behaviour and physiology of social insects, and such results provide convincing evidence of a negative impact of electromagnetic waves on insects, at least on those whose life depends on communication and memory (Cammaerts et al., 2012). Wireless technology has negative impacts on living organisms; ants react quickly to the existence of electromagnetic waves in their environment, and bees may behave abnormally when exposed to EMFs generated by GSM masts (Cammaerts et al., 2013).

To replace chemical insecticides for controlling pests of various species of plants and seeds, in several different studies, radiofrequency exposure was applied to *Callosobruchus chinensis* (Coleoptera), *Maruca vitrata* (Lepidoptera), *Nysius plebeius* and *Nysius hidakai* (Hemiptera). The EMF affected the developmental period, adult longevity, adult weight and the fecundity of subsequent generations in all these species of insects from different orders in the same way (Maharjan et al., 2019a, 2019b, 2020).

Studies have also been conducted on other invertebrates. A study performed in an RF electromagnetic field (RF EMF) anechoic chamber, irradiating ticks (*Dermacentor reticulatus*) with a 900 MHz RF EMF at levels below the proposed limit for public exposure to mobile phone base stations, found that exposure induces an immediate tick locomotor response manifested as a jerking movement, and ticks exhibited overall significantly greater movement in the presence of this electromagnetic radiation (Vargová et al., 2017).

In some studies conducted in natural habitats with real phone masts, electromagnetic radiation (EMR) emitted by telecommunication antennas affected the abundance and composition of several guilds of wild pollinator insects (Lázaro et al., 2016). Another study, also carried out in the field, examined the impact of exposure to the fields from mobile phone base stations (GSM 900 MHz) for a 48 h period on the reproductive capacity of four different invertebrate species. Although a significant impact on reproductive capacity was not found, probably because the exposure time was too short, the authors warned that more attention should be paid to the possible impacts of EMF radiation on biodiversity because the exposure to an RF EMF is ubiquitous and is still increasing rapidly over large areas (Vijver et al., 2014).

As a result of most of the studies carried out, EMF radiation can be a problem for insects and for their orientation (Balmori, 2006, 2009, 2014 and 2015), and both laboratory and field studies on different invertebrate species have shown this.

4. Bee studies on electromagnetic radiation

Bees are highly sensitive to magnetic fields, especially for orientation and navigation, and for this reason, most of such studies have been carried out on bees. Adult honeybees possess a magnetoreception sense, and significant differences in their return rates have indicated that interactions exist between forager losses and exposure to magnetic fields, as well as during fluctuations in the Earth's magnetosphere (Ferrari, 2014).

The first study on the effects of EMFs on bees were carried out under power lines. Honeybee colonies exposed to a 765 kV, 60 Hz transmission line at 7 kV/m showed increased motor activity, abnormal propolisation, impaired hive weight gain, queen loss, abnormal production of queen cells, decreased sealed brood and poor winter survival. When the colonies were exposed to different electric fields with increasing distance from the line, different thresholds for biological effects were obtained (Greenberg et al., 1981). Another more recent study has shown that the extremely low frequency EMF (50 Hz) emitted from powerlines affects honeybee olfactory learning, flight, foraging activity and feeding and may represent a prominent environmental stressor for honeybees, potentially reducing their ability to pollinate crops (Shepherd et al., 2018). In Italy, deleterious results of both pesticides and EMFs from a 132 kV (50 Hz) high voltage power line have been found. In the electromagnetic stress site, the effect of a behavioural over activation of all analysed biomarkers was observed at the end of the season, and this finding poses potential problems for the winter survival of bees (Lupi et al., 2020).

Lopatina et al. (2019) studied the effect of non ionising EMR from a Wi Fi router on sensory olfactory excitability, food motivation and memory in honeybees and observed that a 24 hour exposure to Wi Fi EMR had a significant inhibitory effect on food excitability and short term memory. In natural conditions, worker piping announces either the swarming process of the bee colony or is a signal of disturbance, and active mobile phone handsets have a dramatic impact on the behaviour of the bees by inducing the worker piping signal (Favre, 2011). In another study, with GSM (900 MHz) cell phones, a significant decline in colony strength and egg laying rate by the queen was observed. The behaviour of exposed foragers was negatively influenced by such exposure: there was neither honey nor pollen in the colony at the end of the experiment (Sharma and Kumar, 2010). In another study, queens exposed to telephone radiation in the test colonies produced fewer eggs/day compared to the control (Sainudeen Sahib, 2011). A more recent study provided solid evidence that mobile phone radiation significantly reduces hatching and may alter pupal development (Odemer and Odemer, 2019).

In a study carried out in Germany, with bees exposed to DECT radiation, only a few bees returned to the beehive, and they needed more time; also, honeycomb weight was lower in irradiated beehives (Stever et al., 2005; Harst et al., 2006). The concentrations of carbohydrates, proteins and lipids in the haemolymph increased under the influence of cell phone radiation (Kumar et al., 2013). Another study observed an increase in mortality in two conditions: after exposure to HF (13.56 MHz) and to UHF (868 MHz) (Darney et al., 2016).

Regarding the colony collapse disorder (CCD) observed in honeybee colonies around the world, several authors consider that EMR exposure provides a better explanation than other theories (Sainudeen Sahib, 2011; Cammaerts et al., 2012). Several authors warn that the massive amount of radiation produced by mobile phones and towers disturbs the navigational skills of honeybees, preventing them from returning to their hives (Warnke, 2009; Sainudeen Sahib, 2011). In fact, winter colony losses in the northeast USA correlated with the occurrence of annual geomagnetic storms, and abnormal fluctuations in magnetic fields related to the epidemiology of honeybee losses are consistent with their behaviour and development (Ferrari, 2014).

5. Action mechanisms

There are well known mechanisms of action of low frequency pulsed RF, such as interference with calcium channels in cells (Pall, 2013; Panagopoulos and Balmori, 2017) and deleterious effects on sperm and reproductive systems (Panagopoulos et al., 2004;

Panagopoulos, 2012; Adams et al., 2014). In vertebrates, studies have also found a pathologic leakage across the blood brain barrier (Salford et al., 2003) and interference with brain waves (Mann and Roschkle, 1996; Beasond and Semm, 2002; Kramarenko and Tan, 2003). Microwave radiation has particular effects on nervous, immune and reproductive systems (Balmori, 2009).

In recent years, there has been an important advance in understanding the underlying mechanisms for orientation in birds, insects and other groups. It has also been verified that RF EMFs alter the biological response characteristics of cryptochrome receptors. These results are consistent with the radical pair mechanism of magnetosensing. Since cryptochromes are molecules highly sensitive to RF radiation and are found in many organisms, including humans, these results also may have more general implications for the capacity of living organisms to respond to man made electromagnetic noise by analogy with broad band RF, which has previously been shown to disrupt the orientation of birds (Engels et al., 2014). These possible risks have already been indicated by Balmori (2015).

A recent study has warned that future, more short wavelengths of electromagnetic fields used for the wireless telecommunication systems (5G), will become comparable to the body size of insects, and therefore, the absorption of RF EMF in this group is expected to increase (Thielens et al., 2018).

6. The precautionary principle and the importance of seriously considering EMR as a factor of insect decline

Despite the strong scientific evidence of the negative impacts of electromagnetic radiation on insects, a recent study funded by the European Union's Horizon 2020 Research and Innovation Programme (EKLIPSE) stated that our current knowledge concerning the impact of anthropogenic RF EMR on pollinators (and other invertebrates) is inconclusive (Vanbergen et al., 2019). Thus, the extent to which anthropogenic EMR represents a significant threat to insect pollinators is unresolved. For these reasons, and taking into account the benefits they provide to nature and humankind, the precautionary principle of the European Union (Communication from the Commission on the Precautionary Principle, 2000) should be applied.

The potential effects of RF EMFs on most taxonomic groups, including migratory birds, bats and insects, are largely unknown, and the potential effects on wildlife could become more relevant with the expected adoption of new mobile network technology (5G), raising the possibility of unintended biological consequences (Sutherland et al., 2018). Thus, before any new deployment (such 5G) is considered, its effects should be clearly assessed, at least while conclusions are drawn and these existing uncertainties are overcome, according to the official document 'Late Lessons of Early Warnings' (European Environment Agency, 2013).

A letter by the United States Department of the Interior sent to the National Telecommunications and Information Administration in the Department of Commerce warns about the scarcity of studies carried out on the impacts from non ionising EMR emitted by communication towers (United States Department of the Interior, 2014). The precise potential effects of increases in EMR on wildlife, which are not yet well recognised by the global conservation community, have been identified as an important emerging issue for global conservation and biological diversity (Sutherland et al., 2018). Thus, as we have explained in this review, EMR should be seriously considered as a complementary driver for the dramatic decline in insects in recent studies, acting in synergy with agricultural intensification, pesticides, invasive species and climate change.

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Review Article

B. Blake Levitt*, Henry C. Lai and Albert M. Manville II

Effects of non-ionizing electromagnetic fields on flora and fauna, part 1. Rising ambient EMF levels in the environment

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Abstract: Ambient levels of electromagnetic fields (EMF) have risen sharply in the last 80 years, creating a novel energetic exposure that previously did not exist. Most recent decades have seen exponential increases in nearly all environments, including rural/remote areas and lower atmospheric regions. Because of unique physiologies, some species of flora and fauna are sensitive to exogenous EMF in ways that may surpass human reactivity. There is limited, but comprehensive, baseline data in the U.S. from the 1980s against which to compare significant new surveys from different countries. This now provides broader and more precise data on potential transient and chronic exposures to wildlife and habitats. Biological effects have been seen broadly across all taxa and frequencies at vanishingly low intensities comparable to today's ambient exposures. Broad wildlife effects have been seen on orientation and migration, food finding, reproduction, mating, nest and den building, territorial maintenance and defense, and longevity and survivorship. Cyto- and geno-toxic effects have been observed. The above issues are explored in three consecutive parts: Part 1 questions today's ambient EMF capabilities to adversely affect wildlife, with more urgency regarding 5G technologies. Part 2 explores natural and man-made fields, animal magnetoreception mechanisms, and pertinent studies to all wildlife kingdoms. Part 3 examines current exposure standards, applicable laws, and future directions. It is time to recognize ambient EMF as a novel form of pollution and develop rules at regulatory agencies that designate air as 'habitat' so EMF can be regulated like other pollutants. Wildlife loss is often unseen and undocumented until tipping points are reached. Long-term chronic low-level EMF exposure standards, which do not now exist, should be set accordingly for wildlife, and environmental laws should be strictly enforced.

Keywords: 2G – 4GLTE; 5G; cell phone towers/masts/base stations/small cells; "Internet of Things" (IoT); magnetoreception; millimeter waves (MMW); nonionizing electromagnetic fields (EMF); radiofrequency radiation (RFR); satellites; wildlife.

***Corresponding author: B. Blake Levitt**, P.O. Box 2014, New Preston, CT 06777, USA, E-mail: blakelevitt2@gmail.com, blakelevit@cs.com
Henry C. Lai, Department of Bioengineering, University of Washington, Seattle, WA, USA, E-mail: hlai@uw.edu
Albert M. Manville II, Advanced Academic Programs, Krieger School of Arts and Sciences, Environmental Sciences and Policy, Johns Hopkins University, Washington DC Campus, USA, E-mail: amanvil1@jhu.edu

PART 1: DEFINING THE PROBLEM: TECHNOLOGY AND RISING EMF LEVELS

Introduction: environmental disconnect

Since the advent of electrification in the late 1800s and wireless communications in the 1930s, ambient levels of radiation from devices, broadcast facilities, land-based telecom infrastructure, satellites, and military applications have gradually risen across a range of frequencies in the nonionizing bands of the electromagnetic spectrum. There has been broad discussion in the media and elsewhere about nonionizing electromagnetic fields (EMF) effects to humans, especially since the International Agency for Research on Cancer (IARC) at the World Health Organization (WHO) classified extremely-low frequency (ELF) magnetic fields and radiofrequency radiation (RFR) ([1, 2] respectively) as 2B possible human carcinogens — similar to lead, exhaust fumes, DDT and formaldehyde. But is there a larger environmental downside to rising ambient EMF exposures — particularly RFR — from popular mobile communication devices, WiFi antennas, and all accompanying infrastructure that is being overlooked by environmentalists, researchers, and government regulators alike. We may be missing critical physiological effects across species based on obsolete assumptions about low-level far-field exposures being too weak to adversely affect living tissue. We have yet to take into consideration the unique physiologies of other species, or how they use the environment in ways that humans do not, when we assume that the unfettered use of EMF/RFR can continue unabated and be allowed to grow indefinitely. Ambient electromagnetic fields, such as ELF from powerlines, wiring and electrical appliances, and RFR used in all broadcast, wireless communications, and transmitting devices, are biologically active and may cause adverse effects to different species of living organisms.

Because of the extensive research that applies to this subject, this work is divided into three consecutive parts:

Part 1 explores the research on rising ambient levels of EMFs, how fields are measured, the use of tracking devices in animals, and what new technologies like 5G will add.

Part 2 explores the Earth's natural geomagnetic fields and non-human species mechanisms of magnetoreception, as well as cyto- and genotoxin effects from manmade EMFs. It focuses on the unique physiologies of non-human species, their specific habitats, and how energy travels through different environments. The section then ties what has been seen in the laboratory, as well as field studies, in all frequencies and representative biological taxa at exposures now seen in ambient environments.

Part 3 discusses government exposure standards and explores existing laws already in place in Western countries, then points to how a new vision of aeroecology and electroecology can use those laws to inform policy regarding nonionizing radiation's impacts.

Supplementary materials include extensive Tables of applicable studies per section at extremely low intensity exposures and accompanying references.

There is abundant research on how low-level EMFs affect non-human species, including extensive reviews of nonionizing radiation across all frequencies and environments about which many environmentalists and regulators are unaware [3–14]. In research into the biological effects of EMF, it has been known since the 1960s that many species are sensitive to low-level energy exposures. Numerous laboratory and field studies have noted heightened sensitivity and adverse effects in birds [15–32]; mammals (cows and bats [33–38]); insects [39–54] bacteria/protozoa [55–61]; amphibians [62–67]; fish and turtles [68–82]; and in trees and plants [83–85], among many others.

Living organisms evolved in a matrix of environmental nonionizing electromagnetic fields, particularly the Earth's geomagnetic field. These natural fields are required to keep organisms well and living in harmony. For example, it has long been known that the geomagnetic field is needed to coordinate embryonic development and provide information for directional migration of insects and birds. These fields are relatively weak and also vary with location. For millions of years, living organisms lived and thrived in these fields. It is therefore logical to assume that man-made fields, which are unfamiliar to living organisms, could disturb their normal physiological functions. And this could happen at very low intensities of the unfamiliar fields. The proliferation of wireless communication systems in particular may pose a dangerous challenge to living organisms on Earth. In addition, there is the more difficult challenge that these novel EMF exposures do not allow living organisms to adapt or adjust since technology's signaling characteristics change rapidly as new technologies emerge and are constantly being developed.

Despite accumulating evidence, there has been a broad disconnect in environmental circles regarding the possibility that there may be serious consequences to this increasing cumulative EMF background from devices like cell phones, smart phones/tablets (iPods, iPads, Kindles), wireless Internet (WiFi, 2G, 3G, 4G, 4G LTE, and now the 5G "Internet of Things"), tower/antenna infrastructure needed to support vast wireless services, and the recent 'smart' grid/metering systems being built across industrialized countries by numerous utility companies, as well as the auto industry with anti-collision/remote-sensing devices now embedded in vehicles, among others. In fact, major national organizations like the Natural Resources Defense Council [86] and the Sierra Club [87] are active proponents of smart grid/meters and other wireless technologies in the name of energy conservation without considering EMF's biological effects. When organizations fail to address the growing database of EMF impacts, however, the result is the tacit and/or explicit approval to introduce whole new layers of EMF into every home and neighborhood, without a full examination of what potential consequences may arise. Federal and state regulatory environmental protection agencies in the U.S. are also proponents of smart grid technology [88] with no mention of possible effects to wildlife from EMF.

Reasons for this disconnect include the fact that many biologists are unfamiliar with the research that exists and/or lack the specialized knowledge of bioelectromagnetics needed to assess the published research. There is also an absence of familiarity — and often low comfort levels — with the cross-discipline of bioelectromagnetics, as well as a professional bias against or feelings of intimidation in biologists regarding the 'hard' sciences of physics and engineering which are the natural homes of technology. In fact, other than the embrace of technology to facilitate various research objectives, such as imbedding RFID microchips and/or attaching radio-transmitters to wildlife in order to track migration, behavior, and breeding patterns, biologists can seem incurious about the effects of environmental EMF on living systems. They appear more focused on technology's end point of what it can accomplish rather than how it actually functions as a biologically active entity.

At one time, electromagnetism was understood as integral to the natural world, and still is in many indigenous cultures and throughout Asia. But that knowledge was largely lost in Western cultures during the 20th Century during an era of over-specialization among the sciences, especially between the physics/engineering disciplines, which provide the underpinnings of EMF and energy propagation, and the biological sciences. This has created a chasm in which background levels of EMF continue to rise with each new added technology, yet little research is called for by environmentalists to determine what effects, if any, may be occurring in technology's path in myriad species as well as their habitats.

We are on the cusp of introducing a massive new level of exposures in the extremely high frequency range (EHF 30–300 GHz) never previously used in civilian telecommunications, although it has been used in military radar and some medical applications. This is the new 5G and Internet of Things [89], which uses complex phased millimeter waves that are smaller in wavelength, and therefore capable of reaching resonant match with some insect species [90], as well as disrupting crucial biological functions of numerous other organisms. In theory, this one technology has the ability to disrupt important ecosystems with broad-based effects to food webs. In addition, the top end of these ranges reach infrared frequencies, some of which are actually visible to other species — especially birds — and can impede their ability to sense natural magnetic fields necessary for migration and orientation [91]. Yet no environmental review in the U.S. has been recommended before buildout [89]. Other countries, especially in Europe, are being more cautious.

Historically, the U.S. was the leader in EMF health and environmental research, but now most of that work — and any accompanying public policy recommendations — are coming from Europe and elsewhere [92, 93]. There is virtually no public or private funding in the U.S. for ambient EMF research into the effects on wildlife, despite appeals from federal agencies such as the U.S. Fish & Wildlife Service [94–96] to study the effects of EMF on nonhuman species, and requests to the U.S. EPA and FCC to address exposures to wildlife [94, 96–100]. Industry funded research cannot be considered unbiased. There are no regulations specifically designed to protect wildlife from EMF. All regulations are intended for human health, even as most research has historically been conducted on animal models [94, 95]. The unintended consequences of this, in fact, may be that we know more about EMF effects to nonhuman species than we realize, making a large amount of information available for ecological integration and environmental utilization.

Review studies chosen: defining how low level spatial energy may translate to non-human tissue absorption

Studies on the biological effects of anthropogenic electromagnetic fields number in the thousands (101) and span more than eight decades. However, the majority of the early research studied EMF at intensities much higher than those of man-made EMF in the environment. We raise a fundamental question in this paper: Is low-intensity anthropogenic EMF in the environment capable of affecting physiological functions in living organisms? There is an abundance of studies in very low-level ranges to draw from (see Part 2: Supplements 1, 2, 3 and 4).

The primary focus of this review is on low-intensity far-field EMF exposures, i.e., at some distance for the radiating source, comparable to ambient fields that various species might repeatedly encounter. The studies we reference were chosen according to general significance and specific relevance to the species being discussed in both the text and Supplemental Charts.

There are literally thousands of studies going back to the 1930s (e.g., [90, 102–107]) that used test animals in controlled laboratory conditions to determine EMF effects on humans. To conduct such work directly on humans is ironically considered unethical at the same time we allow technology to flourish. Although most research has been conducted on rodent models such as mice and rats, one unintentional byproduct is that we actually know a considerable amount about how both high and low intensity EMF can affect species such as rabbits, dogs, cats, chickens, pigs, primates, amphibians, fruit flies, bees, Earth worms, various microbes, and yeast cells which have all been used as research models. Typically this work has not been understood as broadly germane to wildlife but in many instances it can be seen as important as illustrated throughout this paper.

The vast majority of the early research prior to the 1960s using animal models was done with high-intensity RFR [108–112] unlike most low-level ambient exposures today. The early work was specifically designed to determine gross thermal effects in humans at a time when electrophysiology and thermoregulatory mechanisms were not well understood. The more subtle non-thermal effects were of little interest then, although certainly known to exist [104–106, 113–115]. Additionally, signaling characteristics were unlike today's complex pulsed digital exposures. Thus the large body of early work is not included in this review except where appropriate for the general understanding of trans-species physiological patterns and for an overall understanding of how energy couples with living tissue which the early work helped delineate.

How government exposure standards relate to wildlife

To develop a sense of the potential relevance of ambient exposures to wildlife, it is necessary to briefly compare standards for human exposure. In the U.S., the Federal Communications Commission (FCC) is the agency authorized by law to regulate the communications industry and grant licenses for radiation transmission/reception/exposure from communications devices. FCC adopted exposure standards [116–118] that include both power density for ambient exposures from transmitting sources (generally defined as the rate of energy transmitted in space) and specific absorption rates (SARs) reflecting the dose rate of energy absorbed in tissue – both potentially relevant metrics to species in the wild.

For power density, the U.S. standards are between 0.2 and 1.0 mW/cm^2 and for SAR between 0.08 and 0.40 W/kg of human tissue. For cell phones, SAR levels require hand-held devices to be at or below 1.6 W/kg averaged over 1.0 g of tissue. For whole body exposures, the limit is 0.08 W/kg. In Canada and throughout most European countries that use the exposure standards created by the International Commission on Non-ionizing Radiation Protection [119, 120], the SAR limit for hand-held devices is 2.0 W/kg averaged over 10 g of tissue. Whole body exposure limits are 0.08 W/kg. At 100–200 ft (30.5–61 m) distances from a cell phone base station (i.e., an antenna or antenna array), a person or animal moving through the area can be exposed to a power density of 0.001 mW/cm^2 (i.e., 1.0 μW/cm^2). The SAR at such a distance can be 0.001 W/kg (i.e., 1.0 mW/kg) for a standing man.

For the purposes of this paper we will therefore define low-intensity exposure to RFR for power density of 1 μW/cm^2 or a SAR of 0.001 W/kg.

Many biological effects have been documented at low intensities comparable to what the population — and therefore wildlife — experience within 200–500 ft (61–152 m) of a cell tower [100]. These can include effects seen in *in vitro* studies of cell cultures and *in vivo* studies of animals after exposures to low-intensity RFR. Reported effects include: genetic, growth, and reproductive alterations; increases in permeability of the blood brain barrier; stress protein increases; behavioral changes; molecular, cellular, and metabolic alterations; and increases in cancer risk (see Ref. [100], Table 1).

Sensitivity to RFR and the setting of exposure standards for humans are mostly based on research data from rats (another mammalian species). In general, however, it is not valid to apply the same data to species more distant on the evolutionary scale, e.g., birds, insects, and trees. Realistically one should only use the available dosimetric data on each particular species to understand its RFR sensitivity, which is why this paper goes into such detail in Part 2 on EMF studies covering all taxa. However, exposure standards set by the FCC and others do not set limits with nonhuman species in mind.

Unlike field research, *in vivo* and *in vitro* laboratory studies are conducted under highly controlled circumstances often with immobilized test animals, typically at near-field, for set durations, at specific frequencies and intensities. Extrapolations from laboratory research to species in the wild are difficult to make regarding uncontrolled far-field exposures, other than for example to seek possible correlations with laboratory-observed DNA, behavioral, or reproductive damage. In the wild, there is more genetic variation and mobility, as well as variables that confound precise data assessment. In addition, there are complex variables like orientation toward the generating source, exposure duration, animal size, species-specific physical characteristics, and genetic variation that also come into play. Assessments for wildlife may vary considerably depending on numerous factors.

It is highly likely that the majority of wildlife species are constantly moving in and out of varying artificial fields. Precise exposure data, however, are difficult to estimate. Nevertheless, there is a growing body of evidence that finds damage to various wildlife species near communication structures, especially where extrapolations to radiation exposure have been made [15, 17, 32, 36, 37, 121–123].

The major question of whether man-made environmental EMF creates biological effects in wildlife species has now become urgent with 5G technologies and potentially more lenient allowances being considered by the major standards-setting committees at FCC and ICNIRP (see Part 3 on government exposure standards and new proposed changes).

Are we using the right physics model in standards setting?

From the beginning, there has been discussion regarding basic physics models used to determine manmade EMF effects to living systems [124–131]. The discussion has focused on classic models of photonic energy vs. wave energy in relationship to thermodynamic equilibrium. These are highly complex biophysics discussions beyond the scope of this paper in anything other than the broadest description. They are included here because of ramifications to the standards-setting models noted above and in Part 3, and particularly regarding effects to DNA discussed in Part 2. These factors are linked and apply to all species.

The electromagnetic spectrum is divided into ionizing and nonionizing bands. Classic quantum theory EMF photon models used to assess ionizing radiation [132] established long ago that ionizing radiation has enough inherent energy to knock electrons off orbits within atoms thereby causing structural cellular changes that are potentially carcinogenic and mutagenic due to DNA damage.

Those same models were then extrapolated to conclude that since nonionizing EMF does not have enough inherent power to displace electrons from atoms, it therefore cannot damage molecules such as DNA directly and certainly not indirectly. Historically, held against that one definition regarding inherent photonic energy, man-made nonionizing EMF has been presumed to be relatively innocuous beyond its ability to heat tissue and cause electrical shock. Most modern technology, including all current exposure standards and categorical exclusions, are based on that rationale, along with observed behavioral effects in animal models. Exposure standards have been strictly based on the easily quantifiable thermal hazards of tissue heating with safety margins built in [116–120]. While those safety margins vary between countries, the fundamental exposure mechanism assumption is not challenged.

What is left out of that narrow model, however, is the fact that all living things are fundamentally coherent electrical systems that interact in highly sensitive ways to minute levels of nonionizing EMF — sometimes at vanishingly low intensities far below current standards [3, 4, 100, 133–135]. This is particularly true of other species that have evolved to sense and use low level EMF fields in surprising ways (see Part 2).

In addition, much of biology is nonlinear. For example, a small amount of bee venom can create an outsized effect (anaphylaxis) in people allergic to bee stings. The weather is also nonlinear [136], e.g., a small perturbation in one part of the world can theoretically result in a major weather event like a tornado in a far distant area [137–139] (This is not to be confused with the so-called Butterfly Effect — or chaos theory of butterfly wing flapping affecting weather events in other parts of the globe, which has never been documented). Evidence has been mounting for decades that biology is more related to quantum states and resonant responses, not to the traditional linear equilibrium thermodynamic models currently used to define what biological effects *should* occur but often do not [127].

Also left out of that narrow linear model, which is based on a single photon acting on a single cell at a singular moment in time, is the fact that today's uses of EMF/RFR involve many photons acting in unison [140] in extremely complex ways such as in phased array technology. In other words, the entire thermodynamic model traditionally used to promote RFR safety regulation may not apply. It also excludes most recent research pointing to both cumulative and synergistic effects [141], and is unable to embody the complexity and totality of today's exposures, much less biological sensitivity in general.

Radiation is not a classical closed system in a thermodynamic equilibrium [142]. Yet it has been repeatedly put forth that devices and infrastructure must be safe because a single microwave photon, for instance, does not have enough energy to break a chemical bond. While that might be accurate for some sources of ionizing radiation, it may not hold true for lower frequency bands that operate within the classical wave limit of high photon densities where the energy of each photon is often irrelevant ([132], updated 2017).

Panagopoulous et al. [143–146] have written extensively on this issue, noting that man-made electromagnetic emissions are very different than what is found naturally in light spectra and the ionizing bands; that man-made EMF is not "quantized." They posit instead that nonionizing EMFs do not consist of photons but rather of continuous waves in high-density photon "packets" described in classical electromagnetism that interact very differently with biological systems than traditional models assume. It remains to be seen if this hypothesis gains wide acceptance.

If we are to truly shift to safer exposure standards, we need an accurate model based on biology, observation, and experimentation, not just physics theory. Typically when contradictory information that goes against popular assumptions reaches a sufficient critical mass, those assumptions eventually give way to more current knowledge. At present, there are no true biologically based standards in existence other than for a narrow range of heating effects. What we appear to have are dosimetry models that easily allow technology to function.

What may be the most accurate model has yet to be determined but may evolve into a new hybrid. It is already well known that distribution of absorbed RF energy in living tissue is not uniform, varying widely within cells and different body areas and organs, which is why SARs are generally averaged [142]. If nonuniformity can be more accurately factored in, subthermal interactions may make sense with or without new mechanistic models being delineated. What has become increasingly clear is that current models no longer withstand close scrutiny in the face of so much contradictory science begging for a more accurate assessment.

Increasing ambient background levels

Exposure to anthropogenic environmental RFR began little more than 100 years ago – an extremely short window from an evolutionary perspective. Amplitude modulation (AM) radio broadcasting was first introduced in the 1920s in the medium-frequency band (500–1,600 kHz), with both frequency modulation (FM) radio and television broadcast in the very-high frequency band (VHF 30–300 MHz) introduced in the 1930s. The end of World War II and advances in technology saw the rapid expansion throughout the 1950s with television stations operating in the ultra-high frequency ranges (UHF 300 MHz–3 GHz; [147]). Throughout the 1970s and 1980s, FM came to dominate commercial radio but AM never stopped broadcasting. From the 1980s through the present, large swaths of high-powered commercial radio infrastructure (50,000,000 W and more) has moved from terrestrial-based towers to satellite platforms, while low-powered FM stations (1,000 W) have increased their terrestrial footprint. There was another exponential increase from the mid-1990s through the present with the introduction of cell phone technology, also in the UHF bands, which has become by far the dominant RFR exposure today [148, 149]. Ambient RFR has since grown into a constant ubiquitous exposure in all industrialized nations from both terrestrial and satellite-based infrastructure.

Today's wireless applications are legion. The latest include smart grid/metering, 3G/4G LTE and now 5G telecommunications networks offering endless click-on "apps," TV/music/video downloads, e-books, photos in the "Cloud", voice, 'smart' homes and personal assistants like Amazon's Alexa, Apple's Siri, and Google Homes, WiFi/WiMax Internet connectivity and texting — all available from a cell phone. Then there are universal GPS systems that work off of satellites and a host of vehicle-mounted radar RFR collision avoidance devices built into vehicles to automatically stop, detect people or animals on the road, or park the vehicle without engaging the driver. Already out of prototype are driverless cars and trucks, as well as a new broadband wireless service that will introduce a new form of ubiquitous WiFi with antennas capable of transmitting in a 12,000 mi^2 (31,080 km^2) radius with a 62 mi (100 km) reach from one antenna. Also rapidly being built in many areas are augmented cell services via distributed antenna systems (DAS) and small cells mounted on utility poles targeted for urban as well as rural mostly RFR-free areas. DAS/small cells will host the 5G Internet of Things (IoT). Then there are new Homeland Security networks like GWEN and FirstNet, and emergency first responder systems like Terrestrial Trunked Radio (TETRA). All of these technologies use extremely complex signaling characteristics carrying a lot of information with potentially complex biological effects. Each new technology introduces a new level of environmental exposure. Just 70 years ago, very little of this existed and its consequences had been little studied or understood until now — a focus of this paper.

With the exception of some developing countries, 2G has largely faded from use in most industrialized nations where third generation (3G) is still operational for global system mobile communications (GSM), while fourth generation (4G) long-term evolution (LTE) has become increasingly popular for smart phones/technology using the universal mobile telecommunications system (UMTS). Gonzalez-Rubio et al. [150] found the highest environmental mean radiation values measured today are for GSM/UMTS/DCS, accounting for approximately 70 percent of outdoor environmental mobile communication exposures, although in some countries, like Turkey, the highest exposure still comes from radio and television broadcasts. First and second generation systems were very frequency specific (850–1,200 MHz) but today there are multi-frequency bands used within systems for up-and download frequencies from devices and base stations — e.g., GSM + UMTS 900 MHz, UMTS 2,100 MHz, LTE 800 MHz, LTE 2,600 MHz and GSM 1,800 MHz bands.

Prior to the telecom buildout in the early 1990s, a detailed sample of ambient baseline data existed based on a 1980 study by the U.S. Environmental Protection Agency

(EPA) which we can compare to today's rising exposures. In the first study of its kind, EPA researchers Tell and Mantiply [151] assessed background levels of broadcast signal field intensity of RFR for three years and obtained data at 486 locations distributed throughout 15 large U.S. cities. The data collectively represented 14,000 measurements of very high frequency (VHF) and ultra high frequency (UHF) radiation (used in television broadcast) in ambient environments with estimated exposure at 47,000 census districts within the metropolitan boundaries of those cities. At the time, ground-based broadcast signals from TV, AM radio and the then-increasing FM radio transmissions were the primary exposures. There were no cellular services, very few wireless devices, and very little satellite transmission compared to today.

The Tell and Mantiply [151] study found that 20 percent of the total U.S. population was exposed to time-averaged VHF and UHF broadcast radiation at a median level (i.e., the middle value of the highest and lowest measured values) of 0.0005 μW per centimeter squared ($\mu W/cm^2$). This represents a measurement of power density in a set space commonly used to delineate RFR field intensity. In Los Angeles, for instance, Tell and Mantiply [151] found the median level was 0.005 $\mu W/cm^2$ [152]. Their data also suggested that only 1% of the population, or about 441,000 people, were potentially exposed to levels greater than 1 $\mu W/cm^2$ — the safety limit recommended by the USSR which was 1,000 times more stringent than the U.S. safety guidelines in 1980. At the time, the researchers clearly found the data reassuring for the general population.

Tell and Kavet [147] revisited the subject in 2014 but specifically did not replicate or try to update the large 1980 study. Their goal was to determine if, and how, environmental levels could now be assessed, given the number and variety of RF transmitters used today. They tested in four small-to-medium size municipalities and found that the FM bands were still a major contributor to overall RFR exposure, but noted that over time, intensities in the VHF bands decreased while the UHF bands increased, reflecting the shift in the UHF bands for cellular use since 1980. European researchers, however, did not find FM to be a significant factor in today's exposures [153–155].

The original 1980 U.S. study cannot be replicated since the profile and nature of RFR has completely changed since that time. But an international team of researchers [149] measured EMF/RFR in 94 matched microenvironments in six countries, including Switzerland, Ethiopia, Nepal, South Africa, Australia and the Los Angeles area of the U.S. — one of the 1980 EPA sites — where they found a 70-fold increase in RF levels compared to the late 1970s measurements [152]. See below for more information on this study with cell phone infrastructure as the dominant contributor. Other than the one Sagar et al. [149] study, there are no current data on background radiation levels in the U.S. However, findings from U.S. and Canadian cities are thought to be comparable to studies coming from Europe which takes more interest in the subject in general as well as quantifying the continuously rising indoor and outdoor levels in particular.

Although cell service did not exist when the original 1980 EPA study was performed, cell technology now functions in similar UHF bands measured by Tell and Mantiply in 1980 [151]. Thus today's rising exposures can be assessed against the baselines noted back then. When the U.S. switched to digital television in 2008, it freed up spectrum "white space" previously used for analog TV transmission. That spectrum space is now allocated for 4G wireless Internet, and both the VHF and UHF bands will be used in expanding ubiquitous broadband/Internet service in rural areas. But the advent of digital technology, which simulates pulsed waves, significantly changed communications signaling characteristics, essentially allowing for a second universal transmission system to be built on top of the old analog signals [100]. This not only doubled overall environmental RFR exposures, it introduced a completely new kind. It was the global introduction of digital technology that facilitated the reshuffling of various RFR bands in the finite "real estate" of the electromagnetic spectrum. The introduction of 5G is now doing the same thing.

There is never enough spectrum to satisfy society's desire for it, a consequence of which is that we have now completely filled in most of the lower nonionizing bands with commercial and military use, and are branching into much higher frequencies using millimeter waves between 30 and 300 GHz for communications and other applications. The U.S. was the first country to approve the buildout of the fifth Generation (5G) communications, to date in the 28, 37, and 39 GHz ranges for 5G. The new 5G systems, using small cells and Distributed Antenna Systems (DAS) networks, are being built with antennas attached to buildings and powerline utility poles in very close proximity to the population, using extremely complex phased array signaling heretofore mostly used by the military. Neither these frequencies nor signaling characteristics existed for civilian use in 1980 and therefore constitute a whole new and novel environmental exposure since that early EPA review, along with all of the other wireless technologies since introduced. One thing is certain — exposure patterns are rapidly changing with each new technology development, far in advance of our biological understanding of the consequences.

With the advent of cell technologies in the mid-to-late 1990s, background ambient RFR exposures began to steadily increase, particularly — though not exclusively — in urban areas [18–149, 156–165]. Cellular infrastructure, though orders of magnitude lower in power density than that from broadcast facilities, has become vastly more ubiquitous and is placed much closer to the human population in both urban and rural areas [155].

Difficulties in assessing ambient exposures

Assessing ambient exposures, both indoors and outdoors, has frustrated researchers and regulators alike regarding how best to capture field exposure data. Should it be through computer simulation or actual field measurements? Variables in environmental assessments can be blindingly complex. Power density and distance from a generating source have traditionally been used as the surrogate for ambient exposures but those metrics can be imperfect given how RFR couples with the environment once transmitted, as well as the necessary factoring in of multiple overlapping sources today. Aside from distance and multiple sources, environmental assessments involve variables such as orientation toward the transmitting source, species, size, physical composition, the presence of metal objects, and topography, to name but a few [100, 155].

RF field strength falls off rapidly with distance from the transmitting source (Maxwell's inverse square law) but predicting actual exposures based on simple distance from antennas using standardized computer formulas is inadequate. Actual exposures are far more complex in both urban and rural environments to both humans and wildlife.

Contributing to the complexity is the fact that the narrow vertical spread of the beam creates a low RF field at ground level directly and at some distance below the antenna. As a person or wildlife species moves away from or within a particular field, exposures create peaks and valleys in field strength. In addition, scattering and attenuation alter field strength in relation to building placement, architectural composition, the presence of trees, soil type, and topographical features such as mountains and rock formations [166]. Power density levels can be 1–100 times lower inside a building, for instance, depending on construction materials used and antenna gain [155]. Exposures can differ greatly depending on the presence of conductive mediums like water or soil containing mineral salts with sodium, iron, copper, and zinc, among others. Exposures can be twice as high in upper floors of buildings as in lower floors [167, 168]. This would also apply to birds/bats/bees and other insects receiving higher exposures when flying at a lateral plane with transmitting antennas mounted on a tower or atop other structures.

Although distance from a transmitting source has been shown to be an unreliable determinant for accurate exposure measurements due to potential creation of RFR hotspots [155], the metric is nevertheless useful in some general ways. For instance, Rinebold [169] has shown that radiation levels from a tower with 15 non-broadcast radio systems will fall off to natural background levels at a distance of approximately 1,500 ft (457 m). This would be in general agreement with the lessening of symptoms in human populations living near cell towers at a distance greater than 1,000 ft (300 m; [170]). There is, of course, no adequate or reasonable way to restrict wildlife from approaching, defending territories, and/or living near towers, including birds nesting directly on or immediately near them.

Animal radiotracking devices: RFID and radio collars

In human populations, wearing or carrying personal dosimetry devices appears to be a promising area for capturing cumulative exposure data. But attaching such devices for the same purposes to wildlife is ill-advised given the amount of tracking equipment — RFID chips, radio collars, and radio/satellite implants — already globally deployed by biologists on/in numerous species of avian, terrestrial, aquatic and marine wildlife for study and media entertainment.

Arguably, important behavior and migratory findings have been discovered for myriad species from such use — including the deep dives of great white sharks (*Carcharodon carcharias)* and the 50,000+ mi (80,470 km) annual "figure eight" migrations of Arctic Terns (*Sterna paradisaea)*, among many others. One of the authors [171] radio-tagged black bears (*Ursus americanus*) in Michigan's Lower Peninsula for three years using receivers on the ground and in aircraft, investigating impacts from humans on bears, but at the time he was unaware of possible impacts from EMF. Aside from the newest telemetry technologies with safety features such as immediate break-away telemeter/collar options, lost collar signaling, and data-card download capabilities, there can still be difficulty removing such devices after attachment/insertion, if at all, or collecting such devices once an animal has died, or devices have slipped off and/or self-released in remote areas.

Most important, however, are data available that confound the additional exposures [172] from the devices themselves, which has not been broadly addressed by the wildlife community. Balmori [8] noted that radio transmitters attached to animals can induce negative effects leading to biased results. Documented effects from use of the devices include decreased productivity, behavioral and movement changes/patterns, increased energy expenditure, biased sex ratios, and reduced survival. Biologists often attribute such factors to the weight of the radio transmitter and/or associated devices. Also the type of attachment (harness, collar, leg clamp, glue, or implant) and where mounted (subcutaneous anchoring, tail, head, wing, etc.) are also considered factors in adverse outcomes. So far, however, EMF/RFR has largely been left out as a confounder, even as adverse effects were found to be significantly associated with the duration of RFR transmitter attachment [8, 173]. This parallels similar effects seen in all wildlife taxa from RFR as demonstrated throughout this paper. Balmori [8] posited that ironically scientists investigating animal orientation understand they must shield their labs to prevent anthropogenic EMF from distorting or skewing research results, yet they directly attach transmitters to species in field studies without considering the confounding exposure of the radio tracking devices themselves on behavior, movement, orientation, and even survival.

Barron et al. [173] published a meta analysis of effects to avian species from use of radio tracking devices. Up until this large analysis, studies were limited to investigations of either the type of device or to a single species. The researchers reviewed 84 studies to determine if devices had an overall effect on avian species, which aspects of behavior and ecology were affected, and importantly, if mere capture and restraint were factors. They found significant overall device-induced negative effects as well as negative effects from eight of 12 specific aspects — most markedly from increased energy expenditure and reduced likelihood to nest. In fact, devices negatively affected every aspect considered except flying ability. Effects were independent of sex, age, primary method of locomotion and body mass. They also found no evidence of greater effects from heavier devices, but breast-mounted and harness attached equipment increased device-induced behaviors such as preening. Device-induced mortality differed between attachment methods with anchored and implanted transmitters (which generally require anesthesia) showing the highest reported device-induced mortality rates. Harnesses and collars also had relatively high mortality rates, possibly due to entanglement with vegetation. They further noted that cumulative impacts from some aspects of attachment were substantial. For example, reductions in nesting propensity, success, productivity, and foraging can all decrease reproductive potential, while reduced foraging, body condition and flying ability, along with increased device-induced behaviors and energetic expenditure, are likely to increase bird mortality with use of transmitters. Also, transmitters on some birds indirectly reduced the fitness of untagged mates if they had to compensate for decreased parental activities by the bird with the transmitter. Capture and restraint however, as independent variables, were not found to be of consequence. The authors deduced negative effects were primarily due to transmitters. They concluded that transmitters and other devices could negatively affect birds and may bias resulting data. Unlike Balmori's 2016 review [8], this study did not specifically include EMF/RFR but it can generally be implied.

Deadly sarcomas have also been observed in tissue around RFID chips imbedded in research animals and domestic pets [174–182] which some attributed to the casing material. Also noted were severe metabolic changes in animals exposed to 915-MHz RFID [183].

Not all animals studied with RFID chips however showed adverse effects [184–187] although most of those tests were of short duration [174]. Very little follow-up data have been collected on possible effects to wildlife after radio collars or other tracking devices have been attached, or what contribution, if any, such devices may be contributing to ambient exposures. Much still remains unknown about the impacts of telemeters in and/or on wildlife.

One field study by Raybuck et al. [188] of Cerulean Warblers (*Setophaga cerulea*), a small long-distance migratory songbird, found a 35% lower return rate when geolocators (also known as dataloggers or geologgers) were attached than in control populations without geolocators. Geolocators are miniature devices with tiny computers that produce a small magnetic field and record light at regular intervals, usually two times per day, enabling general position to be calculated. Birds must be re-captured to gather the range of location information over time. Devices are externally attached to birds with thin straps under their legs or harnesses on their backs and are widely used by biologists to track avian migration over their full annual cycle of spring return, mating, nesting, fledging, fall migration and overwintering. While Raybuck et al. [188] found no negative effects from geolocators during the breeding season, the return rate of geolocator-tagged birds was lower than that of control birds (16 ± 5% vs. 35 ± 7%). They attributed the loss to increased weight from the devices, adverse weather patterns especially to species flying over large bodies of water, return to areas other than expected, and death. The researchers did not explore potential effects from EMF but noted that caution was warranted.

Most wildlife biologists do not factor in the effects of exposures from microcurrents in batteries/computers, RFID chips that do or do not transmit RFR, or GPS radio collars that transmit to satellites which can create independent exposures to wildlife and surrounding environments. Because there is so little information regarding effects of EMF exposure in tagged wildlife, the use of dosimeters carried by humans may provide better information about ambient exposures that may then be extrapolated to wildlife as they move in and out of different habitats. Wildlife should not be equipped with devices to assess ambient EMF, even in remote wilderness areas. Biologists should reconsider the abundant use of such devices as if there are no consequences or confounding of data gathered from them.

Human personal dosimetry devices: capturing ambient field measurements

A novel approach for capturing and quantifying ambient exposures for larger built areas was created by Estenberg and Augustsson [153] for the Swedish Radiation Safety Authority. It involved a car-based measuring system for estimating general public outdoor exposures. The complicated but carefully designed system enabled fast, large-area, isotropic spectral bandwidth measurements covering the frequency range between 30 MHz and 3 GHz. The method allowed the complete mapping of a town with 15,000 inhabitants and a 115 km (71+ mi) reach performed in one day. Areas chosen in Sweden represented typical rural, urban and city areas. The data sets consisted of more than 70,000 measurements performed between 8:00 AM and 6:30 PM local time. Results found median power density was 0.0016 μW/cm2 in rural areas, 0.027 $\mu W/cm^2$ in urban areas, and 0.24 $\mu W/cm^2$ in city areas. In urban and city areas, mobile phone base stations were the clear dominating sources with GSM and UMTS downlinks. The many factors that affected measurement results were discussed, most crucial being the variation of the actual field strength over time caused by sporadic, pulsed or moving transmitters or by multipath fading due to reflections from moving objects. The authors said "…a single measurement of the field strength from transmitters like the global system for mobile communication (GSM) base stations can be both under- and overestimated depending on whether the burst is caught by the measurement," but added that "the extensive amount of measurements in each data set still ensures that the median or mean power density within a measured district is robust." They also noted that due to the antenna mount on top of the vehicle, both over- and underestimates may also occur between transmitters closer to the ground vs. those placed at a higher level, but added that the repeatability of the measurement method and its ability to locate local hotspots is a positive outcome acquired from using this method. While there are many complexities involved with such mobile measurements, on top of the fact that no standard or existing solution for how such mobile measurements should be carried out yet exists, the approach summarized above nevertheless seems a good start.

Gonzalez-Rubio et al. [150] tried another creative mobile method by placing an EME Spy 140 inside the plastic basket of a bicycle, performing measurements in all 110 administrative (electoral) regions with homogenous population counts in the city of Albecete, Spain. The use of the bicycle allowed better access to all areas of those districts — especially those areas inaccessible with motorized vehicles. The authors specifically sought to correlate exposure levels to known fixed mobile base station sites but surprisingly found they did not correlate. Possible reasons given for the absence of correlation were: orientation of the base station antennas, building construction features, land topography, RFR deflection off of buildings and signal attenuation. Gonzalez-Rubio et al. [150] did not characterize what, if any, contribution to outdoor ambient levels were made by possible leakage from indoor RF transmitters or handheld devices but they did use domestic DECT phones as their control since DECT operates without involving links with outside base stations. Their results averaged three bands of mobile telephone antennas (GSM, Digital Combat Simulator [DCS], and UMTS) in the different regions and found variations of average intensity from 0.04 V/m (0.00042 $\mu W/cm^2$) to 0.89 V/m (0.21 $\mu W/cm^2$). The study points to the complexities of how RFR dissipates in the environment and that distance from a generating source is an unreliable metric. Calvente et al. [189] earlier found similar wide spatial variability outside of 123 residences in Southern Spain using the same variables, plus seasonal differences. Lahham and Ayyad [190] measured environmental RFR in Palestine using a personal exposure meter EME SPY 140. The total daily exposure from all radiofrequency electromagnetic field sources varied widely among participants depending on their location, the mobile network they use, their activities, and their mode of transportation, ranging from about 0.2 to 0.9 V/m, mainly from WiFi 2G, GSM900 uplink, GSM900 downlink, and FM broadcasting.

Using such mobile measurement approaches in expansive rural areas with road access, as well as fixed measurement sites in very remote locations, would better capture real-time exposures (including intermittent peaks from space-based networks capable of affecting wildlife) than computer simulations or personal dosimeter methods, although dosimeters carried or properly attached to trekking gear could gather pertinent information as well.

Measured levels: (for a table of studies, see Part 1, Supplement 1, "Environmental EMF measurements from around the world")

Prior to the widespread use of the UMTS network in one of the earliest ambient environmental studies after Tell and Mantiply [151], Hamnerius and Uddmar [191] investigated EMF/RF at 16 different sites in Sweden, both indoors and outdoors in city areas like bus stops. The maximum value observed was 0.3 μW/cm^2 and was dominated by GSM 900 MHz. An indoor measurement in an office revealed a value of 0.15 μW/cm^2, 96% of the power density coming from a GSM-900 MHz antenna 328 ft (100 m) away. Measurements in the vicinity of radio and TV transmitters resulted in values up to 0.23 μW/cm^2.

Frei et al. [157] used dosimeters to examine the total exposure levels of RFR in the Swiss urban population. What they found was startling — nearly a third of the test subjects' cumulative exposures were from cell tower base stations. Prior to this study, exposure from base stations was thought to be insignificant due to their low emissions and to affect only those living or working in close proximity to such infrastructure. But this study showed that the general population moves in and out of these particular fields with more regularity than previously expected. That assessment would apply to wildlife, too.

In Frei et al.'s [157] sample of 166 volunteers from Basel, Switzerland, study participants wore a dosimeter for one week and also completed an activity diary. Results found a mean weekly exposure to all RFR and/or EMF sources was 0.013 μW/cm^2. Exposure was mainly from mobile phone base stations (32.0%), mobile phone handsets (29.1%), and domestic digital enhanced cordless telecommunications (DECT) phones (22.7%). Mean values were highest in trains (0.116 μW/cm^2), airports (0.074 μW/cm^2), and tramways or buses (0.036 μW/cm^2) and were higher during the daytime (0.016 μW/cm^2) than the nighttime (0.008 μW/cm^2).

Another surprising finding of the Frei et al. (157) study implied that at the belt, backpack, or in close vicinity to the body in test subjects, the mean base station contribution corresponded to about 7 min of mobile phone use. In other words, ambient exposure from infrastructure alone was a significant contributor beyond one's personal choice to use individual devices. Frei et al. estimated that there had been a 10-fold increase in RFR outdoor radiation since mobile phone technology was introduced than when broadcast RFR had been quantified by Tell and Mantiply [151]. That trend has continued to be measured by numerous researchers today.

Joseph et al. [158] tried to make sense of the measured but differing results coming from various countries. Their objectives were to compare exposure levels and contributions from different sources in different European countries, including Belgium, Switzerland, Slovenia, Hungary, and the Netherlands, standardizing with the same personal dosimeter across countries. Results found that levels were of the same magnitude in all countries except the Netherlands, which was higher in all environments. There was no adequate explanation for these Netherland findings. Highest total exposures, like other studies, were in transport vehicles (trains, cars, buses) due to mobile phone handsets (up to 97%). Exposure in offices was higher than in urban homes. For outdoor urban environments, mobile phone base stations and handsets dominated the exposure.

Others have also looked at various ambient exposures relevant to this paper, including domestic pets and animals sheltering in indoor environments. Viel et al. [165] investigated varying exposures according to day of the week, concluding that the highest exposure to residents was on Sundays, primarily due to UMTS upload transmission and domestic DECT phone use. Markakis and Samaras [159] took indoor measurements with dosimeters in 40 different urban and suburban locations throughout Greece from 2010 to 2012 and found that RF from mobile base stations was dominant in workplaces and schools during the day, whereas in home environments dominant exposures at night were from DECT/wireless phones and computer networks. Bolte and Eikelboom [156] posited that body-worn dosimeters may both under- and -over estimate actual exposures depending on how they are worn and that a calibration determination should be made. They found in their study, using 98 subjects wearing dosimeters, that train stations had a high mean power density of 0.0304–0.0354 μW/cm^2, but that pubs or cafés where more people gathered using mobile phones and laptops in crowded quarters showed even higher exposures with mean exposures of 0.0526 μW/cm^2. That study was conducted in 2011 when GSM use was prevalent, before smart phones using UMTS proliferated. Similarly, Gryz and Karpowicz [192] measured indoor RFR in the Warsaw, Poland, metro. The major source of exposure was the 900 GSM system. Rowley and Joyner [160] found the mean exposure based on 173,323 measurements in 21 countries worldwide was 0.073 µW/cm^2 over a decade. Joyner et al. [193] did further assessments in Africa for seven years and found results consistent with the previous 2012 study. Rowley and Joyner [161] further analyzed a database of more than 50 million data points from the Italian fixed radiofrequency field monitoring network between June 2002 and November 2006 and found the mean value for mobile communications band was 0.047 µW/cm^2. They concluded that the findings of all three studies were consistent irrespective of continent, country, network operator or regulatory RFR exposure limit, leading to confidence that mean environmental levels from cellular mobile communications systems are less than 0.1 µW/cm^2. However, according to Estenberg and Augustsson [153], the methods of these last studies were not well described.

With the introduction of new communications systems and more mobile phone use, measured background levels, not surprisingly, increased. Urbinello et al. [162], who used dosimeters, found a combined 57.1% increase in total RFR levels in European outdoor areas studied within just one year from 2011 to 2012, representing a significantly altered environment over a very short period. They measured three European cities — Basel, Switzerland; Ghent, and Brussels, Belgium — in various microenvironments that included public transportation hubs (train and bus stations), indoor areas (airports, railways, shopping centers), and outdoor areas (residential, downtown and suburb). The highest RFR radiation occurred in public transportation areas which found combined measurement values from 0.32 (272 µW/m^2) to 0.59 V/m (862 µW/m^2). In all outdoor areas combined, values ranged from 0.0128 µW/cm^2 to 0.0446 µW/cm^2. The authors found that the strongest increase in outdoor areas was from communications infrastructure rather than from mobile handsets.

Ambient levels in urban areas can be quite site specific as demonstrated by Hardell et al. [154] when they investigated the Stockholm Central Railway Station, Sweden, using the dosimeter EME Spy 200, which scans 20 different radiofrequency bands from 88 to 5,850 MHz, in order to collect RF exposure data. A total of 1,669 data points were recorded with primary exposures found from downlinks. The median value for total exposure was 0.092 µW/cm^2. The mean total RF radiation level varied between 0.28 and 0.49 µW/cm^2 for each scanning survey (High mean measurements were obtained for GSM + UMTS 900 downlink varying between 0.17 and 0.21 µW/cm^2. High levels were also obtained for UMTS 2100 downlink; 0.044–0.16 µW/cm^2. Also LTE 800 downlink, GSM 1800 downlink, and LTE 2,600 downlink were in the higher range of measurements). Hot spots were also identified, such as close to a wall mounted antenna yielding over 9.55 µW/cm^2 and exceeding the dosimeter's detection limit. It should be noted that these are mostly transient exposures to humans moving through the station, although employees there are subjected to extended exposures as well as any urban wildlife in such environments. This work illustrates the high indoor levels experienced today, perhaps affecting pets, and contributing to rising background levels in general beyond a building's walls. It is also generally indicative of what wildlife would encounter moving near such installations in outdoor areas.

Hardell et al. [155] later investigated outdoor exposures in major areas of Stockholm, Sweden. RF levels were measured during five tours in Stockholm Old Town in April of 2016 using the EME Spy 200 dosimeter with the same 20 predefined frequencies noted above. The results were based on a total of 10,437 samples from which they found the mean total RFR level was 0.4293 µW/cm^2. Similar to their indoor study, the highest mean levels obtained were for GSM + UMTS 900 downlink and long-term evolution (LTE) 2,600 downlink at 0.16 and 0.13 µW/cm^2, respectively. The town squares displayed highest total mean levels, with one example at Järntorget Square measured at 2.4 µW/cm^2 (minimum 0.0257, maximum 17.33 µW/cm^2), compared with results in other areas near the Supreme Court that showed the lowest total exposure with a mean level of 0.0404 µW/cm^2 (minimum 0.002, maximum 0.4088 µW/cm^2). Street measurements surrounding the Royal Castle area were lower than the total for Old Town, with a mean of 0.0756 µW/cm^2 (min 0.00003, max 5.09 µW/cm^2).While their results were below the reference level of 1,000 µW/cm^2 established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), that high-exposure standard, Hardell et al. [155] said, is less credible since it does not take effects into consideration below thermal thresholds for tissue heating and are "…not based on sound scientific evaluation". Their highest measured mean level at Järntorget was 0.24% of the ICNIRP level. Numerous studies have found adverse health effects far below ICNIRP or other such guidelines [100].

The Hardell et al. [155] studies were not compatible with Tell and Kavet [147] that found FM bands were still a significant contributor to ambient RFR exposures. Indeed, Hardell et al. [154, 155] found FM orders of magnitude lower than the most current frequencies used for mobile telecommunications from all sources, the highest contributors were download frequencies from base stations at GSM + UMTS 900, UMTS 2, 100, LTE 800, LTE 2,600 and GSM 1,800 bands.

Similarly, in a study in Switzerland, Sagar et al. [194] reported RFR measurements in 51 different outdoor microenvironments in 20 different municipalities while walking with backpack-mounted exposimeters (ExpoM-RF) through five city centers, five central residential areas, five non-central residential areas, 15 rural residential areas, 15 rural centers, and six industrial areas. They too found infrastructure downlink exposures were most relevant in outdoor areas and that exposures increased with urbanity. They also found uplink exposures from cell handsets were only relevant within public transportation areas (trains, buses, trams), and that repeat measurements were highly reproducible within 2–4 months. Their reported mean RF-MF exposure (sum of 15 main frequency bands between 87.5 and 5875 MHz) was 0.53 V/m in industrial zones; 0.47 V/m in city centers; 0.32 V/m in central residential areas; 0.25 V/m non-central residential areas; 0.23 V/m in rural centers and rural residential areas; 0.69 V/m in trams; 0.46 V/m in trains; and 0.39 V/m in buses. The major exposure in all outdoor locations was from cell phone base stations (480% for all outdoor areas regarding power density).

In the most comprehensive review to date, Sagar et al. [148, 149] measured EMF/RFR in 94 matched microenvironments in six countries, including Switzerland, Ethiopia, Nepal, South Africa, Australia and the Los Angeles area of the U.S. They included both urban and rural areas and matched microenvironments in city centers, central residential, non-central residential, rural centers, rural residential, industrial, and tourist and university areas. This was the first study — ironically initiated by European researchers — to reassess one of the original EPA/Tell and Mantiply (1980) sites in the U.S. where they found a 70-fold (i.e., 7,000%) increase in mean ambient levels since that pioneering 1980 baseline data were recorded [152]. Cell infrastructure was the dominant contributor to the increase. Using portable RFR ExpoM-RF and EME Spy 201, walking with backpack-mounted devices at head height at a distance of 7.8–11.8 in (20–30 cm) from the body, or by driving a car with the devices roof mounted at 5.57–5.9 ft (170–180 cm) above the ground, they measured 94 outdoor microenvironments as well as within 18 public transport vehicles throughout the six countries. Measurements were taken for approximately 30 min while walking and about 15–20 min while driving in each microenvironment, with a sampling rate of once every 4 s (ExpoM-RF) and 5 s (EME Spy 201). They found great variability between countries, and regions within countries, with cell phone infrastructure being the major outdoor contributor to background levels today. Broadcast RFR was second. Total mean RFR exposure in various outdoor microenvironments varied between 0.23 V/m in Swiss non-central residential areas and 1.85 V/m in an Australian university area; and in buses in rural Switzerland between 0.32 and 0.86 V/m in an auto rickshaw in urban areas in Nepal respectively. Uplink RFR connections from mobile phone handsets was generally very small, except in Swiss trains and buses and other transport in sample countries.

Exposure in urban areas tended to be higher. Mean total RFR exposure for city centers was 0.48 V/m in Switzerland, 1.21 V/m in Ethiopia, 0.75 V/m in Nepal, 0.85 V/m in South Africa, 1.46 V/m in Australia and 1.24 V/m in the U. S. Corresponding downlink exposure was 0.47 V/m (Switzerland), 0.94 V/m (Ethiopia) 0.70 V/m (Nepal), 0.81 V/m (South Africa), 0.81 V/m (Australia) and 1.22 V/m (U.S.).

Compared to other countries, the U.S. had high exposure levels, ranging from 1.4 mW/m^2 in a non-central residential area of Los Angeles to 6.8 mW/m^2 in a less populated area within the center of the city near a freeway. The median total exposure to RFR across all eight outdoor microenvironments in Los Angeles was 3.4 mW/m^2. Switzerland, which has stricter exposure standards based on precautionary limits, had the lowest measured levels among all countries in the study.

What the above studies show are steady increasing environmental levels of RFR, primarily due to the introduction of mobile telecommunications. All of the above studies were conducted prior to the introduction of 5G which will greatly increase RFR background levels. The above RFR levels now ubiquitous in the environment are capable of affecting wildlife, as we report in Part 2.

Wilderness areas: cell towers in national parks; military training over the Olympic Peninsula

The studies cited in Part 1, Supplement 1 were conducted primarily in urban and suburban areas with limited attention paid to rural environments. No one has yet measured environmental RFR in heavily forested areas, likely because it is assumed exposures are negligible to nonexistant. Investigators are traditionally more curious about effects in human populations. However, cell towers now transmit into our deepest vast wilderness areas. In addition, sources of environmental RFR include space-based transmissions aimed back toward Earth for military and commercial use, universal satellite transmissions for GPS, airborne transient infrastructure exposures such as Google blimps [195] intended for rural areas, new satellite platforms for 5G Internet connectivity, drone technology, and military blimps used in both war zones and/or for security and surveillance in remote areas [196]. Such blimp "airships" create their own infrastructure by circling large areas or being positioned over a single point on the Earth's surface for both civil and defense applications. They are intended to provide mobile communications specifically in remote areas lacking land-based infrastructure, as well as during disasters when land-based infrastructure becomes dysfunctional. There may actually be more ambient RFR exposure in our remote regions than we have assumed.

In the U.S., the National Aeronautics and Space Administration [197] houses the Socioeconomic Data and Applications Center (SEDAC) and along with the Wildlife Conservation Society, and Center for International Earth Science Information Network (CIESIN 2018, [198]) at Columbia University, published "The Last of the Wild Project, Version 2, 2005 (LWP-2): Global Human Footprint Dataset (Geographic), v2 (1995–2004)." Under this program, which accumulated information between 1995 and 2004, NASA facilitated large global data sets to map the Human Influence Index (HII) regarding impacts on the environment intended for use in wildlife conservation planning, natural resource management, and research on human-environment interactions. In 1 km (0.6 mi) grid cells created from nine global data layers, the HII assessed human population pressure (population density), human land use/infrastructure (built-up areas, nighttime lights, land use/land cover), and human access (coastlines, roads, railroads, navigable rivers). CIESIN 2018 had not considered cell technology or transmission infrastructure as factors in wildlife conservation but it is an important new yardstick for future consideration.

A group of researchers [199] used cell phone coverage as a surrogate measurement for human influence on wildlife. In a case study of the vast Brazilian Atlantic forest, the researchers first demonstrated the correlation between cell phone coverage and the global human wireless footprint, using a database of over 23 million antennas. They then correlated the presence of 45 species of medium to large-size mammals and cell phone coverage for the forest. Researchers recorded 18,211 points of mammalian presence from in-person sightings, animal tracks, and remote camera images. They found wildlife probability of being present under cell phone coverage conditions was on average only 18%, with threatened species correlated far lower at 4%. In other words, species appeared to be avoiding such radiated areas. They further noted: "Most of the species showed a clear negative relationship with cell phone coverage, and threatened species presented an even lower probability, of at least 4% when compared with non-threatened ones. The strong positive relationship between cell phone coverage and the Human Footprint gradient at a global scale corroborated our *a priori* hypothesis that cell phone coverage can act as a surrogate for human presence, even in forested areas were no other footprint evidence is easily detectable." Large cat species, like the Jaguar (*Panthera onca*), and other threatened mammals appeared most affected due to their absence in areas studied. The authors did not take RFR into consideration or individual cell phones in use, only the ability to make a cell phone call.

There are many reasons for wildlife abandonment of such areas, including human presence itself as well as the increased cell infrastructure with accompanying lighting, noise, access roads, and powerline connections creating disturbed/broken habitat since the 2005 Human Footprint Index work noted above. Mining, logging, road building, dams, and other human perturbations can also result in wildlife abandonment. The Macedo et al. study [199] may be a useful new metric for detecting human interference along with what is currently being used in conservation planning and decision making. Factoring the introduction of increased EMF from transmissions, electrical conduit, and new ground currents in pristine areas may create important new exposures that wildlife may sense (see Part 2 for information on magnetoreception), also leading to wildlife abandonment. Areas without cell phone coverage may provide an important new indicator for areas needing enhanced protection before wildlife damage is done [200].

In 2016, Yellowstone National Park, Wyoming, had five towers that provided coverage into some of the remotest regions with additional coverage coming into the Park from towers on all of its vast perimeters [201]. There were proposals for Theodore Roosevelt National Monument, North Dakota, to put a 4G cell tower on the edge of one of the largest stretches of designated wilderness there. Mount Rainier National Park, Washington State, despite opposition, planned to install a 4G cell system at a visitor center that would send RFR deep into the surrounding wilderness [202]. Mount Rainier National Park also reviewed right-of-way permit applications from Verizon Wireless and T-Mobile to install wireless communications facilities within the Jackson Visitor Center in Paradise, an area completely surrounded by wilderness. There was already significant coverage to that federally designated wilderness from surrounding towers on its periphery.

Within a few short years, tower proposals increased exponentially as the U.S government, spurred by industry, made coverage into our remotest regions on federally owned public lands a priority. While many see this as necessary for public safety, others see it as an incursion into our last iconic wild sacred refuges. Grand Teton

National Park, Wyoming, is planning a sprawling network of cell towers within its boundaries to run along its 45 mi (72 km) length from which there may be significant signal penetration [203]. Yosemite National Park has seen six new towers permitted in recent years; Sequoia National Park has a new 138' (42 m) tower; Mt. Rainier has new antennas on a visitor center; Grand Canyon has five new towers proposed along the canyon's rim and Yellowstone is improving infrastructure that would increase capacity by 38 times [203]. The fact that the National Park Service is promoting a sweeping tech build-out of wireless sites — including small cells attached to existing buildings, towers, and enhanced WiFi hubs across many of the 62 national parks — is troubling. Grand Teton alone is slated for nine new tower sites in addition to two existing ones, as well as 60 mi (100 km) of new fiberoptic cable as backhaul. Glacier National Park, Montana, is planning at least four new towers; new towers are also planned at Olympic and Bryce Canyon, and Glen Canyon National Recreation Area. At Yellowstone, cell phone users can reportedly already get weak signals across significant portions of the 3,500-square-mile (9,065 km^2) Park's backcountry [204].

While some of the early tower applications got minimal environmental review, the most recent build-outs have evaded regulatory oversight due to the National Park Service declaring specific proposals as categorically excluded, thus negating full National Environmental Policy Act (NEPA) review and implementation of an Environmental Impact Statement/EIS [204]. All of this was made easier by new FCC rules that limited local control, environmental review, and compliance with the National Historic Preservation Act. That FCC ruling has since been successfully challenged in Federal court by the Natural Resources Defense Council [205]. Potential effects to forest wildlife from RFR have not been included but should be part of all applications under NEPA review (see Part 3).

It is well known that signal propagation loss can be due to several factors, including antenna height, depolarization, humidity/rain, tree species, and other variables [206]. Any attempt to intentionally direct strong RFR signals into remote forested areas from ground-based transmitters is confounded by tree leaves that absorb, defract, and scatter signals in myriad directions due primarily to moisture content. Live trees with wet leaves absorb RFR most efficiently while dead trees without leaves absorb the least [207]. Some evergreen tree species also have resonant properties due to needle configurations.

5G is of particular concern regarding vegetation, especially if satellite-based. The technicalities of propagation loss in forest environments are therefore getting renewed attention since rural areas are targeted 5G-service regions for satellite use. The subject is also of interest in the development of wireless sensor networks using low-power transceivers in remote regions for scientific and surveillance purposes [206]. As far back as 1997, the U.S. Federal Communications Commission issued a report [208] on millimeter wave (MMW) propagation characteristics that included information on signal loss due to foliage. In the frequency range between 200 MHz–95 GHz, the foliage signal loss at 40 GHz at a penetration of 32.9 ft (10 m) — equivalent to one large tree or two in tandem — was determined to be about 19 dBm (a unit of measurement of EMF-RFR power levels expressed in decibels referenced to 1 mW). The report noted this is not a negligible signal loss value. The report also discussed signal attenuation effects due to rain, as well as water vapor absorption and oxygen, noting resonant frequencies below 100 GHz occur at 24 GHz for water vapor and at 60 GHz for oxygen. Hakusui [209] also investigated 60 GHz and O_2 absorption properties, as have others. There may be implications for climate change (see Part 3).

Clearer dosemitry standardization is being called for regarding 5G buildout in general, including in urban areas as trees can also affect 5G network designs there too. Government entities are now issuing reports on performance impacts to 5G networks from physical features not previously considered in network planning, including vegetation. The accumulation of new propagation data is now considered an essential prerequisite to 5G's use of higher frequencies [210].

Unfortunately, such reviews are conducted as a component of cost-effective 5G buildout which will use the broadband spectrum spanning low-MHz-through-MMW, not as a tool to mitigate damage to flora which can be considerable. Ultimately the 'greening' of cities to offset impacts of climate change may prove incompatible with 5G. And there is no way to know at this point what 5G exposures from satellites may do to deep forested areas or to climate conditions given resonant factors involving water and oxygen molecules.

Military training over the Olympic National Forest and Olympic National Marine Sanctuary: a case study

One of the more dramatic intentional RFR incursions into pristine government protected forest lands was proposed in 2012 by the U.S. Department of the Navy's Northwest Training & Testing program [211–213] to practice electronic war-gaming exercises in airspace over the Olympic National Park (a UNESCO World Heritage Site), Olympic

National Forest, and Olympic National Marine Sanctuary — all in or off Washington State. The Marine Sanctuary is the preferred key habitat for 29 species of marine mammals, including migrating gray whales. The National Park and National Forest are key habitats for two migratory bird species listed on the Endangered Species List — the Marbled Murrelet (*Brachyramphus marmoratus*), a diving seabird that nests in old growth forests, and the Northern Spotted Owl (*Strix occidentalis caurina*), which thrives only in quiet intact old-growth forest habitats. In fact, the entire Pacific Coast is on the critical Pacific flyway for migratory birds with an estimated one billion birds migrating along the pathway annually [214]. The Olympic National Park is widely seen as among the most beautiful wilderness areas on Earth where temperate rainforest lowlands are topped by majestic glacier peaks. Once designated the "quietest place" in America by the acoustic ecologist Gordon Hempton from the One Square Inch project [215–217], it is home to several plant and animal species that exist nowhere else on Earth.

The massive Navy project includes training over land, air, and sea as well as underwater, including offshore areas of northern California, Oregon, and Washington, the inland waters of Puget Sound, the San Juan Islands, many portions of the Olympic Peninsula, parts of Canada, and Western Behm Canal in southeast Alaska [218, 219]. The Navy has been conducting similar exercises — though nothing like the magnitude of the current upgrade — in this area for decades because it includes the complex environments that service personnel may encounter [220].

After significant community comment and a lengthy environmental review by experts opposing the proposal, the Navy released its Draft Supplemental Environmental Impact Statement (DEIS) calling for increased training and flights over Olympic National Park [221]. Potential adverse EMF effects from the upgraded exercises should not be underestimated. Manipulation of the electromagnetic spectrum has become a pre-eminent offensive and defensive war feature waged on land, in the air, and on/under the world's oceans. The Navy's exercises, conducted under the Northwest Training and Testing [222] program, has not given information (for stated security reasons) on all signaling characteristics, but for the overland activity they will be using frequencies between 4 and 8 GHz at a power output of 90–300 W, 45 min per hour, at thermal and nonthermal intensities, according to personal communications between the Navy and the U.S. Fish and Wildlife Service [223, 224].

While the Navy has operated the Naval Air Station on nearby Whidbey Island since World War II, the proposed upgrades could in time add up to 160 new "Growler" EA-18G supersonic jet warplanes — the loudest aircraft in the sky — to the Northwest Electromagnetic Radiation Warfare program [221, 222, 225]. Training exercises can fly as low as 1,200 feet (366 m) above sea/ground level (AGL) — well within the height of migratory and daily bird-flight movements of numerous avian species ranging from waterfowl, shorebirds, raptors, songbirds and more [226]. In studies conducted by USDA/APHIS Wildlife Services on movements of Osprey (*Pandion haldiaetus*) around Langley Air Force Base, Hampton, VA, Osprey frequently reached these altitudes on feeding and territorial forays and migrated at flight heights averaging 1,300 ft (396 m) AGL at speeds of around 35 mph (56 kph) [227].

On land, the exercises include mobile trucks carrying RFR emitters mounted 14 feet high along remote dirt roads that can reach elevated peaks/ridgelines deep within the forest to communicate with warplanes. There are also new fixed cell towers. There are 2,900 allowed exercises over wilderness and some communities, 260 days a year, lasting 8–16 h per day. There are additional training exercises over/under the water using sonar and lasers capable of causing adverse effects to fish and marine animals [228]; also see Part 2 for potential effects to aquatic mammals, fish, and turtles).

Growlers are equipped with extreme high intensity, multi-frequency detectors and radar jamming technology capable of thermal and non-thermal effects to humans and wildlife alike. One exposure estimate during exercises noted that spending more than 15 min in designated areas could result in thermal damage [213]. Mid-air two-way training involves RFR directionally aimed from plane-to-plane, ground-to-air, and air-to-ground. Despite environmental reviews which were limited in scope there is no clear understanding of what this may do to the environment [228].

After a long review process required by the National Environmental Policy Act [229], the Navy released a final Environmental Impact Statement (EIS) and an Overseas Environmental Impact Statement (OEIS) [230] but the final findings, which remained the same as in earlier drafts, had been widely criticized as inadequate for its broad findings of "no harm," grossly under-estimating present and proposed activities, improperly segmenting activities to minimize scrutiny of collective substantial impacts in violation of NEPA which does not allow such segmentation, and ignoring potential noise effects [225, 231–233]. In March 2017, the U.S. EPA requested more information on potential noise effects but mentioned nothing about EMF effects to wildlife or humans. The Navy's DEIS minimally addressed EMF but repeatedly adhered to parsed language from the Endangered Species Act, noting that electromagnetic devices used during training may affect — but are *not likely to adversely affect* — the various species reviewed, primarily marine animals and some birds. Their conclusions remained the same in 2020 [234].

The U.S. Fish and Wildlife Service (FWS) concurrence [235, 236] was despite former agency career scientists requesting more caution [212]. Extensive attention was paid to the endangered Marbled Murrelet known to nest there, and the Northern Spotted Owl which was said to be shielded from EMF exposures under the forest canopy. Forest canopies, however, are easily penetrated by RFR even though trees are efficient attenuators [237, 238]. U.S. FWS noted that clear line-of sight transmission would limit wildlife exposures; that only birds in flight over the tree canopy could be affected. They found Marbled Murrelets could be intermittently exposed to RFR during flight but that Spotted Owls under forest canopies are not. They then concluded that the effects of brief, intermittent exposures to 4–8 GHz would likely be insignificant to in-flight birds. They discounted physical effects from tissue heating and/or burns [235].

By most measures, the Navy and U.S. FWS conducted poor reviews [233]. Although they did include several bird/wildlife studies [9, 15, 20, 22, 95, 239, 240], they dismissed them for various reasons. Only Bruderer et al. [241], at approximately 9 GHz exposure, was deemed applicable but it found no effects to birds' flight patterns in the presence of radar. Other uninvestigated research that could have applied included in-field RFR behavioral studies [17, 242]; mortality [134, 243, 244]; reproductive outcomes [16, 18]; and bat insect foraging [36] in the presence of radar. Presence of exogenous RFR could also disturb the sensitive magnetoreception of many species, affecting bird and insect migration patterns.

There continues to be no monitoring for EMF/wildlife effects over the wide on-land/over-sea training areas, despite the fact that the final Navy EIS/OEIS noted sources of in-air electromagnetic exposures from a single ship would operate continuously across a wide range of frequencies from 2 MHz to 14,500 MHz, with maximum average power between 0.25 and 1,280,00 W [234]. A publication from one of the authors of this paper [96] was used to justify program approval based on birds‘ natural avoidance behaviors when physical discomfort is caused, such as thermal heating. The Navy and U.S. FWS conclusions that no long-term or population-level impacts to birds will occur may not be supportable.

Although the military is by law allowed use of public lands for training, this deep incursion into pristine protected public lands in Washington State sets a bad precedent. The Navy's project is possibly in violation of federal statutes including U.S. Code 475 (LII, 2018), which outlines the purposes for which national forests were established and how they are to be administered. The U.S. Forest Service, nevertheless, granted the Navy a preliminary Special Use Permit. The National Parks Conservation Association (NPCA) had submitted a Freedom of Information Act (FOIA) request in 2016 to the Navy regarding Growler noise and environmental disruption. After the Navy repeatedly withheld critical FOIA information on the aircraft overflight training, NPCA sued the Navy in mid-2019 for that information's release. As of this writing, no federal court decision has been reached on the FOIA lawsuit.

In 2020, after the upgraded training exercises commenced, noise levels from the flyovers were found by Kuehne et al. [245] at 110 ± 4 dB re 20 μ Pa rms and 107 ± 5 dB A, to exceed known thresholds of behavioral and physiological impacts for humans, as well as terrestrial birds and mammals. Even underwater sound levels from the aircraft, at 134 ± 3 dB re 1 μ Pa rms, exceeded thresholds known to trigger behavioral changes in fish, seabirds, and marine mammals, including endangered southern resident killer whales (*Orcinus orca*). Although soundwaves are not strictly considered EMF, their inclusion here illustrates adverse anthropogenic effects due to inadequate regulatory oversight.

The Navy has been allowed to introduce the loudest aircraft in the sky into one of the quietest places in the U.S. with accompanying complex close-range EMF. With the exception of this high-intensity RFR training program in Washington State, most of the studies cited throughout these consecutive papers found ambient exposures were below any international guidelines for humans but well within the range seen to affect flora and fauna.

New technologies: 5G and the internet of things (IoT)

We are on the cusp of introducing a dense and expansive new layer of RFR into the global built-environment and throughout rural regions using Extremely High Frequency (EHF) millimeter waves (MMWs) between 30–300 GHz for Fifth Generation (5G) telecommunications. On the electromagnetic spectrum, this band lies between the super-high-frequency (microwave) bands and optical (infrared) bands.

5G is a wireless network of machine-to-machine communications called the Internet of Things (IoT) that will allow remote communications between a host of devices and appliances, such as between cell phones and refrigerators, lights, furnaces, entertainment units, security systems for homes and businesses, medical appliances, driverless cars, and every imaginable and "… yet-to-be imagined …" thing [89]. Some of these applications are already available over 4G LTE for 'smart' home environments that consumers can remotely control via their own WiFi systems. Others are programmable, like thermostats, and require no real-time human interaction beyond setup. Since any one of these wireless portals opens access to all others, including computer systems as well as wireless phones, security is a serious concern. Numerous incidences of hacking through smart domestic appliances like refrigerators and baby monitors have already been reported [246]. While the above description is for 5G consumer applications, 5G is primarily for business data accumulation and uses like Internet/consumer tracking.

Because 5G functions in much higher frequencies with shorter wavelengths than previous iterations of wireless communications, a vast new layer of infrastructure requiring millions of new antennas placed very close together — by some estimates every 2–5 houses apart — will be needed to provide ubiquitous coverage. The reason for this densification is because MMWs are easily attenuated and diffracted by buildings, trees, other vegetation, topography and weather conditions (including rain), as well as the shift to higher frequencies because there is little room left in the ultra high frequency (UHF) microwave bands currently used for telecommunications between 800 MHz and 2,250 GHz. 5G networks work mostly off taller cell towers (macro cells) via Distributed Antenna Systems (DAS) and/or small cell antennas (micro cells) attached to buildings, powerline utility poles and municipal lampposts in very close proximity to the human population. Fiberoptic cable provides the backhaul between antennas. Environmentally safer 100% wired fiber-to-the premises networks and 5G wireless applications can no longer be kept separate. Where fiber networks exist, wireless small cells will piggyback onto them [247, 248]. At 28–95+ GHz, that frequency range is significantly higher than the 2.45 GHz used in today's telecom or in products like microwave ovens. In fact true 5G is designed to be an ultrawide-broadband network that can encompass a wide swath of frequencies between the low MHz range and eventually 95+ GHz. In addition, there are general categorizations for low (<1 GHz), mid (between 1 and 6 GHz), and high (>24 GHz) bands that may be used in various iterations of 4G LTE and eventually 5G [247].

The U.S. was among the first countries to approve the buildout of 5G with licensing auctions in the 24, 28, 37, 39, and 47 GHz ranges thus far with higher bands extending above 95 GHz allocated for future use [89, 249, 250]. As of this writing, there has been limited buildout of true 5G networks — some systems advertised as 5G are really enhanced 4G LTE — in select U.S. cities and on military reservations [251]. Other countries have leapt ahead with 5G, including China, South Korea, the United Kingdom, Italy, Spain, Germany, Ireland, Australia, and The United Arab Emirates [252]. But overall, broad 5G buildout has been somewhat slow in coming for technical, financial, human health, and societal reasons. Some countries in Europe, as well as Canada and Russia, are being cautious [92, 93, 253]. There has also been large-scale consumer resistance in many countries and numerous petitions by professionals calling for a slowdown until more is known about the impacts of 5G [254]. Space-based 5G networks are also being built, beaming MMWs back toward Earth from thousands of new mid-and-low Earth orbiting satellites.

All of this development has been done with virtually no environmental consideration or review [89, 249]. Beginning in 2017, the U.S. Congress passed several 5G-enabling bills but significant local and state resistance arose to what is widely seen as a giveaway of public utility corridors (where most ground-based 5G antennas will be mounted) to private enterprise without adequate compensation or local zoning review [255]. Nevertheless, industry pressure has successfully influenced U.S. legislators and the FCC to bypass local review for environmental and historical significance regarding infrastructure siting. No environmental review in the U.S. was recommended before buildout [89]. Indeed, the FCC streamlined local and state review for environmental effects and historic significance against overriding federal legislation requiring such reviews under the National Environmental Protection Act (NEPA) and the National Historic Preservation Act (NHPA). But the Natural Resources Defense Council challenged that ruling in court and won [205], thus preserving NEPA for now (for more, see Part 3).

Military use of millimeter waves

Millimeter waves have been used by the U.S. military since the early 1980s [256, 257]. Millimeter waves are so-called because the wavelengths are smaller (about 1/8th inch or 3.2–5 mm long) than microwaves used in cell phone/WiFi technology at 2.4 GHz (6.3 inch or 12.5 cm). The smaller the wavelength, the higher the energy density per wavelength unit. In this case, with MMW it is about 25 times higher than with cell technology microwaves [258]. This means MMW are capable of resulting in significant damage throughout the biome, including possibly to all flora and fauna present, but not due to wavelength alone. The multiple biological effects from intense energy absorption at very small wavelengths, e.g., in human skin cells or any thin-skinned species, and especially in insects which lack efficient heat dissipation, may cause intense heating with concomitant cellular destruction and organism death. Many of these effects are independent of power density, and therefore not covered by current regulations which are power-density and/or SAR-based. There is, however, a provision in the new ICNIRP standards that makes MMW and 5G subject to dosimetry measurements in power density in the higher frequencies, not SAR (see Part 3).

Millimeter waves have never been used before for civilian telecommunications although the U.S. military has used MMWs at 95 GHz for crowd control and perimeter defense in a skin-heating directed-energy technology called "Active Denial" as part of the U.S. Non-Lethal Weapons Program [259]. The military deployed MMW technology in 2006 in Afghanistan and in the second Iraq war with an Active Denial weapon mounted on Humvees. Named Project Sheriff, it is a Raytheon-designed device in their Silent Guardian Protection System. Biological effects have been researched for decades at the Directed Energy Bioeffects Division, Human Effectiveness Directorate, Air Force Research Laboratory at Brooks Air Force Base in San Antonio, TX [260], as well as other military laboratories and programs like the Defense Advanced Research Projects Agency [261]. Unfortunately, most of this tax-payer-funded research is classified even as there is a critical public need-to-know with the 5G buildout, the proliferation of media misinformation, and burgeoning conspiracy theories. Other countries, like Russia and China, have adopted directed energy technologies too.

Active Denial weaponry was originally developed by the military for large roof-mounts on military vehicles but much smaller mobile units have now been deployed in moving aircraft and ground vehicles. Raytheon has developed a smaller version of Silent Guardian for use by non-military law enforcement agencies and other security providers. That system is operated with a joystick plus an aiming screen that can target people over 820 ft (250 m) away. One Los Angeles county jail has installed a unit on their ceiling. Such systems base their response on an intolerable heating sensation in the skin with the accompanying instinctive avoidance behavior. The sensation supposedly stops quickly when the beam is turned off or a person moves out of range. However, several reports note that numbing sensations can last for hours and blistering has occurred [262].

The U.S. military continues to develop its non-lethal weapons program, announcing in 2019 a $30.8 million (U.S. dollars) contract to General Dynamics for research on directed energy systems, bio-mechanisms, human effectiveness analysis, and integration under the U.S. Air Force's Directed Energy Bio-effects Research (DEBR) program. The aim is to quantify the effects of directed energy weapons using optical, RFR, and MMW radiation, as well as electromagnetic propagation characteristics [263]. It remains to be seen if this information will be declassified or if any will be applied to impacts on wildlife.

Russia has taken a different approach using lower frequencies for 5G, and set up monitors in Moscow to measure/study 2G through 5G effects on citizens under The Izmerov Research Institute of Occupational Health. The Institute will send results to the Ministry of Health and the Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing for the final determination regarding human safety standards [264]. There are no similar epidemiology studies being conducted in the U.S. and it remains to be seen if Russia will release their findings or even the parameters of their research.

Adaptations for civilian telecommunications for 5G in frequencies lower than 95 GHz are theoretically below thermal power intensities [111, 265]. However that does not mean serious concerns are unfounded. Recent updates to the ICNIRP standards propose allowances that will permit exposures to exceed thermal thresholds under certain circumstances (see Part 3). This is a region of the electromagnetic spectrum that has had little attention from the civilian professional groups that set exposure standards, partly because few consumer devices have operated in this frequency range before and devices already using MMW have traditionally had little applicability to high levels of human exposure [111, 265]. All of this is about to change. The new 5G networks also use extremely complex signaling characteristics that are not well studied or understood, including beam steering, massive MIMO (multiple-input, multiple-output) and phased array that have unique biologically active properties.

Some assume minimal and/or reversible risk in humans due to MMW shallow energy penetration, short wavelength, and induced quick fleeing behavior. Damage to wildlife is considered collateral, if considered at all.

Millimeter waves and biological effects

It has been known for over 100 years that MMW are highly biologically active [266–268]. As noted in Pakhomov et al. [269], coherent oscillations in this frequency range are virtually absent in the natural electromagnetic environment, indicating important potential consequences since living organisms could not have developed adaptive mechanisms to MMW during evolution and development, unlike in other areas of the electromagnetic spectrum. In addition, Golant [270, 271] and Betzkii [272] noted that some specific features of MMW radiation, plus the absence of background MMW external "noise," may indicate this band is important for communication within and between living cells. In other words, there may be a reason for the absence of MMWs in the background environment, and more importantly, because of that absence, living cells may have developed their own dedicated uses in that area of electromagnetic spectrum.

Betskii et al. [273] also pointed out that MMW radiation is virtually absent from the natural environment due to strong absorption by the atmosphere and the fact that MMW waves are readily absorbed by water vapor. The authors elaborated on the hypothesis that low-intensity MMW may have broad nonspecific effects on biological structures/organisms and that vital cell functions may be governed by coherent electromagnetic EHF waves. Their results included alternating EHF/MMWs used for interaction between adjacent cells, thereby interrelating/controlling intercellular processes in the entire organism. The above authors [269–273] noted that while these ideas are theoretical, they may plausibly explain the high MMW sensitivity observed in biological subjects.

Chronic long-term, low-level ambient exposures to MMWs are yet to be studied but some extrapolations can be made based on the extensive database that does exist. These higher frequencies may also have unique biological effects to nonhuman species due to size differences, distinctive physiological characteristics, and diverse habitats. Both aqueous environments and the high water content in living organisms may make MMW exposures particularly unique due to the way MMWs propagate though water with virtually no impedance [274–279]. Also, unlike RFR at lower frequencies, in the EHF/MMW range a small power density can lead to a very high local SAR due to the concentration of energy in a small volume in an exposed organism. Heating may be inevitable [280].

Millimeter wave energy, with the very small wavelengths associated with such high-frequency radiation, couples maximally with human skin tissue. Because of this efficient skin coupling, beneficial/therapeutic effects have been known for decades, especially in former Soviet Union countries, from short-term MMW exposures, while longer exposures have produced potentially adverse effects [258, 269, 281, 282].

In humans, Gandhi and Riazi [257] estimated that 90–95% of incident energy of MMWs can be absorbed in human skin with dry clothing, with or without an air gap. Because of sub-millimeter depths of penetration in skin tissue, superficial SARs as high as 65–357 W/kg are possible. Eyes are of particular concern. MMW frequencies penetrate less than 1/64 of an inch (0.4 mm) — about the thickness of three sheets of paper. Except for adult human eyelids and exposure to infants, MMWs supposedly avoid the skin's second dermal layer [265].

However, skin tissue contains critical structures like blood and lymphatic vessels, nerve endings, collagen, elastin fibers, and hair follicles, as well as sweat, sebaceous and apocrine glands. MMW effects to skin have been found to be considerable in glandular tissue with multiple cascading effects throughout the human body even without deep penetration [283]. Effects to lipid cells decreased cell membrane water permeability, with partial dehydration of the cell membrane, and cell membrane thickening/rigidity was seen at 52–72 GHz at incident power densities of 0.0035–0.010 mW/cm^2 [284]. Human sweat ducts in particular may act as coiled helical antennas and propagate MMW energy as a waveguide at these higher frequency exposures causing uniquely higher specific absorption rates [285] not reflected in today's standards. A significant new look at the 5G standards is clearly called for.

Betskii et al. [273] noted that with MMW exposure, skin presented five mechanistic entry points capable of affecting an entire organism. For example, they noted that because MMWs penetrate human skin to a depth of 300–500 μm and are almost completely absorbed in the epidermis and the top dermis, MMWs are therefore capable of directly influencing central nervous system receptors. These include mechanoreceptors, nociceptors, and free nerve endings; APUD cells such as diffuse neuroendocrine cells, mastocytes, and Merkel cells; and immune cells such as T-lymphocytes. In addition, they noted that MMWs produce direct effects on the microcapillaries and other biologically active cells. These five "entry gates" can determine both therapeutic and/or adverse effects as a novel trigger to basic regulatory systems, involving the complete organism. Depending on the parameters of the MMW stimulus and the functional state of the subject exposed, effects produced can be both nonspecific and specific.

In their review, Betskii and Lebedeva [286] also discussed MMW effects on human and non-human models as dependent on exposure sites and noted such effects were highly frequency sensitive. They also described the complex hypothetical mechanism that stochastic resonance (see Part 2) may play in very sensitive water-containing biological species to very-low intensity EMF (in μm ranges) based on the generation of intrinsic resonance frequencies by water clusters that fall between about 50 and 70 GHz. When biological species are exposed to extremely weak EMF at these frequencies, their water-molecule oscillators lock on to the external signal frequency and amplify the signal by means of synchronized oscillation or regenerative amplification. Since MMWs pass through aqueous media almost without loss but also with high absorption, in the process they are capable of deep penetration involving internal tissue and organ structures. The researchers summarized what is known about effects of MMWs. These included a long list of findings in human and non-human models, e.g., EHF's strong absorption by water and aqueous solutions of organic and inorganic substances; affects to the immune system; changes in microbial metabolism; stimulation of ATP (adenosine 5′-triphosphate) synthesis in green-leaf cells; increases in crop capacity (e.g., pre-sowing-seed treatment); changes in certain properties of blood capillaries; stimulation of central nervous system receptors; and the induction of bioelectric responses in the cerebral cortex. Biological effects depend on exposure site, power flux density and wavelength in very specific ways. In addition, low-intensity MMWs were detected by 80% of healthy people, but perception was asymmetrical. Peripheral applications were found to affect the spatiotemporal organization of brain biopotentials, resulting in cerebral cortex nonspecific activation reactions. MMW-induced effects are perceived primarily by the somatosensory system with links to almost all regions of the brain. The authors also discussed water and aqueous environments' unique role on MMW effects, which induce convective motion in the bulk and thin fluid layers and may create compound convective motion in intra- and intercellular fluid. This can result in transmembrane mass transfer and charge transport can become more active. EHF can also increase protein molecule hydration.

In wildlife, especially small thin-membrane amphibians like frogs and salamanders, even at penetration less than 1/64 of an inch (0.4 mm), deep body penetration would result. Effects to wildlife could be significant. In some insect species that would equal deadly whole body resonance exposure [90]. In a recent study, Thielens et al. [287], modeled three insect populations and found that a shift of just 10% of the incident power density to frequencies above 6 GHz would lead to an increase in absorbed power between 3 and 370% in some bee species, possibly leading to behavior, physiology, and morphology changes over time, ultimately affecting their survival. Insects smaller than 1 cm showed peak absorption at frequencies above 6 GHz. In a follow-up study of RFR, Thielens et al. [288] used *in-situ* exposure measurements near 10 bee hives in Belgium and numerical simulations in honey bee (*Apis mellifera*) models exposed to plane waves at frequencies from 0.6–120 GHz – frequencies carved out for 5G. They concluded that with an assumed 10% incident power density shift to frequencies higher than 3 GHz, this would lead to an RFR absorption increase in honey bees between 390 and 570% — resulting in possible catastrophic consequences for bee survival.

In birds, hollow feathers have piezoelectric properties that would allow MMWs to penetrate deep within the avian body cavity [26, 27]. 5G's complex phased MMWs may also be capable of disrupting crucial biological function in other species. In theory this one technology has the ability to disrupt critical ecosystems and the living organisms within them with broad effects throughout their entire food webs. In addition, the top end of these ranges reach infrared (IR) frequencies, some of which are actually visible to other species, especially birds, and could impede their ability to sense natural magnetic fields necessary for migration [91] as well as other crucial aspects of avian life.

There were several early reviews of MMW studies beginning in the 1980s that examined subjects like theoretical modeling and possible interaction mechanisms [289–293]. Pakhomov et al. [269] also published an extensive review of MMW research, examining over 300 former Soviet Union Block studies, which had focused primarily on therapeutic/clinical applications of MMWs, as well as about 50 studies from other countries that had focused on public health effects. They were looking to close the gap between those very different orientations between countries. Much of the Soviet Block research had never previously been seen by Western scientists and because of the language barrier, as well as differences in test protocols, measurements, and reportage styles, Western scientists often dismissed Russian research as incomplete. The large review included effects from low-intensity exposures (MMWs 10 mW/cm^2 and less) in everything from molecules, microbes, and cells, to the unique qualities of water, resonance, and MMW therapy. Studies covered dosimetry/spectroscopy issues, as well as cell-free systems, cultured cells, and isolated organs in animals and humans. Pakhomov et al. [269] found effects to cell growth/proliferation, enzyme activity, genetic structures, excitable membrane function, peripheral receptors, and other biological systems. In human and animal models, local MMW therapeutic applications stimulated tissue repair and regeneration, alleviated stress reactions, and facilitated recovery from a wide range of diseases. Former Soviet Block countries claim to treat approximately 50 diseases with MMW. The reviewers reported that many effects could not be readily explained by temperature changes alone.

Some of the animal models with potential significance to wildlife cited in Pakhomov et al. [269] included: yeast: *Saccharomyces cerevisiae*, [294–298]; *Candida albicans* [299]; *barley seeds* [300]; protozoans *Spirostum* spp. [301]*;* blue-green algae *Spirulina platensisby* [302]; midge *Acricotopus lucidus* [303]; *Escherichia coli* [304]; rats [305]; frog/nerve cells [306–310]; antibiotic resistance to *Staphylococcus aureus* [311] and others.

Of particular challenge to the popular wisdom that MMWs are "safe" due to superficial skin penetration, is the research on peripheral nerve receptors cited in Pakhomov et al. [269]. Akoev et al. [312] studied MMW effects to the specialized electroreceptor cells called Ampullae of Lorinzini in anesthetized rays and found that the spontaneous firing in the afferent nerve fiber from the cells could be enhanced or inhibited by MMWs at 33–55 GHz continuous wave (CW). The most sensitive receptors increased firing rates at intensities of 1–4 mW/cm^2, which produced less than a 0.1 °C temperature increase. Higher intensities (10 mW/cm^2 and up) evoked delayed inhibition of firing, indicating that the response became biphasic. The authors emphasized they were not observing just a MMW bioeffect but rather a specific response to that frequency range by an electro-receptor cell.

Work also cited in Pakhomov et al. [269] regarding similar nerve cells/pathways and MMW-induced arrhythmia included a paper by Chernyakov et al. [307] where they observed induced heart rate changes in anesthetized frogs from MMW irradiation to remote skin areas. This suggested a reflex mechanism possibly involving specific peripheral receptors. Later, Potekhina et al. [313] similarly found that certain frequencies from 53–78 GHz band (CW) effectively changed the natural heart rate variability in anesthetized rats when applied to the upper thoracic vertebrae for 20 min at 10 mW/cm^2 or less. MMWs at 55 and 73 GHz caused pronounced arrhythmia: the variation coefficient of the regular rhythm (R-R) interval increased 4–5 times while exposure at 61 or 75 GHz had no effect, and other frequencies caused intermediate changes. Skin and whole-body temperatures remained unchanged. Similar frequency dependence was observed in additional experiments with 3 h exposures. However, approximately 25% of experiments were interrupted because of sudden animal death that occurred after 2.5 h of exposure at 51, 61, and 73 GHz. This body of work suggests that the link between superficial cellular effects and whole-organism effects — the least understood aspect of MMWs — may be due to peripheral receptors and afferent nerve signaling, leading to larger systemic reactions from what are assumed to be superficial exposures. This may prove particularly significant in non-human species.

While some of the above cited studies are at a higher power density than most of the focus in this paper, because of the ubiquity of millions of new antennas planned for 5G small cells, near-field exposures to wildlife, even in rural areas, are far more likely than from distant infrastructure.

In 2000, the U.S. Central Intelligence Agency declassified and released a compendium of theoretical and experimental papers, primarily from Russia, many already covered in Pakhomov et al. [269] on high frequency MMW and ELF studies. Cited works included a review of 6,000 papers by Kholodov [314] that appeared in Markov and Blank [315] demonstrating EMF interactions with a variety of animal and human biological systems. Effects were seen in the central nervous system with the degree of response dependent on myriad radiation parameters, including frequency, pulse shape and exposure duration. Wide ranging effects were documented from microbiota to mammals. They included: MMW effects on the central and peripheral nervous system [316] with a majority (80%) of human subjects detecting and being cognitively aware of exposures as low as 10 billionths of a W/cm^2, i.e., 10 nW/cm^2; 50 μ/W affected *Proteus* bacteria [317]; MMW as low as 1 $\mu W/cm^2$ within a very narrow frequency range (51.62 < vs. 51.85 GHz) induced changes in *E coli* bacteria, indicating a resonance response; and sharp resonances in HF/MMW ranges were seen, indicating that MMW act as a catalyst for intra- and inter-cellular communication. HF/MMW may trigger complex non-linear oscillations capable of affecting fundamental processes in whole living systems [270, 271, 318–324]. See below for more on MMW and nonlinear effects.

There are more updated reviews of the MMW frequency range [273, 325] with the most recent from Simko and Mattson [326] and Alekseev and Ziskin [327].

Simko and Mattson [326] focused on potential 5G safety and nonthermal effects. They investigated works (between 6 and 100 GHz MMW divided into seven ranges) for health impacts, analyzing 94 studies, characterized for type (*in vivo, in vitro)*; biological material (species, cell type, etc.); biological endpoints; exposure parameters (frequency, duration, power density); results; and critical study quality. They found 80% of *in vivo* studies and 58% of *in vitro* studies showed effects, with responses affecting all biological endpoints investigated. They also found no consistent relationship between power density, exposure duration, and frequency with exposure effects across the studies investigated although there were consistencies within some groupings for effects that were frequency dependent. They concluded that overall the studies did not provide adequate information to determine meaningful safety assessments, or to answer questions about non-thermal effects, adding there is a need for research on small surface local heating developments (e.g., skin or eyes), and on environmental impacts. They called for significant quality improvement in future study design and implementation. They also noted that no epidemiology studies exist for these frequency ranges — an important observation — and that it is important to investigate effects to wildlife as the depth of MMW penetration in very small organisms can result in potentially significant heating.

Alekseev and Ziskin [327] reviewed MMWs, sub-MMWs and THz ranges with close attention to skin properties/permittivity as well as other physiological endpoints in the early literature. Their focus was primarily on thermal intensities although some nonthermal works are included. They concluded that effects below thermal intensities were negligible.

One U.S. MMW study by Siegel and Pikov [328] at very-low-intensity produced effects far below regulatory standards. The authors noted the growing need to understand MMW mechanisms of interaction with biological systems for both adverse effects and therapeutic uses and said that independent of health impacts of long-term high-dose MMW exposure on whole organisms, that potential subtle effects on specific tissues or organs also exist. Their focus was on quantifying real-time changes in cellular function as energy was applied in a series of experiments. Effects found changes in cell membrane potential and the action potential firing rate of cortical neurons under short (1 min) exposures to continuous-wave 60 GHz radiation at mW/cm^2 power levels more than 1,000 times below the FCC maximum permissable exposure (MPE). After review of papers on neuronal activity in MMW frequencies at low intensities, Siegel and Pikov [328] examined MMW-induced apoptosis and transient membrane permeability in epithelial cells *in vitro*, as well as real-time changes in the activity and membrane permeability of individual pyramidal neurons in patch-clamp probed cortical slices. One study, using *in vitro* cerebral cortex slices from 13-to-16-day-old rat pups, was exposed to MMW 60 GHz (at 7.5, 15, 30, 60, 120 and 185 mW exposures) introduced in random sequences, held fixed for 1 min for three current cycles, then turned off. Bath temperature was constantly monitored with temperature rise between 0.1 to 3 °C. They found changes in firing at power levels of 0.3 μW/cm^2 and above after four different MMW power levels at approximately 0.1–1 mW/cm^2. Rise and decay slopes of individual action potentials and membrane resistance were also strongly correlated with MMW power levels indicating opening of membrane ion channels. They concluded that at power levels of approximately 300 nW/cm^2 and above, a strong inhibition of the action potential firing rate in some neurons existed, as well as an increased firing in others. This indicated possible functional heterogeneity in the studied neuronal population. Further they said that rise in bath temperature could not fully account for such dramatic changes in membrane permeability. These results are believed to be the first positive correlative measurements of real-time changes in neuronal activity with ultra-low-power MMW exposures. They said that although there was a lack of high-accuracy SAR data for each sample, further investigation was warranted as effects recorded were at levels well below recommended MPE's. Their findings also have therapeutic implications for non-contact stimulation and neurologic function control in suppression of peripheral neuropathic pain and other central neurological disorders.

There are hundreds of MMW studies at high intensities not included in this paper that may also be environmentally relevant to ambient near-field 5G exposures.

5G's unusual signaling characteristics: phased array, MIMO, Sommerfeld and Brillouin precursors

5G employs unusual signaling characteristics not broadly deployed before now. Phased array (multiple antennas that fire at different rates/times) has been used for decades in military radar and a few other industrial applications. Phased arrays can boost signal strength which in turn helps signals penetrate deeper into buildings. In its adaptation to civilian-based wireless networks, phased array is considered a unique characteristic that has not been well studied as a specific biologically active entity although that was called for over 20 years ago [329, 330]. However, enough research does exist in similar frequencies to raise safety questions. Still, all extrapolations for safety regarding 5G transmission designs have been made from inapplicably different radiation models for continuous (always-on) or pulsed (intermittently on) wave forms using single element or non-phased systems. While phased array is pulsed, it is a system in which the pulses overlap (thus the term "phased") which constitutes a unique biological exposure since there is no cellular recovery time between exposures. It is therefore in essence always "on."

Although not everyone agrees this is a unique enough characteristic to warrant further research or different safety considerations from what traditionally have been used [111, 112, 130, 131, 331, 332], there are nevertheless serious concerns regarding phasing because it interacts with living cells in extremely complex ways that have nothing to do with traditional thermal thresholds. The wave form itself is the biologically active component [329, 330, 333–338].

Phasing is created by multiple antennas and sub-antennas transmitting at simultaneous or slightly different intervals at different frequencies, creating what can become steep wave banks that interact with living cells from many different angles and time sequences. Because of varying impedance factors of radiation moving through air and microsecond differences in transmission rates, each antenna in a multiple radiating element reaches the body — human and non-human alike — at slightly different times, creating multiple overlapping wave fronts. Each wave front strikes from a slightly different location and/or angle, creating a characteristic sequence of layered modulation unlike any other electromagnetic propagation source. Nothing like this exists in nature. Although phased array has been around since the 1940s, it has not heretofore been used for broadband civilian telecommunications infrastructure or in widely used consumer devices until now.

5G is a combination of line-of-sight transmission with simultaneous ground-level side-lobe pulsed phased exposures, involving an incredibly complicated infrastructure with accompanying extensive ambient exposures from what is projected to be millions of new antennas in the U.S. alone. 5G will use phased broadband signals emitted in constant pulsed overlapping waves that gradually rise in frequency, simultaneously transmitted from slightly different locations and angles that build up in a kind of stair-step fashion. As designed, 5G will employ 'Massive' MIMO (multiple input, multiple output) compound-element transceivers — over 100 per physical antenna encasement — for simultaneous signal/data sending and receiving. Because the EHF frequency is higher on the electromagnetic spectrum with shorter wavelengths, individual antenna elements are smaller so more elements can be located in the same place. Multiple antenna elements are also necessary for phasing. In time, user devices will also contain EHF MIMO and phased array technology embedded in devices like iPhones, which already contain multiple antennas. 4G LTE technology already uses compound elements and although the two systems will be interdependent in the near future, 5G as designed is substantially different enough that new phones will eventually be needed.

In addition, 5G will employ beam steering technology (of which there are several types) that allow antennas to produce and focus very narrow beams in a specific direction. By concentrating and focusing the signal, the effective radiated power is boosted which means narrow signals can travel farther and more effectively penetrate buildings and other obstacles. Beam steering also allows antennas to direct signals to user devices rather than the 360° radiation patterns of omnidirectional antennas now commonly used in telecommunications infrastructure. Beam steering is accomplished by changing phases and/or switching antenna elements. To plot the best route between signal and user, highly advanced signal processing algorithms are required.

Proponents of 5G are enamored with the network's brilliant RF engineering and hypothesize that 5G will increase system efficiency, reduce RF interference from other sources, reduce overall ambient exposures because it is a highly directed network, and be faster and more energy efficient. But 5G's sheer scale will prove some of these projections incorrect and one industry estimate holds that 5G will require 10 times more energy than is used today for telecommunications [340]. Additionally, beam steering does not reduce ambient exposures with systems at such a scale. It does, however, with the densification of infrastructure create a whole new layer of novel RFR exposures.

Any exposure standards in place today being applied to 5G control mostly for near-field exposures. But phasing creates unpredictable far-field biological effects. With phased array transmission, the wave front arrival rate and buildup can increase as it moves away from the radiating source, creating multifaceted wideband dispersion/exposures ([341], see Figures 1 and 2 below), making exposures potentially more complex in far field environments in many different frequency ranges.

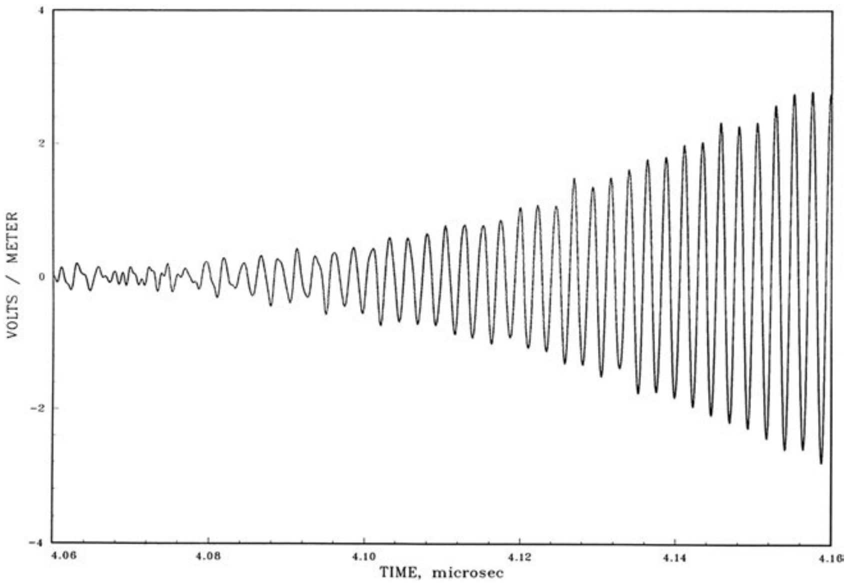

Figure 1: Phased array transmission can create wideband dispersion.
Near normal at the array face, buildup can occur as signal moves away from the generating source. Illustration shows how phased array radar buildup occurs in radar frequencies between 420 and 450 MHz [341]. From National Research Council, 2005. An Assessment of Potential Health Effects from Exposure to PAVE PAWS Low-Level Phased-Array Radiofrequency Energy, p 63. https://doi.org/10.17226/11205. Reproduced with permission from the National Academy of Sciences, Courtesy of the National Academies Press, Washington, D.C.

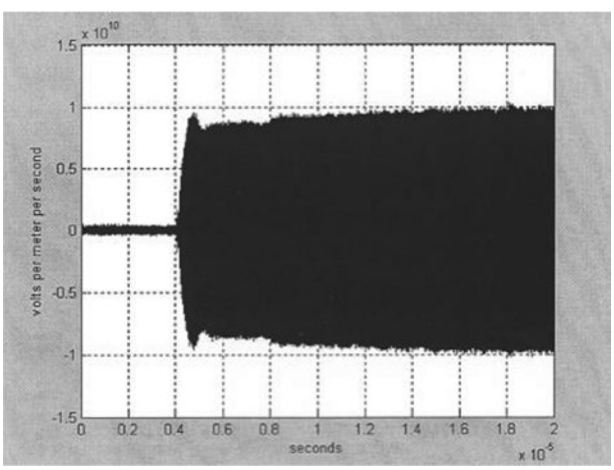

Figure 2: MMW bank buildup can also be near instantaneous.
At 500 m: the variation in slopes or rise times encountered through a pulse with many slopes being significantly greater than ±1 V per meter per nanosecond. Used with permission from Richard Albanese. Appeared in, An Assessment of Potential Health Effects from Exposure to PAVE PAWS Low-Level Phased-Array Radiofrequency Energy. National Research Council, 2005 p. 70. https://doi.org/10.17226/11205 [341].

The reason that phasing may have a unique biological impact is because very fast peak radiation pulses generate bursts of energy that can give rise to what are called Sommerfeld and Brillouin precursors in living cells that can in turn penetrate and disperse much deeper than traditional models predict [333–338, 339, 342–347]. Sommerfeld/Brillouin precursors most notably form with ultra wideband exposures as proposed with 5G.

Arnold Sommerfeld's [348] and Léon Brillouin's [349] writings on how wave fronts enter and move through 'lossy' materials (materials that absorb radiation like soil, water or living tissue) go back at least 100 years but their interest was in energy penetration and movement, not biological effects, and their orientation was on physics, not medicine. Sommerfeld and Brillouin's work noted that with the movement of a sinusoidal wave through a Lorentz medium, two transients formed. The first — now called the Sommerfeld precursor — travels at the speed of light and oscillates at very high frequencies, while the second — now called the Brillouin precursor — follows the first at slower speed. Oughstun and Sherman [339] established more current mathematical modeling for precursor formation. Both Sommerfeld and Brillouin precursors were observed in a waveguide apparatus by Plesko and Palotz [350]. The Sommerfeld precursor is estimated to have small amplitude in water-based materials like cells and tissue but has not actually been seen in such materials, while Brillouin precursors have been seen in water-based materials. Wide bandwidths in general — like 5G broadband which uses multiple frequencies — have been found to produce more precursors than narrow bandwidths; precursor formation is directly related to bandwidth (or rise time) and dispersion, but not always to electric field slope (V/m/nsec). Once generated, pulses can propagate without much attenuation and are thought to decay slowly only after significant attenuation has occurred in cellular media. That means precursors are long lasting in tissue. Precursors can occur any time during exposure [341].

With precursor formation, the salient factor is the speed at which energy is introduced. A slow introduction into material will not result in precursor formation. Precursors result from an external field being introduced at a rate faster than the motional response times of the medium itself [329, 351]. While typical continuous sinusoidal waves and pulsed exposures do not create wave fronts but are capable of causing thermoregulatory changes and other effects, phased array's sequence of wave fronts under certain circumstances may be capable of both thermoregulatory changes and electrostrictive perturbations thereby creating an unpredictable nonlinear feedback loop in living systems [329, 333–338, 351]. In other words, with 5G functioning in the EHF ranges with phased array signals, these are no longer simply physics theories. Precursors are capable of overwhelming living cells in highly unpredictable nonlinear patterns, potentially causing structural cellular fatigue and material changes throughout the entire organism.

According to Richard A. Albanese, M.D., (per. comm. 4/5/2021), when leading or trailing edge slopes (rise times) are ±1 V per meter per nanosecond or greater, a precursor will occur. Also when the signal spikes up or down such that the absolute difference between slopes/rise times is ±1 V per meter per nanosecond or greater, a precursor will occur. An example precursor is shown below in Figure 3.

Also note in Figure 3 that the slope/rise time caused by the precursor frequently exceeds ±5 V per meter per nanosecond – a factor of considerable concern. Of equal concern is that when such exposures are averaged the way that ICNIRP and FCC standards currently are (see Part 3), the slope/rise times theoretically "disappear" but not the actual biologically pertinent exposure itself in ambient field conditions.

With phased arrays, peak wave fronts arrive with time differentials in pico- and nanosecond ranges from multiple angles and distances. When wave fronts are sufficiently sharp, there is evidence that molecular re-radiation can occur as cell membrane potentials change. In other words, cells can function as small internal antennas [333, 339, 352, 353]. Wave fronts are thought to place energy quickly into molecules. When that happens, molecules are shown to re-radiate energy rather than produce heat according to the classic thermoregulatory models, and therefore travel deep into a living organism [339, 344, 347]. Rogers et al. [354] found that short pulses of 5 ns stimulated excised frog muscle contraction, demonstrating that wave fronts can depolarize membrane potentials. D'Ambrosio et al. [355] contrasted continuous waves with GMSK phased signals at 1.7 GHz and found a statistically significant rise in genotoxicity at the same SAR levels with phasing but not continuous waves.

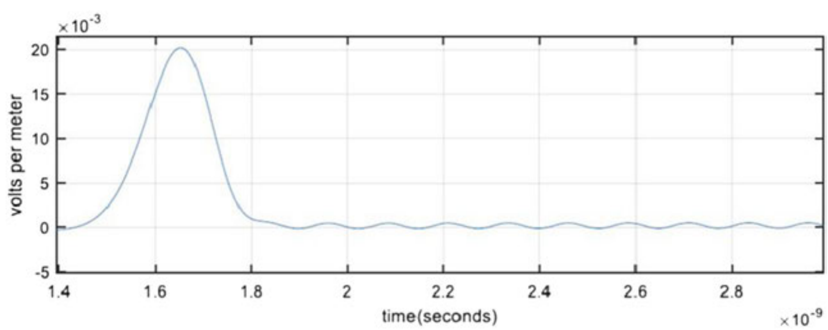

Figure 3: The above illustration shows a 20 mV precursor arising from a 1 V per meter square sinusoidal wave modulated at ~8 GHz. Of significance is the slope or rise time measured in volts per meter per nanosecond, not the carrier frequency. The above graph shows that the small amplitude of the carrier wave in tissue and the precursors that form can carry into the medium at a short duration direct-current level. However, if a sequence of these occurs – such as in phased exposures – and if the incident amplitudes are of higher magnitude, a living subject will receive a DC exposure that can depolarize cell membranes. Used with Permission by Richard A. Albanese.

Oughstun and colleagues have published many predictive mathematical and experimental papers on precursors,[1] especially those occurring in infrared (IR) laser waveforms. Infrared is visible to some species, especially birds, where it is thought to relate to breeding vigor. Although 5G is not yet licensed in IR wavebands, the upper ranges of EHF allocated for 5G are near the IR range with very similar biological effects; other technologies plan to use IR for communications purposes.

Similar observations to those described above regarding unusual propagation characteristics at these significantly higher frequencies have recently been made in studies of THz waves (between 0.3 and 30 THz in the far infrared range) by Yamazaki et al. [356]. They found that despite strong absorption by water molecules, the energy of THz pulses (250 μJ/cm^2) transmits at a millimeter thick in aqueous solution, possibly as a shockwave, and demolishes cellular actin filaments. Collapse of actin filaments induced by THz irradiation was also seen in living cells under an aqueous medium. They found that while the viability of the cell was not affected by THz pulses, the potential of THz waves as an invasive method to alter protein structure in the living cells still existed.

While our present paper does not include studies in the THz range, it is briefly mentioned here because technology in the THz range is already deployed in airport scanners and is planned for use in future Li-Fi wireless and some 5G applications [357]. The Yamazaki et al. [356] study in the THz range mentioned above challenges popular assumptions that THz radiation effects are negligible on deep tissues due to strong absorption by water molecules. The researchers found the potential opposite.

Satellites

The use of satellites for two-way broadband communications goes back to the 1960s for military applications, academic/government research, and weather prediction. Widespread adaptations for civilian use only began in the late 1980s and 1990s for radio/TV broadcast and Internet connectivity. Today civilian use has exploded, along with significant concerns.

Satellites cover entire regions, mostly broadcasting back toward Earth in both line-of-sight arrays and wide radiation patterns much like a flashlight's beam. The farther away the satellite, the broader the beam and higher the power density needed to reach Earth; some satellites transmit at millions of watts of effective radiated power. Satellites have the ability to reach rural and remote areas in ways terrestrial networks cannot, and therefore affect wildlife in ways that may never be detected.

There are already thousands of satellites circulating the Earth today. Like earth-base systems, the radiofrequency bands traditionally used for satellites have become so crowded that engineers are turning to two-way systems using laser frequencies. In 2013, the U.S. NASA Lunar Atmosphere and Dust Environment Explorer used a pulsed laser beam to transmit data over 239,000 mi (384,633 km) between the moon and Earth at a record-breaking download rate of 622 MB/s [358]. The laser frequencies are close to the upper ranges planned for 5G, and are visible to many species which see far broader light spectra than humans.

There are three general categories of satellites based on their height above the Earth's surface [359]. The first is in low Earth orbit (LEO) at about 111–1,243 mi (180–2,000 km, respectively) above Earth, used for Earth surface observations, military purposes and weather data. Medium Earth orbit (MEO) occurs at about 1,243–22,223 mi (2,000–36,000 km, respectively) used for navigation like GPS and telecommunications. High Earth orbit occurs at an altitude greater than 22,223 mi (36,000 km). High Earth orbits are also called geosynchronous orbits (GEO). Satellites there orbit every 24 h, the same as Earth's rotational period. GEO's can be fixed over one spot or circle elliptically. Some are aligned with the Earth's equator; others not. There are several hundred television, communications and weather satellites in geostationary orbits.

Space above us has now become very crowded. Satellites vary enormously in size, design, and construction according to their purpose. They are used for everything from weather-data gathering, communications (cell/Internet), broadcast radio/TV, scientific research, navigation, emergency rescue, Earth observation and military purposes. Many — though not all — weather and some communications satellites are in high Earth orbit; satellites in a medium Earth orbit include navigation and specialty satellites used to monitor a particular region, while most scientific satellites, including NASA's Earth Observing System fleet, have a low Earth orbit. A small number of satellites turn their attention (and radiation) toward space for research purposes.

There are many satellite companies, all with different models and configurations depending on their goals. Historically, satellites have relied on C band frequencies

1 For a list of 30 Oughstun studies current to 2005, see An Assessment of Potential Health Effects from Exposure to PAVE PAWS Low Level Phased Array Radiofrequency Energy PAVE PAWS 2005, Annex 5 5, pp. 90 93. http://www.nap.edu/catalog/11205.html and Dr. Oughstun's website, www.emba.uvm.edu/~oughstun.

between the 4 and 8 GHz portion of the microwave range with the least amount of attenuation through Earth's atmosphere — best for long distance transmission. But that traditional range has a lower data-carrying capacity than today's demands, so increasingly the Ku band between 12 and 18 GHz and the Ka band between 26 and 40 GHz are being used. The 60 GHz band has been used by the military for satellite-to-satellite communication. Increasingly satellite systems like Telstar will use a combination: C band for wide area coverage mixed with higher frequency Ku and Ka bands for more focused spot beams, also called high-capacity beams. One apt analogy of this combination likens the human eye to the "wide view" whereas an insect's eye is a compound structure, like spot beams capable of pointing in different directions.

New complex multifrequency satellite networks are increasing and therefore Earth exposures are too. Large or small, most satellites communicate with earth-based stations at significant power outputs.

Recent increases in satellites

Today's entrepreneurs — including Elon Musk with SpaceX/Starlink, Jeff Bezos with Amazon's Project Kuiper, Mark Zukerberg with Facebook's Athena, Telestat in Canada, OneWeb in the UK, the Russian Roscosmos, the Hongyun Project in China, and several others — are extending satellite communication to 5G technology, employing thousands of new low-to- mid-earth orbiting satellites that will create another low-level layer of novel exposures that do not now exist. There have been no Environmental Assessments (EAs) or Environmental Impact Statements (EISs) reviewed under NEPA by the FCC, which determined in 1986 that satellites were categorically excluded ([360]; also see Part 3).

By 2021, Musk plans to have launched 1,584 satellites, with another 11,943 by 2025, in contrast to the approximate 1,500 in obit as recently as 2019 [361].The ultimate plan, if allowed by FCC, is for 42,000 Starlink satellites covering the globe (placed at three different atmospheric stratas: 211 mi/340 km, 342 mi/550 km, and 715 mi/1,150 km). In October 2019, Musk sought permission for 30,000 more, to orbit between 203 mi/328 km and 380 mi/614 km, using frequencies between 10.7 and 86 GHz in overlapping phased array cells — and that's just one provider [362]. As of this writing, SpaceX/Starlink has deployed 597 satellites with 14 more multi-satellite launches planned by 2021. About 500 are functioning, ready to provide internet to some locations on Earth [363].

The FCC also granted Starlink a 15-year license for up to one million fixed-earth user terminals to communicate with Starlink's network [364], plus the FCC granted temporary approval for test stations in six states (California, Minnesota, Idaho, Alabama, Georgia and Montana) as proof of concept in advance of Starlink's official commercial opening by the end of 2020. The company intends to use the 28.6–29.1 and 29.5–30.0 GHz spectra for uploading data from the Earth stations to Starlink satellites; and 17.8–18.6 and 18.8–19.3 GHz for downlinks [365]. In addition to Starlink, Amazon's Kuiper Systems won the endorsement of the FCC's chairman, Ajit Pai, in July 2020 for 3,236 new satellites [366].

Satellite transmission in the upper atmosphere has always suffered from cloud cover interference and high latency (the time for signal to get from one place to another). SpaceX's 5G Earth orbiting design bypasses some of these problems by putting satellites in low and very-low orbits above Earth, unlike typical internet satellites in geostationary orbit at or above 22,000 mi (35,405 km) [367]. Being closer to the ground means more satellites will be needed as each satellite will cover a smaller area. While SpaceX plans to create global Internet coverage with its initial deployments in low Earth orbit in the U.S., it will then fill in gaps with thousands more at very low Earth orbit (VLEO) at approximately 211 miles (340 km) above Earth. SpaceX plans to cover rural areas first which theoretically could affect wildlife that likely will go undetected.

The U.S. is also implementing the new U.S. Space Force under the Department of Defense (DOD) and will deploy five new missile-warning satellites by 2029 in high altitude stationary orbits [368]. Additionally, DOD will augment with satellites in low Earth orbits for hypersonic missile defense [369]. SpaceX is expected to handle 40% of national security satellites that will be deployed within the next decade [370].

There have been numerous negative comments to FCC from NGO's, businesses, government agencies, and legislators about this unprecedented commercial satellite increase, especially regarding projects earmarked for 5G civilian communications due to potential interference with other agencies' use of similar frequency bands for critical weather forecasting, GPS communications, and astronomy, among others. One focus has been on FCC's 2020 licensing of Ligado Networks' (formerly LightSquared) use of the L-Band for a national civilian mobile broadband network. The L-Band is spectrum for GPS used by the military, businesses, and consumers. FCC's decision is opposed by the Pentagon; numerous U.S. agencies including The Department of Transportation; professional organizations like the Air Line Pilots Association and the International Air Transport Association; and industries like Iridium Communications and Lockheed Martin. Thirty-two U.S. senators have also asked FCC to reconsider [371].

Comments to FCC include those from the National Oceanic and Atmospheric Administration (regarding weather forecasting and research), and the Department of Energy (regarding power grid security) among others. In January 2020, The International Astronomers Appeal was filed at FCC stating “extreme concern” over tens of thousands of satellites greatly outnumbering the 9,000 stars visible to the unaided human eye, permanently blocking visibility and altering astronomical research forever. They warned there could be over 50,000 small satellites encircling the Earth at different altitudes for telecommunications purposes, primarily 5G Internet connectivity. Night-time migrating species also use stars for orientation. This sudden infusion of artificial “stars” may have adverse effects that go undetermined.

None of these agencies or companies appear concerned about the massive infusion of novel RFR into various strata of the atmospheric or ground-based environment, and the U.S. Environmental Protection Agency — the agency with primacy over environmental radiation effects — has been defunded for nonionizing radiation research and regulatory oversight since 1996 [372].

Since the ionosphere is a dynamic system capable of nonlinear excitation from external stimulation, there are reasonable concerns that satellites may be contributing to atmospheric perturbation, climate change, and weather instability [373, 374]. In addition, oxygen (O_2) molecules readily absorb the 60 GHz frequency range and rain easily attenuates signals [208, 209, 375]. At 60 GHz, 98% of transmitted energy is absorbed by atmospheric oxygen. This makes that frequency spectrum good for short-range transmission but no one understands how a large infusion of RFR in that band — or any other — may affect atmospherics. It could be highly destabilizing [376].

The FCC has allocated MMW from 57.05-to-64 GHz for unlicensed use. While all wireless equipment operating at 60 GHz must obtain FCC certification, once certified, products can be deployed license-free throughout the United States [209]. This frequency band may prove popular for myriad uses. It may also be capable of destabilizing both local micro-climate weather systems as well as broader atmospheric events due to maximal coupling with oxygen and resonance factors with water molecules [208].

By the time satellite transmissions reach the Earth’s surface, the power density is low but with 5G’s phased array signals, the biologically active component is in the waveform, not power density alone. There is no research to predict how this will affect wildlife in remote areas but given what is known about extreme sensitivity to EMFs in many species, it is likely that effects will occur and likely go undetected. Because much of the research on phased array and precursors has been done in lossy materials like water, we have models to suggest that 5G may have particular effects not only on insect populations (due to resonance factors) and amphibians (due to thin membranes and deep body penetration) but also in some aqueous species since water is a highly conductive medium. Even weak signals from satellites using phased array characteristics may be a significant contributor to species effects in remote regions.

There have been no EAs or EISs conducted through NEPA reviews to study this [377]. FCC exempted satellites from NEPA review in 1986 [360] largely based on the fact that NEPA applies to the human environment and satellites are far away. There appears to be no specific mention of satellites being specifically exempt from NEPA but the tradition of exemption continues to the present [378] although the FCC is being asked to reconsider [379].

Conclusion

Ambient background levels of EMF have risen sharply in the last four decades, creating a novel energetic exposure that previously did not exist at the Earth’s surface, lower atmospheric levels, or underwater environments. Recent decades have seen exponential increases in nearly all environments, including remote regions. There is comprehensive but outdated baseline data from the 1980s against which to compare significant new surveys from other countries which found increasing RFR levels in urban, suburban and remote areas, primarily from cell infrastructure/phone/WiFi exposures. One indicative comparison of similar sites between 1980 and today found a 70-fold (7,000%) increase in ambient RFR [149]. The increased infrastructure required for 5G networks will widely infuse the environment with new atypical exposures, as are increasing satellite systems communicating with ground-based civilian networks. The new information provides broader perspective with more precise data on both potential transient and chronic exposures to wildlife and habitats. Biological effects have been seen broadly across all taxa at vanishingly low intensities comparable to today’s ambient exposures as examined in Part 2. The major question presented in Part 1 was whether increasing anthropogenic environmental EMF can cause biological effects in wildlife that may become more urgent with 5G technologies, in addition to concerns over potentially more lenient allowances being considered by major standards-setting committees at FCC and ICNIRP (examined in Part 3). There are unique signaling characteristics inherent to 5G transmission as currently designed of particular concern to non-human species. Background levels continue to rise but no one is studying cumulative effects to nonhuman species.

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Review Article

B. Blake Levitt*, Henry C. Lai and Albert M. Manville II

Effects of non-ionizing electromagnetic fields on flora and fauna, Part 2 impacts: how species interact with natural and man-made EMF

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Abstract: Ambient levels of nonionizing electromagnetic fields (EMF) have risen sharply in the last five decades to become a ubiquitous, continuous, biologically active environmental pollutant, even in rural and remote areas. Many species of flora and fauna, because of unique physiologies and habitats, are sensitive to exogenous EMF in ways that surpass human reactivity. This can lead to complex endogenous reactions that are highly variable, largely unseen, and a possible contributing factor in species extinctions, sometimes localized. Non-human magnetoreception mechanisms are explored. Numerous studies across all frequencies and taxa indicate that current low-level anthropogenic EMF can have myriad adverse and synergistic effects, including on orientation and migration, food finding, reproduction, mating, nest and den building, territorial maintenance and defense, and on vitality, longevity and survivorship itself. Effects have been observed in mammals such as bats, cervids, cetaceans, and pinnipeds among others, and on birds, insects, amphibians, reptiles, microbes and many species of flora. Cyto- and geno-toxic effects have long been observed in laboratory research on animal models that can be extrapolated to wildlife. Unusual multi-system mechanisms can come into play with non-human species — including in aquatic environments — that rely on the Earth's natural geomagnetic fields for critical life-sustaining information. Part 2 of this 3-part series includes four online supplement tables of effects seen in animals from both ELF and RFR at vanishingly low intensities. Taken as a whole, this indicates enough information to raise concerns about ambient exposures to nonionizing radiation at ecosystem levels. Wildlife loss is often unseen and undocumented until tipping points are reached. It is time to recognize ambient EMF as a novel form of pollution and develop rules at regulatory agencies that designate air as 'habitat' so EMF can be regulated like other pollutants. Long-term chronic low-level EMF exposure standards, which do not now exist, should be set accordingly for wildlife, and environmental laws should be strictly enforced — a subject explored in Part 3.

Keywords: cell phone towers/masts/base stations; Earth's geomagnetic fields; magnetoreception, radiofrequency radiation (RFR); nonionizing electromagnetic fields (EMF); plants; wildlife.

***Corresponding author: B. Blake Levitt**, P.O. Box 2014, New Preston, CT, 06777, USA, E-mail: blakelevitt2@gmail.com and blakelevit@cs.com
Henry C. Lai, Department of Bioengineering, University of Washington, Seattle, WA, USA, E-mail: hlai@uw.edu
Albert M. Manville II, Advanced Academic Programs, Krieger School of Arts and Sciences, Environmental Sciences and Policy, Johns Hopkins University, Washington DC Campus, USA, E-mail: amanvil1@jhu.edu

Introduction: electromagnetic fields — natural and man-made

In Part 1 of this three-part series, rising ambient EMF levels were explored. Part 2 focuses specifically on the unique magnetoreception physiologies found in wildlife as well as the mechanisms by which they interact with the Earth's natural geomagnetic fields and man-made EMF at intensities now commonly found in the environment. Part 2 Supplements contain tables of studies showing effects at extremely low intensity exposures comparable to today's ambient levels.

Energy is a part of nature affecting every living thing in positive, negative and neutral ways. The Earth itself is a dipole magnet with a north and a south pole. All living things have evolved within the protective cradle of the Earth's natural geomagnetic fields. In fact, magnetic oscillations emanate from the Earth's molten iron core around 10 times per second (10 Hz) where relaxed but alert human thought/brainwaves occur between 8 and 14 Hz.

In addition to the Earth's natural emanations, vast Schumann Resonances (SR) that constantly circle the globe were theorized in 1952 by physicist Windfried Otto Schumann and reliably measured in the 1960s [1, 2]. SR are a global electromagnetic phenomenon caused by a complex relationship between lightening at the Earth's surface and the ionosphere. Excited by the 2,000 thunderstorms that occur globally at any given time and approximately 50 flashes of lightening every second, the space between Earth and the ionosphere 60 miles (97 km) above it form a resonant cavity and closed waveguide [3]. Schumann Resonances occur in the ELF bands between 3 and 60 Hz with distinct fundamental peaks around 7.83 Hz. Since the 1960s, scientists have discovered that variations in the resonances correspond to seasonal changes in solar activity, the Earth's magnetic environment, in atmospheric water aerosols and various other earth-bound phenomena, including increased weather activity due to climate change. There are an estimated 1.2 billion lightening flashes globally each year, 25 million in the U.S. alone [4], not all of which are of sufficient length to contribute to the resonances.

Many behavioral aspects in biology are thought to be synchronized with both the Earth's natural fields and the Schumann Resonances. Many species rely on the Earth's natural fields for daily movement, seasonal migration, reproduction, food-finding, and territorial location, as well as diurnal and nocturnal activities. Human circadian rhythms, mainly regulated by light targeting signaling pathways in the hypothalamic suprachiasmatic nucleus, are known to be finely tuned to the Earth's day/night cycles as well as natural seasonal variations, as are most species [5–8]. Artificial ELF-EMF is also known to adversely affect human circadian clocks, possibly through modulation in circadian clock gene expression itself [9].

Nonionizing electromagnetic fields (EMF; 0–300 GHz) include all the frequencies that fall between visible light below the ultraviolet range and the Earth's natural static fields. The nonionizing bands are used in virtually everything involved with communications and energy propagation so useful in modern life, including electric power production/distribution, all wireless technologies and accompanying infrastructure for cell phones, WiFi, baby/home monitoring systems, 'smart'grid/meters, all 'smart' technology/devices, 2-through-5G Internet of Things, AM/FM broadcast radio and television, shortwave and HAM radio, surveillance/security systems, satellites, radar, many military applications, and myriad medical diagnostic tools like MRI's, to name but a few (see Figure 1).

In its natural state, very little radiofrequency radiation (RFR) reaches the Earth's surface. Aside from the Earth's natural extremely low frequency (ELF) direct current (DC) magnetic fields, lightening and sunlight would primarily comprise our normal exposures to the electromagnetic spectrum. Most harmful radiation coming from outer space is blocked by the Earth's magnetosphere. But now, for the first

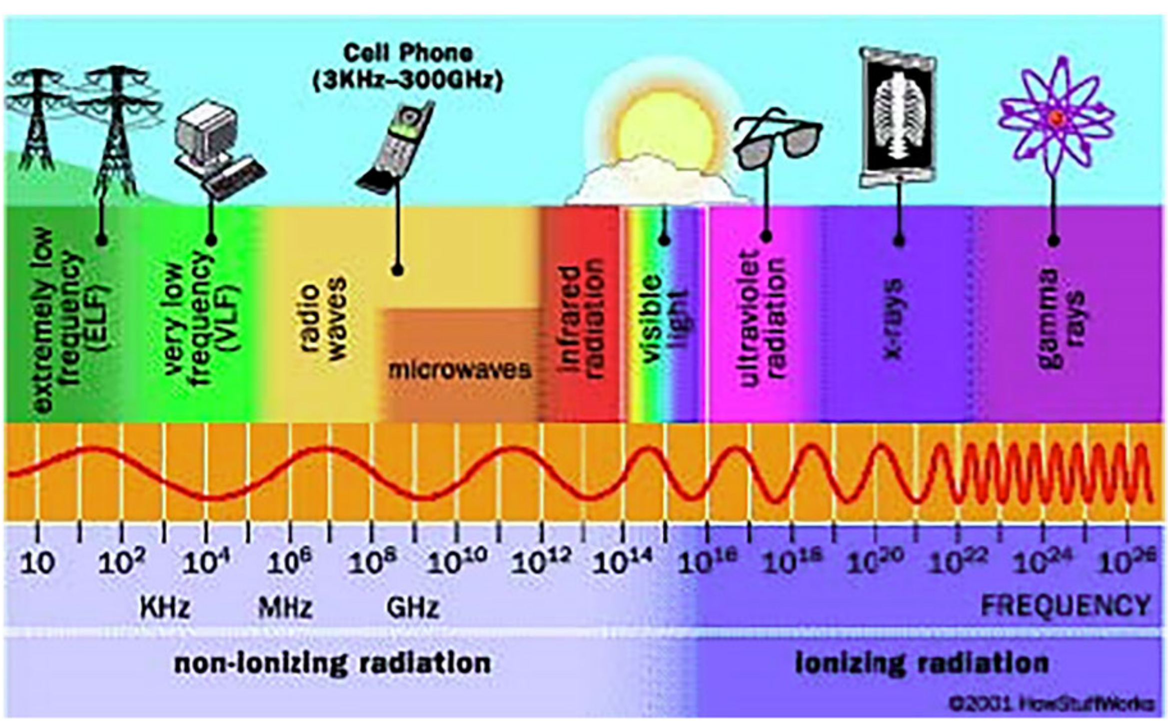

Figure 1: The electromagnetic spectrum.
The electromagnetic spectrum is divided into ionizing and nonionizing radiation. Ionizing radiation falls at and above the ultra violet range in the light frequencies. Examples of ionizing radiation include gamma rays, cosmic rays, X-rays and various military and civilian nuclear activities. It is the nonionzing bands that we have completely filled in with modern technology.

time in evolutionary history, we have infused the Earth's surface with a blanket of artificial energy exposures with no clear understanding of what the consequences may be.

And although "natural," not all energy is alike. Man-made exposures contain propagation characteristics — such as alternating current, modulation, complex signaling characteristics (e.g., pulsed, digital, and phased array), unusual wave forms (e.g., square and sawtooth shapes), and at heightened power intensities at the Earth's surface that simply do not exist in nature. These are all man-made artifacts. In our embrace of technology, we have completely altered the Earth's electromagnetic signature in which all life has evolved, in essence bypassing the magnetosphere's protection. And because so much of wireless technology is satellite based, increasing exposures are no longer just ground-generated. All atmospheric levels are now affected by increasing ambient exposures (see Part 1 and Part 1 Supplement). This is especially true in the lower atmosphere, which is 'habitat' (beyond mere oxygen and clean air standards) for all species that mate, migrate, and feed in the air — including birds, mammals (such as bats), insects and some arachnids.

Species extinctions

There has been an unprecedented rate of biodiversity decline in recent decades according to the International Union for Conservation of Nature [10] which maintains a "Red List of Threatened Species" that is considered the world's most comprehensive source on the global conservation status of animal, fungi and plant species — all critical indicators of planetary health.

IUCN's 2018 list showed that 26,000 species are threatened with extinction, which reflected more than 27% of all species assessed. This was greatly increased from their 2004 report that found at least 15 species had already gone extinct between 1984 and 2004, and another 12 survived only in captivity. Current extinction rates are now at least 100 to 1,000 times higher than natural rates found in the fossil record.

The more recent May 2019 report by the Intergovernmental Science and Policy Platform on Biodiversity and Ecosystem Services, Paris, France [11] projected that at least 1 million plant and animal species worldwide are at imminent threat of extinction if our current human actions and activities are not immediately reversed. A review of 73 reports by Sanchez-Bayo and Wyckhuys [12] found those rates had greatly accelerated. The authors noted that biodiversity of insects in particular is threatened worldwide with dramatic declines that could lead to a 40% extinction of insect species over the next several decades. In terrestrial ecosystems they found *Lepidoptera, Hymenoptera, and Coleoptera* (dung beetles) were most affected, while in aquatic ecosystems *Odonata, Plecoptera, Trichoptera and Ephemeroptera* have already lost a considerable proportion of species. Affected insect groups included niche specialist species, as well as common and generalist species, many of which are critically important for pollination, as well as seed, fruit, nut and honey production, and natural pest control, among others of immeasurable economic and ecological value.

Humans are the primary cause for most declines via habitat destruction/degradation; over-exploitation for food, pets, cattle and medicine; artificially introduced species; pollution/contamination; pesticides; and disease. Climate change is increasingly established as a serious threat, as well as agricultural practices like monoculture crops for cattle feed, biofuels, and timber. New pesticides and weed killers introduced within the last 20 years, using neonicotinoids, glyphosphate, and fipronil, are especially damaging since they are long-lasting and capable of sterilizing soil of beneficial microorganisms, including worms and grubs, which can then extend to areas far beyond applications sites.

One example of multi-factorial damage includes the iconic American Monarch butterfly (*Danaus plexippus)* which is found across America and Southern Canada and generally geographically divided into eastern and western migratory groups by the Rocky Mountains. That species has declined by a full 99.4% in the west since the 1980s — 85% of that being since 2017 [13, 14]. According to the Center for Biological Diversity [15], the eastern monarch population has shrunk by 90% in the past two decades. Massive habitat loss, wildfires, climate change, droughts, enhanced storm ferocity, and the 1990s introduction of Monsanto "Roundup Ready" crops capable of surviving herbicides that kill other weeds — including milkweed, which monarchs need for breeding and as their sole food supply along their migratory routes — are thought to be the primary culprits.

Here, we argue, environmental EMF should be added to this list since many insects and other living species have sensitive receptors for EMF, e.g., monarchs were found to have light sensitive magnetoreceptors in their antennae that serve as an inclination compass when daylight is absent [16]. RFR is also known to alter the time period needed for a butterfly to complete morphogenesis, plus gastrulation and larval growth can be accelerated [17]. And the devastating loss of pollinating insects like honey bees and other wild pollinators may also be related to environmental EMF (see "Insects" below.)

Anecdotally, many people recall when there were significantly more insects and far more abundant wildlife. Since about 1980, there has been a steady, almost imperceptible, biodiversity diminishment among many species globally [18–20]. In 2018, scientists estimated that the largest king penguin colony shrank by 88% in just 35 years [21] due in major part to effects from climate change, while according to the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean, over 97% of bluefin tuna have disappeared from the world's oceans, primarily due to industrial overfishing but exacerbated by oil spills, contamination, and climate change. Tree and cave-dwelling bats until recently were common, including in the Eastern United States. Now with the massive impacts from White-nosed Syndrome (a fatal bat fungal disease), annual wind-turbine bat collision mortality estimated at nearly 1 million per year in the U.S. alone [22, 23], and pesticide use, few bats are seen. Bats species are also sensitive to EMF. Impacts from EMF as now seen in extensive reviews add only yet another troubling variable for all wildlife [24–36].

Since all food webs are uniquely tied together, there are negative cascading effects across all ecosystems. Birds that eat insects are hard hit: 8-in-10 partridges have disappeared from French farmlands while there has been a 50–80% reduction in nightingales and turtledoves respectively in the UK. Since 1980 the number of birds that typically inhabit Europe's farmlands has shrunk by 55%, while in the last 17 years, French farmland-bird counts dropped by a full third. Intensified agricultural practices are thought responsible, with loss of insects being the largest contributor [12, 37]. In the United States, of the 1,027 species of migratory birds currently protected under the Migratory Bird Treaty Act of 1918, an estimated 40% are in decline based on breeding bird surveys [38], Christmas Bird Counts [39], and other monitoring tools [22, 23]. This trend is comparable to what is happening globally. What role EMF plays in these declines is unclear but remains a disturbing possibility. Nor do we understand the limits of tolerance any given species has for environmental disturbance — some show high flexibility while others thrive only within the narrowest ranges.

One estimate of Earth's species finds that since 1970, wild animal populations have been reduced on average by 60%. Popularly called the "sixth mass extinction" [40], the term connotes the sixth time in the Earth's history that large numbers of species have rapidly disappeared over a relatively short period, this time due to human activity, not asteroid strikes or volcanic activity. Though not officially so-designated, many now refer to this most recent geologic/ecosystem period as the "Anthropocene" — the Age of Man [41–46].

Insect populations have been especially hard hit with extinctions eight times faster than that of mammals, birds and reptiles [12]. Insect total mass is falling by an estimated 2.5% per year, suggesting they could vanish by the next century. And what affects insect populations affects everything in the food web in one way or another. Loss of insect diversity and abundance can cause devastating effects throughout food webs and endanger entire ecosystems [12]. In Europe, Hallmann et al. [47] found a more than 75% decline over 27 years in total flying insect biomass in 63 protected areas, many throughout Germany. There was an 82% decline in mid-summer flying insect mass. Many European insect species migrate from distances as far away as Africa. The researchers noted that changes in weather, land use, and habitat characteristics alone cannot explain the overall decline and that there may be more than one unrecognized factor involved in evaluating declines in overall species abundance. That unrecognized factor may be the steadily rising ambient EMF that directly parallels these declines (see Part 1, Supplement 1).

Similar alarming invertebrate declines were discovered in the Western Hemisphere in 2017 when American entomologist Bradford Lister, after 40 years, revisited the El Yunque National Forest in Puerto Rico to follow up on a study begun in 1976 [48]. In the ensuing decades, populations of arthropods, including numerous flying insects, centipedes and spiders, had fallen by 98% in El Yunque, a pristine tropical rainforest within the U.S. National Forest System. Insectivores — including birds, lizards, and toads — showed similar declines, with some species vanishing entirely. After controlling for factors like habitat degradation or loss and pesticide use, the researchers concluded that climate change was the primary factor since the average maximum temperature in that rainforest had increased by 4 °F during that period. They did not factor in the large U.S. military VLF installation in Aquada that communicates with submarines all over the world, or the multiple sweeping over-the-horizon phased array radar units aimed at Puerto Rico from coastal sites in the U.S. that irradiate deep into that forest, or the multiple NOAA Doppler weather radar sites scattered all over the small island to track hurricanes, or the many cell towers there too.

These global declines are truly alarming with implications for planetary health as well as human and wildlife integrity. Many who study this say that climate change alone is not the only factor and that something new is going on [47]. The question is: could steadily rising environmental EMF, as one of the most ubiquitous but unrecognized new environmental genotoxins introduced since the 1980s, be contributing to these unprecedented species losses, beginning with insects but now manifesting in other species too? The upper microwave bands couple maximally with some insects the size of fruit flies and are capable of creating devastating resonance and other effects. Historically, radiofrequency radiation (RFR) impacts to insects were among the first biological effects to be studied [49] with the hope of discovering new forms of insect control [50]. All insect metamorphic developments have been studied, including egg, larva, pupa, and adult stages. One hypothesis holds that some adult species are more sensitive than at larval stages because adult appendages act as conducting pathways to the body (see “Insects” below).

It is these exact frequency bands between 30 kHz and 3 GHz used in telecommunications technology that have been on the rise during this period. And 5G is on the horizon which may specifically target insect populations (see Part 1).

Species sensitivity to EMFs

Other species have vastly more complex electromagnetic sensing tools than humans, as well as unique physiologies that evolved to sense weak fields. Many species are highly sensitive to the Earth’s natural electromagnetic fields, as well as geographic and seasonal variations. In fact, it appears that most living things — including many species of mammals, birds, fish, and bacteria — are tuned to the Earth’s electromagnetic background in ways once considered as “superpowers” but are now known to be physiological, even as mechanisms are still imperfectly understood. For example, many animals have been observed sensing earthquakes long before human instruments detect them, including snakes and scorpions that seek shelter; cattle that stampede; birds that sing at the wrong times of day; and female cats that frantically move kittens [7].

This ability is likely due, in part, to numerous species reacting to changes in the Earth’s magnetic field and electrostatic charges in the air detected through a naturally occurring mineral called magnetite found in many species [51, 52]. In fact, honey bees are able to detect static magnetic field fluctuations as weak as 26 nT against background earth-strength magnetic fields that are much higher [53] and to sense weak alternating fields at frequencies of 10 and 60 Hz [54]. Magnetite reacts a million times more strongly to external electromagnetic fields than any other known magnetic material. Authors Kobayshi and Kirchvink [52] and Kirchvink et al. [53, 54] hypothesized results were consistent with biophysical predictions of a magnetite-based magnetoreceptor. Other mechanisms, like radical pair mechanisms and cryptochromes, may also be responsible (see “Mechanisms” below).

Much has been written about magnetoreception — the term used to describe how species sense electromagnetic fields — which is well established but not well understood. Many species use information about the Earth’s natural fields for migration, mating, food-finding, homing, nesting, and numerous other activities. Migratory bird species [55, 56], honey bees [57], fish [58], mammals [59], bats [60], numerous insect species [61], mollusks [62], and even bacteria [63] are known to sense Earth’s magnetic fields in various ways. Magnetoreception may enable some bird species to actually see the Earth’s fields [64].

Some insect and arachnid species (e.g., Trichobothria) can detect natural atmospheric electric fields [65] which trigger ballooning behavior — e.g., climbing to the highest place, letting out silk, and traveling on wind currents using hair-like Trichobothria that detects airborne vibrations, currents, and electrical charge. Some have been found as high as 2.5 mi (4 km) in the sky, dispersing over hundreds of kilometers. Morley and Robert [65] found that the presence of a weak natural vertical e-field elicited ballooning behavior and takeoff in the spiders; their mechano-sensory hairs function as putative sensory receivers which are activated by natural weak electric-fields in response to both e-field and air-flow stimuli. The researchers hypothesized that atmospheric electricity was key to the mass migration patterns of some arthropod fauna.

Even soil nematodes (*Caenorhabditis elegans)* orient to earth-strength magnetic fields in their burrowing behaviors and a recent study by Vidal-Gadea [66] found that weak static fields slightly above Earth’s natural fields determined stem cell regeneration in flatworms (*Planaria*) [67].

Large ruminant mammalian species also orient to the Earth’s fields. Grazing cattle and deer were first observed aligning to geomagnetic field lines by Begall et al. [68]. Using satellite imagery, field observations, and measuring “deerbeds” in snow, they noted that domestic cattle across the globe, as well as grazing and resting red (*Cervus alphas*) and roe (*Capreolus capreolus*) deer, consistently align their body axis in a general north–south direction and that roe deer also orient their heads northward when grazing or resting. Burda et al. [69] discovered, however, that man-made ELF-EMF disrupted the north-south alignment with the geomagnetic field in resting cattle and roe deer when they found body orientation was random on pastures under or near power lines, with the disturbed pattern diminishing with distance from conductors. Cattle exposed to various magnetic field patterns directly beneath or near power lines exhibited distinct patterns of alignment. They concluded there was evidence for magnetic sensation in large mammals, as well as overt behavioral reactions to weak ELF-MF in vertebrates, implying cellular and molecular effects. Slaby et al. [70] also found cattle align along a north-south axis but suggested that such alignment may depend on herd density as the affect disappeared in herds with higher numbers. Fedrowitz [71] expanded this to include bovine sensitivity to other weak ELF-EMF from powerlines but with observed effects due to combined electric and magnetic fields rather than the electric field exposure alone (see “Bovines”below).

Cerveny et al. [72] found red fox (*Vulpes vulpes)* use geomagnetic fields during hunting. Even domestic dogs were found by Hart et al. [73] to be sensitive to small variations in the Earth’s orientation in their excretion habits, preferring a general north-south axis for both defecation and urination depending on geomagnetic field changes. And Nießner et al. [74] found dogs and some other species may actually “see” geomagnetic fields through blue-light sensing photoreceptor proteins in their eyes called cryptochromes.

According to the US/UK World Magnetic Model [75], sensitivity to the geomagnetic field may further complicate issues for migratory species (e.g., some turtles, sea animals, birds, and insects) because the Earth’s magnetic north pole is shifting faster than at any time in human history. Compared to the period between 1900 and 1980, it has greatly accelerated to about 30 mi (50 km) distance per year — moving west from over Canada’s Ellesmere Island, its traditional allocation for most of recorded history — toward Russia [76]. Magnetic north fluctuates according to changes in the Earth’s molten core, unlike true north which aligns according to the Earth’s axis. This trend may indicate a coming pole reversal with north and south trading places, something that occurs approximately every 400,000 years with the last being about 780,000 years ago. Some animals may be capable of recalibrating navigational cues but that remains to be seen. Since some migratory bird species may see geomagnetic fields through special receptor cells in their eyes and via other mechanisms, they could be thrown off course. It is unclear how many other species also see geomagnetic fields but some crustaceans and several insect species, especially those with compound eye structures consisting of thousands of ommatidia — tiny independent photoreception units with a cornea, lens, and photoreceptor cells that orient in different directions and distinguish brightness and many more bands of color than humans — are good candidates. Compared to single-aperture eyes, compound eyes have a very large view angle that can detect fast movement and in some cases light polarization.

In aquatic environments, some lakes have more than 200 species of fish that use some form of electromagnetism to locate food and reproduce. Electric eels can deliver a 500-V zap to kill prey. Sharks have an array of electromagnetic sensors. These include: magnetic field receptors in their mouths, eyes that are 10 times more sensitive than humans, and their perception of tiny electric neuronal discharges from the moving muscles in prey (including humans) guides their attacking/feeding behavior (see “Fish”below). Sharks are often attracted by low-level electromagnetic fields surrounding underwater electric cables and are sometimes electrocuted when they mistake the conduit for living prey and bite into it. Many fish have lateral lines on either side of their bodies that are composed of magnetite, which allows fish to swim in synchronous schools [52].

Many other animals evolved special receptor organs to detect environmental EMF. The duck-billed platypus (*Ornithorhynchus anatinus),* a semi-aquatic primitive egg-laying mammal, has thousands of electric sensors on its bill skin. As noted in Lai [77], using these electroreceptors and interacting with another type of mechanoreceptor, a platypus can detect an electric field of 20 μV/cm [78] — equivalent to that produced by the muscles of a shrimp. The information is processed by the somatosensory cortex of the platypus to fix the location of prey. This type of electroreception is common in the three species of monotremes: platypus, and long (*Zaglossus bruijni)* and short-bill (*Tachyglossus aculeatus*) echidna. Electric fish (elasmobranchs) emit EMF that covers a distance of several centimeters [79, 80]. This allows location of potential prey by comparing its electrical properties with that in its immediate vicinity. Their electroreceptors have been shown to detect a field of 5 nV/cm. Such EMF-sensing systems are highly sensitive and efficient but also highly vulnerable to disruption by unnatural fields. Organisms that use the geomagnetic field for migration have the capability not only to detect the field but also the orientation of the field.

Anthropogenic light frequencies affect wildlife in ways we have only recently grasped. Ecological studies have found that artificial light-at-night is disrupting nocturnal animals in devastating ways, including disorientation and disruption in breeding and migration cycles in turtles, flying insects, birds, butterflies and a host of other wildlife including mammals [81–84]. As much as 30% of nocturnal vertebrates and over 60% of invertebrates may be affected by artificial light [85]. Illumination reflected off of clouds known as “sky glow” can produce unnaturally bright conditions at night from various wavelength spectra that impact different species, with the potential to alter the balance of species interactions [86, 87]. It has been found that changing the color of the light can help some species yet harm another [88]. For instance, low-pressure sodium lights that have more yellow in their spectrum reduce moth deaths around the bulbs, but salamanders cannot navigate from one pond to the next under yellow or red light. Some frogs have been observed to freeze for hours, even after lights have been turned off, and to suspend both feeding and reproduction [83].

One of nature's great mysteries involves "natal homing behavior" — the ability of some animal species to return to their original location of birth in order to reproduce, sometimes over great distances. Natal homing behavior is known in sea turtles [89]; eels [90]; and salmon [91], among other species. The underlying mechanism, though imperfectly understood, involves such species "remembering" the geomagnetic field configurations of their birthplace via a process known as "imprinting," and thus can locate and return to it even if they are thousands of miles/kilometers away at reproduction time. Apparently, newborns of these species are imprinted with the memory of the intensity and the inclination angle of the local geomagnetic field. This information is then later used to locate their place of birth where they return to breed.

The question is whether man-made EMF could distort this imprinting memory in later locating the site. For example, what if RFR-emitting facilities are located near turtle breeding sites? Could that interfere with imprinting? There is some evidence from Landler et al. [92] of adverse effects in turtles. The researchers found that RFR could disrupt a natural orientation, establish its own orientation, and reverse completely a natural orientation, indicating a need for research to further investigate as we simply do not know the full effects to other species from anthropogenic EMF.

Energy conduction in different species: unique physiologies and morphologies

The unique physiology and morphology of non-human species create additional complexities. For instance, quadrapedal species with four feet on the ground have different and potentially more efficient conductivity than bipedal species with two feet. One example is bovine heightened sensitivity to increased ground current near high tension lines [93, 94] and cell towers [95–97]. Also, bodies that are predominately parallel to the ground, which includes most four-legged mammals, rather than a perpendicular upright gait, conduct EMF in different ways than vertical species like humans, apes, and other primates. Species that hug the ground, like snakes, salamanders, and frogs, have unique exposures to ground currents, especially on rainy nights when water, as a conductive medium, can increase exposures [98]. This may make some species more sensitive to artificial ground current caused by electric utility companies using the Earth as their neutral return back to the substation for excess alternating current on their lines instead of running additional neutral lines on utility poles [99].

Hair and whiskers and related appendages in various species are known to detect small variations in electromagnetic fields as well as water and weather alterations [100]. In fact, ants have been observed to use their antennae as "EMF antennas" when subjected by researchers to external electromagnetic fields, aligning themselves to "channel" RFR away from the colony [7]. Species such as birds, as well as some insects with compound eyes structures, can see vastly more colors than humans, while cats, dogs, and owls, for instance, hear many more sound frequencies at incredibly low levels.

Magnetoreception mechanisms: electroreceptor cells, magnetite, cryptochromes/radical pairs

According to Lai [77], "…in order for an environmental entity to affect the functions of an organism, the following criteria have to be met: the organism should be able to detect the entity; the level of the entity should be similar to those in the normal ambient environment which is generally much lower than the level of the entity used in experimental studies; and the organism must have response mechanisms tuned to certain parameters of the entity that allow immediate detection of the presence and changes of the entity. Thus, a variation of the entity would be detected as an aberrant input and trigger a response reaction. In order to understand how man-made EMF affects wildlife, the above criteria must be considered, including multiple sensory mechanisms that vary from species to species."

The questions are: How do diverse species detect weak natural geomagnetic signals, distinguish the subtle internal microcurrent and magnetic fields inherent to all biology from external fields, then get beyond both internal and external background noise to make use of that electromagnetic information?

There are three primary mechanisms used to understand magnetoreception:

(1) Magnetic induction of weak electrical signals in specialized sensory receptors [101].
(2) Magnetomechanical interactions with localized deposits of single-domain magnetite crystals [52, 102, 103].
(3) Radical-pair photoreceptors, which may be the most plausible [104–111].

In the induction model (mechanism 1), according to Lin [102], the first category of electrodynamic interactions with weak magnetic fields is epitomized by elasmobranchs, including sharks, rays, and skates, with heads that contain long jelly-filled canals with high electrical conductivity known as the Ampullae of Lorenzini. As these fish swim through the Earth's geomagnetic lines of flux, small voltage gradients are induced in these canals with electric field detections as low as 0.5 μV/m [101] The polarity of the induced field in relation to the geomagnetic field provides directional cues for the fish. However, in birds, insects, and land-based animals, such cells have not been found, indicating this may not be a universal mechanism but rather are environment/species-specific factors [111].

The magnetomechanical model (mechanism 2) involves the naturally occurring iron-based crystalline mineral called magnetite found in most species [52]. Its function is most simply demonstrated in magnetotactic bacteria [63] with high iron content where biogenic magnetite is manufactured in 20–30 single domain crystal chains [112]. Orientation is patterned according to the geomagnetic field. Blakemore et al. [113] found that magnetotactic bacteria in the northern hemisphere migrate toward the north pole of the geomagnetic field whereas the same strains migrate toward the South Pole in the southern hemisphere. At the equator, they are nearly equally divided in north- and- south seeking orientations [114]. And they all migrate downward in response to the geomagnetic field's vertical component, which, in aqueous environments may be essential for their survival in bottom sediments.

Among the many species where magnetite has been found include the cranium and neck muscles of pigeons [115, 116]; denticles of mollusks [117, 118]; and the abdominal area of bees [119]. Tenforde [103] delineated other species with localized magnetite, including dolphins, tuna, salmon, butterflies, turtles, mice, and humans.

The third mechanistic model (mechanism 3) getting research attention today involves a complex free-radical-pair reaction and conversion of the forms of electrons (singlet-triplet inter-conversion) in a group of protein compounds known as cryptochromes. Cryptochromes have been found in the retinas of nocturnal migratory songbirds by Heyers et al. [55] and Moller et al. [56], showing complex communication with the brain for orientation when relying on magnetoreception. Gegear et al. [61] found cryptochromes to be a critical magnetoreception component in fruit flies (*Drosophila melanogaster)*. As noted in Lai [77], cryptochrones are also present in the retinas of some animals [120]. RFR [121] and oscillating magnetic fields [122] have been reported to disrupt the migratory compass orientation in migratory birds. There are also reports that indicate the presence of cryptochromes in plants, which may be responsible for the effect of EMF on plant growth [123]. Cryptochromes are also known to be involved with circadian rhythms [56, 124]. For an excellent review on plausibility, theories, and complexities of cryptochrome/radical pairs, see Ritz et al. [111].

Many species likely use a combination of these mechanisms as well as more subtle influences as yet undetected. The vector of the geomagnetic field may provide the directional information, while intensity and/or inclination provide the positional information needed for orientation. In behavioral studies [125, 126], Wiltschko et al. found that birds used both magnetite and cryptochrome mechanisms when they responded to a short, strong magnetic pulse capable of changing magnetization of magnetite particles, while their orientation was light-dependent and easily disrupted by high-frequency magnetic fields in the MHz range indicating radical pair processes. These findings suggest that along with electrophysiological and histological studies, birds have a radical pair mechanism located in the right eye that provides compass-like directional information while magnetite in the upper beak senses magnetic intensity, thus providing positional information. However, Pakhomov et al. [122] pointed out that the songbird magnetic compass can be disrupted by an oscillating 1.403-MHz magnetic field of 2–3 nT, at a level that cannot be explained by the radical-pair mechanism.

Light plays a significant role [127], which is of environmental concern today as more technology moves toward using the infrared bands for communications and the increase of satellites create artificial/unfamiliar star-like lights in the night sky that are potentially capable of impacting night migration patterns. There is other evidence that species use a combination of photoreceptors and magnetite-based magnetoreception. As mentioned above, in birds the two mechanisms exist side by side, mediating different types of magnetic information as needed, such as flight on sunny vs. cloudy days or nocturnal flights, and they can be easily disrupted [106, 128–130]. Birds may co-process visual information with magnetic information and be able to distinguish between the two [131, 132]. This function likely occurs in the eye or higher avian brain areas via light-dependent information processing and radical pair cryptochromes [131, 133]. Birds' magnetic compass is an inclination compass and RFR fields in the Larmor frequencies near 1.33 MHz were found to disrupt birds' orientation in an extremely sensitive resonance relationship. Blue-light absorbing photopigment cryptochromes have been found in the retinas of birds. RFR appears to directly interfere with the primary processes of magnetoreception and disable the avian compass as long as the exposure is present [126, 128].

Mammals have also demonstrated magnetoreception indicating radical-pair mechanisms. Malkemper et al. [134] found that the surface-dwelling wood mouse (*Apodemus sylvaticus*) built nests in the northern and southern sectors of a visually symmetrical, circular arena, using the ambient magnetic field, or in a field rotated by 90°, indicating the animals used magnetic cues. When the mice were also tested in the ambient magnetic field with a superimposed radio frequency magnetic field (100 nT, 0.9 to 5 MHz frequency sweep), they changed preference from north-south to east-west nest building. But unlike birds that have been found sensitive to a constant Larmor frequency exposure at 1.33 MHz, that range had no effect on mice orientation. Individual animal physiology clearly plays a role in how various species respond. Malewski et al. [135] also found that the Earth's magnetic field acts as a common directional indicator in five species of subterranean digging rodents. And for the first time, research also found that human brain waves exhibit a strong response to ecologically-relevant rotations of Earth-strength magnetic fields [136].

We need far better understanding of magnetoreception's neural, cellular, and molecular processes because the ultimate question is, given our constant rising background levels of EMF, is this ambient noise reaching a tipping point beyond which species simply cannot "hear?" Are we artificially overwhelming living species' ability to function with innate natural biological sensors that evolved over eons in a far more "electro-silent" world? The electroreception mechanisms described above — electroreceptors, magnetite, and cryptochrone/radical-pairs — enable living organisms to detect the presence and immediate changes in environmental fields of very low intensity. And thus they can be easily disturbed by the presence of unfamiliar low-intensity man-made fields.

Electrohypersensitivity in humans has also shown instantaneous response to EMF at low intensity [137]. According to Lai [77], one wonders whether the underlying mechanisms of electrohypersensivity are similar to those described above. Electrohypersensitivity may be a remnant of the evolutionary responses of living organisms to electromagnetic fields — particularly magnetic fields — in the environment. Similarities include responsiveness to very low-field intensity; the response is persistent and built into the physiology of an organism; and the response is immediate and reacts quickly to the fields. Cryptochrome-free radical mechanisms may be involved. Some people are more sensitive than others. Perhaps non-sensitive people can tolerate and compensate for effects, and/or have lost responsiveness to natural magnetic fields and thus have become evolutionarily aberrant. Electrosensitivity is an issue in need of more careful and systematic study and has yet to be broadly highlighted as a health or public welfare concern.

One recent theory by Johnsen et al. [138] postulates that magnetoreception in animal species may be "noisy" — meaning that the magnetic signal is small compared to thermal and other receptor noise, for instance. They speculate that magnetoreception may serve as a redundant "as-needed" source of information, otherwise animal species would use it as their primary source of information. Many species, they note, preferentially exploit non-magnetic cues first if they are available despite the fact that the Earth's geomagnetic field is pervasive and ever-present. They speculate that magnetic receptors may thus be unable to instantaneously attain highly precise magnetic information, and therefore more extensive time-averaging and/or other higher-order neural processing of magnetic information is required. This may render "…the magnetic sense inefficient relative to alternative cues that can be detected faster and with less effort." Magnetoreception may have been maintained, however, they said by natural selection because the geomagnetic field may sometimes be the only available source of directional and/or positional information.

We already know that some species use various mechanisms to detect EMFs as noted throughout this paper. With new environmental factors from anthropogenic causes, such as artificial light-at-night, air/water pollution, climate change impacting visibility as environmental cues, and rising background RFR — all of which can obscure natural information — magnetoreception may, in fact, become *more* necessary as an evolutionary survival tool as time goes on, not less.

Other mechanisms of biological significance: DNA — direct and indirect effects (See Part 2, Supplements 1 and 2, for tables of ELF and RFR genetics studies)

A significant biological effect in any toxicology research involves the basic genetics of an exposed organism. Genetic effects consist mainly of gene expression, chromatin conformational changes, and genotoxicity. All such effects can influence normal physiological functions. Relevant to this paper is the fact that genetic effects are found at EMF levels similar to those in ambient environments, far below levels from communication devices and infrastructure (see Part 1, Supplement 1).

DNA, the fundamental building block of all life, is a molecular double helix that is coiled, twisted and folded within the nucleus of each living cell. It is essentially identical among species with variations only in number and specific genes along chromosomes on DNA's twisted chains that distinguish various species and their characteristics from one another. DNA damage repeatedly seen in one species can therefore be extrapolated to other species, although not all species react the same to external stimuli.

Many factors, both endogenous and exogenous, damage DNA which is then normally repaired by DNA enzymes. But an absence of adequate repair can result in the accumulation of damaged DNA, which will eventually lead to aging, cell death (apotosis) and/or cancer. DNA breaks occur as both single and double strand events; double strand breaks are difficult to repair correctly and can lead to mutations. DNA damage from endogenous factors can include free radical formation from mitochondrial respiration and metabolism; exogenous factors include chemicals, ionizing and nonionizing radiation, and ultra violet light among others [139]

In several early studies, Lai and Singh [140, 141] found both double and single strand DNA breaks in the brain cells of rats exposed to RFR for 2 h at 2,450 MHz, and whole body SAR levels of 0.6 and 1.2 W/kg. The effects were interestingly blocked by antioxidants [142] suggesting free radical involvement, which could indicate an indirect cause for DNA damage (see below). The low-intensity genetic effects listed in Part 2 Supplements 1 and 2 are at 0.1 W/kg and less. Therefore, the Lai and Singh [140, 141] RFR studies are not included in those Supplements. Very similar effects have also been found by Lai and Singh [143, 144] with 60-Hz magnetic field exposure.

There has also been much study of ELF genetic effects. As discussed in Phillips et al. [139], numerous studies found that ELF-EMF leads to DNA damage [143–158]. Two studies [159, 160] showed that ELF also affects DNA repair mechanisms. Sarimov et al. [161] found chromatin conformational changes in human lymphocytes exposed to a 50-Hz magnetic field at 5–20 µT. EMF-induced changes in cellular free radicals are also well studied [77, 162].

Others investigated DNA damage early on but without the availability of today's more sensitive assays. Sarkar et al. [163] exposed mice to 2,450-MHz microwaves at a power density of 1 mW/cm^2 for 2 h/day over 120, 150, and 200 days. They found DNA rearrangement in the testis and brain of exposed animals that suggested DNA strand breakage. Phillips et al. [164] were the first to use the comet assay to study two different forms of cell phone signals — multi-frequency time division multiple access (TDMA) and integrated digital enhanced network (iDEN) — on DNA damage in Molt-4 human lymphoblastoid cells using relatively low intensities of 2.4–26 W/g for 2–21 h. The authors reported seeming conflicting increases *and* decreases in DNA damage, depending on the type of signal studied, as well as the intensity and duration of exposure. They speculated the fields could affect DNA repair mechanisms in cells, accounting for the conflicting results.

In a recent literature review of EMF genetic effects by Lai [165], analysis found more research papers reporting effects than no effects. For RFR, 224 studies (65%) showed genetic effects while 122 publications (35%) found no effects. For ELF and static-EMF studies, 160 studies (77%) found effects while in 43 studies (23%) no effects were seen.

Research now points to the duration, signaling characteristics, and type of exposure as the determining factors in potential damage [164, 166], not the traditional demarcation between ionizing and nonionzing radiation. Long-term, low-level nonionizing radiation exposures common today are thought to be as detrimental to living cells as are short-term, high-intensity exposures from ionizing radiation. Effects may just take longer to manifest [167]. Nonionizing EMF at environmental levels does cause genetic damage. These have also been shown in humans exposed to environmental levels of EMF in both ELF and RFR ranges [168–171]. Conceivably, similar genetic effects could happen in other species living in similar environments.

This body of genetics work goes against the pervasive myth that low-level, low-intensity nonionizing radiation cannot cause detrimental genetic effects. That premise is in fact the bedrock belief upon which vested interests and government agencies rely in support of current exposure standards. But in fact, biological systems are far more complex than physics models can ever predict [6, 8, 172]. A new biological model is needed because today's exposures no longer fit that framework [173] for humans and wildlife. Enough research now indicates a reassessment is needed, perhaps including the very physics model used to back those traditional approaches (see Part 1).

Direct mechanisms: DNA as fractal antennas, cell membranes, ion channels

DNA as fractal antennas

There are several likely mechanisms for DNA damage from nonionizing radiation far below heating thresholds, both direct and indirect, intracellular, intercellular, and extracellular. Such mechanisms potentially apply to all wildlife. One direct mechanism theorizes that DNA itself acts as a fractal antenna for EMF/RFR [174], capable of receiving information from exogenous exposures.

According to Blank and Goodman [174], DNA has interesting electrical characteristics due to its unique structure of intertwined strands connected by rungs of molecules called nucleotides (also called bases), with each rung composed of two nucleotides (one from each strand) in bonded pairs. The nucleotides are held together by hydrogen bonds in close proximity that results in a strong attraction between the two strands. There are electrons on both molecular surfaces making the symmetrical nucleotides capable of conducting electron current along the entire DNA chain, a phenomenon called electron transfer. This makes DNA a most efficient electrical conductor, something not lost on nanotechnology researchers.

DNA may also act as an efficient fractal antenna due to its tightly packed shape within the cell nucleus. Blank and Goodman [174] characterized DNA properties in different frequency ranges, and considered electronic conduction within DNA's compact construction in the nucleus. They concluded that the wide frequency range of observed interactions seen with EMF is the functional characteristic of a fractal antenna, and that DNA itself possesses the two structural characteristics of fractal antennas — electronic conduction and self symmetry. They noted that these properties contribute to greater reactivity of DNA with EMF in the environment, and that direct DNA damage could account for cancer increases, as well as the many other biological effects seen with EMF exposures.

A fractal is a self-repetitive pattern of sometimes geometric shapes, marked by a larger originating design progressing to small identical designs with a potentially unlimited periphery. Each part of the shape looks like the whole shape. Fractal designs are quite common in nature, e.g., in snail/mollusk shells, some deciduous tree leaves and conifer needles, pine cones, many flowering plants, some reptile scales, bird feathers and animal fur patterns, snowflakes, and crystals forming on cold winter glass windows. Minerals — both inert and biological — can also be fractals.

The varying sizes within fractals are what make them inherently multi-frequency. By mimicking nature, repetitive fractal patterns are also designed into mechanical transceiver antennas that radiate in multiband frequencies with more or less efficiency [175]. Cell phones, WiFi, digital TV, and many other transceivers use fractal antennas to operate.

The complex twisted shape and coiled structure of DNA — small coils coiled into larger coils, or *coiled coils*, which Blank and Goodman [174] note that no matter how far you zoom in or out, the shape looks the same — is the exact structure of a fractal that maximizes the length of an antenna within a compact space while boosting multi-frequency signals. As such, DNA may be acting as a hidden intracellular biological fractal capable of interacting with exogenous EMF across a range of frequencies. In fact, one of DNA's fundamental functions may be specifically to interact with exogenous natural energy and as such may be more sensitive to EMF than other larger protein molecules within any living system. Once thought safely tucked away and protected within the nucleus, DNA may be acting as a most efficient electrical conductor at the nexus of all life. This interesting theory, unfortunately, has not been followed up by others to test its biological validity although fractals have been mimicked widely in technology.

Cell membranes/ion channels

Another direct effect from EMF is at the cell membrane itself. While DNA is life's fundamental building block, cells are DNA's complex electron-coherent architectural expression. The cell's membrane is far more than just a boundary. It is rather the most important ordering tool in the biological space between intracellular and extracellular activities, "… a window through which a unitary biological element can sense its chemical and electrical environment" [176]. And it is replete with microcurrent.

The cell's outer surface contains molecules that receive innumerable electrochemical signals from extracellular activities. Specific binding portals on the cell membrane set in motion a sequence leading to phosphorylation of specific enzymes that activate proteins for cellular 'work.' That includes everything from information processing in the central nervous system, mechanical functions such as muscle movements, nutrient metabolism, and the defense work of the immune system, among many others including the production of enzymes, hormones, antibodies, and neurotransmitters [177]. Complex microcurrent signaling pathways exist from the cell's outside to the inside via protein intramembraneous particles in the phospholipid plasma membrane. These convey information on external stimuli to the cell's interior to allow cellular function.

The cell membrane also has electrical properties. Microcurrent constantly moves from the interior to the exterior and vice versa of the cell membrane. According to Adey and Sheppard [176], some of these properties influence proteins that form voltage gated membrane channels, which is one way that cells control ion flow and membrane electromagnetic potential essential to life. There are specific windows that react according to frequency, amplitude, and duration differences, indicating a nonlinear and non-equilibrium character to exogenous exposures on cells [177–185].

Some pulsed fields are more biologically active than non-pulsed fields and different forms of pulsing also create different effects. As far back as 1983, Goodman et al. [186] found pulsed weak electromagnetic fields modified biological processes via DNA transcription when a repetitive single pulse and the repetitive pulse train were used. The single pulse increased the specific activity of messenger RNA after 15 and 45 min while the pulse train increased specific activity only after 45 min of exposure. Digital technology simulates pulsing and is the most common form of environmental exposure today.

Cellular calcium ion channels have long been of interest and may be particularly sensitive targets for EMFs due to possible increased calcium flux through the channels which can lead to secondary responses mediated through Ca^{2+}/calmodulin stimulation of nitric oxide synthesis, calcium signaling, elevated nitric oxide (NO), NO signaling, peroxynitrite, free radical formation, and oxidative stress — many with implications to DNA as hypothesized by Pall [187]. Calcium is essential to signal transduction between cells and is significant to everything from metabolism, bone/cell/blood regeneration, hormone production and neurotransmissions among many others. These cellular calcium responses to EMF indicate an artificial change in the signaling processes at the cell membrane — considered a switchboard for information between the exterior environment and intracellular activities that guide cell differentiation and control growth [188].

Pall [187] cited 23 studies of effects to voltage gated calcium channels (VGCC) and noted nonthermal mechanisms were the most likely since many studies showed effects were blocked by calcium channel blockers (widely prescribed for heart irregularities having nothing to do with thermal issues). Pall [189] noted that many other studies showed EMF changes in calcium fluxes and intracellular calcium signaling. He hypothesized that alterations in intracellular calcium activity may explain some of the myriad biological effects seen with EMF exposure, including oxidative stress, DNA breaks, some cancers, infertility, hormonal alterations, cardiac irregularities, and diverse neuropsychiatric effects. These end points need further study and verification.

There is much to be learned about calcium effects as studies are contradictory. Changes in free radicals (see below) also affect calcium metabolism. There are more studies showing EMF effects on free radicals than calcium changes. Calcium activates the nitric oxide free radical pathway but there are only a few studies of this pathway following EMF exposure — less than 5% of EMF-oxidative change studies are on nitric oxide mechanisms. Also of interest is the fact that power density and frequency windows were seen in early research at rising harmonic increments along the electromagnetic spectrum beginning in the ELF bands [190–195]. Observed effects were quite dramatic in what researchers described as calcium efflux or ‘dumping’ from cells. The most dramatic effects were seen at 180 Hz in the ELF range. This appears to contradict Pall’s work [189] cited above as increased calcium efflux is the opposite of what Pall’s hypothesis would predict, e.g., calcium *influx*. With more research both calcium influx and efflux effects may be found to be caused by different variables and/or EMF exposures.

In addition, exogenous signaling characteristics are also important to how cells react to both ELF and RFR ranges. Building on the work that demonstrated carrier waves of 50 and 147 MHz, when sinusoidally amplitude modulated at 16 Hz ELF in *in vitro* chick brain tissue [190, 191] and in live awake cat brain models [196] that created frequency windows for calcium efflux, Blackman et al. [194] additionally found that signaling *characteristics* were also significant. Research showed that calcium efflux occurred only when tissue samples are exposed to specific intensity ranges of an ELF-modulated carrier wave; unmodulated carrier waves did not affect ion efflux. Blackman et al. [194] further wrote that cells may be capable of demodulating signals. The authors reported that 16-Hz sinusoidal fields, in the absence of a carrier wave, altered the efflux rate of calcium ions and showed a frequency-dependent, field-induced enhancement of calcium-ion efflux within the ranges 5–7.5 V/m and 35–50 V/m (peak-to-peak incident field in air) with no enhancement within the ranges 1–2, 10–30, and 60–70 V/m. This body of work indicates that living cells interact with, and are capable of taking direction from, exogenous fields in far more complex ways than ever imagined, at intensities barely above background levels. This work may be particularly important to new technology that turns previously wired ELF frequencies into wireless applications, such as “wireless electricity” to charge electric cars.

Blackman et al. [197] found for the first time a link between the ELF/EMF being studied and the density of the natural local geomagnetic field (LGF) in the production of a biological response. Calcium efflux changes could be manipulated by controlling the LGF along with ELF and RF-EMF exposures. In a local geomagnetic field at a density of 38 μT, 15- and 45-Hz electromagnetic signals had been shown to induce calcium ion efflux from the exposed tissues, whereas 1- and- 30-Hz signals did not. Bawin and

Adey [190] found a reduction in efflux when using an electric field; Blackman et al. [194] found an increase when using an electromagnetic field, thus identifying/isolating for the first time the significance of the magnetic field component in exposure parameters. Building on the window ranges noted above, Blackman et al. [197] demonstrated that the enhanced calcium efflux field-induced 15-Hz signal could be rendered ineffective when the LGF is reduced to 19 μT with Helmholtz coils. In addition, the ineffective 30-Hz signal became effective when the LGF was altered to k25.3 μT or to +76 μT. *The results demonstrated that the net intensity of the local geomagnetic field is an important cofactor in biological response and a potentially hidden variable in research.* The results, they noted, appear to describe a resonance-like relationship in which the frequency of the electromagnetic field can induce a change in calcium efflux proportional to LGF density (see Liboff [198, 199] below for more detail).

The bottom line is that changes of this magnitude at the cellular level — be it directly to DNA within the nucleus or via voltage gated channels at the cell's membrane — can lead to direct effects on DNA within and across species. The evidence cited above illustrates the degree, likelihood, and variety of impacts from EMF directly on cellular physiology that are capable of affecting DNA in all living systems in myriad ways.

Indirect mechanisms: free radicals, stress proteins, resonance, Earth's geomagnetic fields

Free radicals

An indirect, or secondary, mechanism for DNA damage would be through free radical formation within cells, which is the most consistently reported with both ELF and RFR exposures under many different conditions in biological systems. According to Phillips et al. [139], free radicals may also interact with metals like iron [142, 151, 152, 158] and play a role in genotoxic effects from something called the Fenton effect — a process "…catalyzed by iron in which hydrogen peroxide, a product of oxidative respiration in the mitochondria, is converted into hydroxyl free radicals, which are very potent and cytotoxic molecules" [139].

The significance of free radical processes may eventually answer some questions regarding how EMF interacts with biological systems. There are about 200–300 papers showing EMF effects on free radicals [77, 168, 200]. Free radicals are important compounds involved in numerous biological functions that affect many species. Increases in free radicals explain effects from damage to macromolecules such as DNA, protein, and membrane lipids; increased heat shock proteins; neurodegenerative diseases; and many more.

Yakymenko et al. [168] published a review on oxidative stress from low-level RFR and found induced molecular effects in living cells, including significant activation of key pathways generating reactive oxygen species (ROS), activation of peroxidation, oxidative damage in DNA, and changes in the activity of antioxidant enzymes. In 100 peer-reviewed studies, 93 confirmed that RFR induced oxidative effects in biological systems and that their involvement in cell signaling pathways could explain a high pathogenic range of biological/health effects. They concluded that low-intensity RFR should be recognized as one of the primary mechanisms of biological activity of nonionizing radiation. In a follow-up study, Yakymenko et al. [200] investigated the oxidative and mutagenic effects of low intensity GSM 1,800 MHz RFR on developing quail embryos exposed *in ovo* (0.32 $\mu W/cm^2$, 48 s On, 12 s Off) during 5 days before and 14 days through the incubation period. They found statistically significant oxidative effects in embryonic cells that included a 2-fold increase in superoxide generation rate, an 85% increase in nitrogen oxide generation, and oxidative damage to DNA up to twice the increased levels of 8-oxo-dG in cells of 1-day old chicks. RFR exposure almost doubled embryo mortality and was statistically significant. They concluded that such exposures should be recognized as a risk factor for living cells, including embryonic integrity.

Lai [77] focused a review on static magnetic field ELF-EMF and found that changes in free radical activities are one of the most consistent effects. Such changes can affect numerous physiological functions including DNA damage, immune system and inflammatory response, cell proliferation and differentiation, wound healing, neural electrical activities, and behavior. Given that many species have proven sensitive to natural static geomagnetic fields and use such information in critical survival skills, some wildlife species may also be adversely affected via free radical alterations from anthropogenic exposures. But Lai [77] noted the inherent contradictions from EMF-induced changes in free radicals, particularly on cell proliferation and differentiation since those processes can affect cancer development as well as growth and development. Induced free-radical changes may therefore have therapeutic applications in killing cancer cells via the generation of the highly cytotoxic hydroxyl free radical by the Fenton Reaction (noted above), thereby creating a non-invasive low-side-effect cancer therapy.

Stress proteins

Another potentially indirect effect to DNA is via protein synthesis required by all cells to function. A living animal converts animal and plant proteins that it ingests into other proteins needed for life's activities — antibodies, for instance, are a self-manufactured protein. DNA is critical to protein synthesis and can create in humans about 25,000 different kinds of proteins with which the body can then create 2,000,000 types in order to fully function.

There are many different classes of proteins. These include stress proteins stimulated by potentially harmful environmental factors to help cells cope and repair damage due to factors like acute temperatures, changes in oxygen levels, chemicals/heavy metals exposure, viral/bacterial infections, ultraviolet light and other ionizing and nonionizing radiation exposures [124].

The presence of stress proteins indicates healthy repair action by an organism and is considered beneficial up to a point as a protective mechanism. According to Blank and Goodman [201], "The 20 different stress protein families are evolutionarily conserved and act as 'chaperones' in the cell when they 'help' repair and refold damaged proteins and transport them across cell membranes. Induction of the stress response involves activation of DNA." Stress proteins are also considered a yardstick to determine what living cells experience as stress that requires remediation in the first place — something not always obvious, especially with subtle environmental exposures like low-level EMF barely above natural background levels.

Whether an effect is thermal or nonthermal, adverse or simply observed biologically, has been subject to fierce debate for decades; thus tissue-heating DNA pathways are also central to this paper. Heat as a cellular stressor was first observed in the 1960s by Italian researcher Ferruccio Ritossa in fruit flies (*D. melanogaster*) when experimental temperatures were accidentally raised by a few degrees and he observed enlarged chromosomes at particular sites. (*Drosophilae* are often used in research because they only have four pairs of chromosomes, are relatively easy to work with, have a fast breeding cycle, and lay numerous eggs.) As cited in Blank [124], as Ritossa's observation became better understood, with effects subsequently seen over decades in animals, plants and yeast cells, it came to be called the "heat shock response." Extensive research established that the heat shock response lead to the formation of a unique protein class — heat shock proteins (HSP) that repair other proteins from potentially fatal temperature damage, as well as assist cells to be more thermo-tolerant. Research has gone on to prove that cells produce other similar proteins to various stressors, now generally called stress proteins but most are still categorized as "HSP" from the original demarcation.

Goodman and Blank [202, 203] found that EMF is a cellular stressor even at low intensities in the absence of elevated temperatures. They found the protein distribution patterns synthesized in response to ELF-EMF resembled those of heat shock with the same sequence of changes even though the energy of the two stimuli differed by many orders of magnitude. Their results indicated that ELF-EMF stimulates a similar gene expression pathway as that of thermal shock and is itself a cellular stressor. Of particular significance is the fact that over-expression of stress genes is found in a number of human tumors and is characteristic of a variety of neoplasia [202]. Increased stress proteins are seen in numerous animal model studies pertinent to wildlife.

Blank and Goodman [201] further noted that both ELF and RFR activate the cellular stress response despite the large energy difference between them; that the same cellular pathways respond in both frequency ranges; and that models suggest that EMF can interact directly with electrons in DNA. They note that low energy EMF interacts with DNA to induce the stress response while the increased energy in RFR can lead to DNA strand breaks. *As such, this makes the stress response a frequency-dependent direct and indirect cause of DNA damage — a significant finding.* They concluded that exposure standards should not be based on exposure intensity alone but on biological responses long before thermal thresholds are met or crossed.

Resonance and geomagnetic fields

There are other important direct and indirect ways that EMFs interact with and effect biological systems, including various forms of resonance — cyclotron, electron paramagnetic, nuclear, and stochastic — as well as through inherently produced biological materials such as magnetite found in bird brains and many other species (see below).

Resonance is the phenomenon that occurs when a certain aspect of a force (like a frequency wave) matches a physical characteristic (like a cell or whole living organism) and the power inherent in the force is transferred to the physical object causing it to resonate or vibrate. Within the object, the resonance is self-perpetuating. The classic example is of an opera singer hitting high C in the presence of a crystal goblet for a sustained period until it shatters.

Following the work of Blackman et al. [197] who found the Earth's local geomagnetic fields (LGF) could influence calcium ions moving through membrane channels (see above), Liboff [198, 199] proposed that cyclotron resonance was a plausible mechanism for coupling interactions between the LGM and living cells. Liboff found cyclotron resonance consistent with other indications that showed many membrane channels have helical configurations; that the model could apply to other circulating charged components within the cell; and that cyclotron resonance could lead to direct resonant electromagnetic energy transfer to selected cell compartments.

All resonance is based on a *relationship*. Cyclotron resonance is based on the relationship between a constant magnetic field and an oscillating (time-varying) electric or magnetic field that can affect the motion of charged particles such as ions, some molecules, electrons, atomic nuclei, or DNA in living tissue. Living systems are filled with charged particles necessary for life, including calcium, sodium, lithium, and potassium ions that all pass through the cell membrane and are capable of affecting DNA. Cyclotron resonance occurs when an ion is exposed to a steady magnetic field (such as the Earth's) which causes the ion to move in a circular orbit at a right angle to the field. The speed of the orbit is determined by the charge and mass of the ion and the strength of the magnetic field. If an electric field is added that oscillates at exactly the same frequency and that is also at a right angle to the magnetic field, energy will be transferred from the electric field to the ion causing it to move faster. The same effect can be created by applying an additional magnetic field parallel to the constant magnetic field. This is important because it provides a plausible mechanism for how living cells interact with both natural and artificial fields, and explains how vanishingly low levels of EMFs can create major biological activity when concentrated on ion particles. It also points to living systems' ability to demodulate — or take direction from — certain aspects of electromagnetic information from both natural and artificial exposures [7]. Resonance should not be underestimated. It applies to all frequencies and is not based on power density alone.

Another subtle energy relationship in biology is called stochastic resonance that has been determined to be significant in how various species interact with their natural environments, in some instances for their survival. Stochastic resonance is a phenomenon where a signal below normal sensing can be boosted by adding wide-spectrum white noise signals. The frequencies in the white noise that match the original signal's frequencies will resonate with each other and amplify the original signal while not amplifying the rest of the white noise. This increase in what is called the signal-to-noise ratio makes the original signal more prominent. Some fish, for instance, can "hear" predators better in the noise of running water than in still water due to stochastic resonance (see "Fish" below.).

The signal-to-noise ratio has been a prominent aspect of EMF research with some scientists long holding that energy exposures below the body's natural signal-to-noise ratio could not possibly damage living tissue. But the most recent research that finds effects to DNA from low intensity EMF indicates that many variables affect biological processes, often in nonlinear patterns far below the signal-to-noise ratio. Some of the most cutting edge research — with an eye toward treating human *in utero* birth defects and adult limb regeneration — is being done by manipulating the electric charge across cell membranes (called membrane potential) via intentional manipulation of genes that form ion channels. Pai et al. [204] found that by putting ion channels into cells to raise the voltage up or down, they could control the size and location of the brain in embryonic African clawed frogs (*Xenopus laevis*), thus demonstrating the importance of microcurrents on membrane potential in growth and development. The research group also studied endogenous bioelectricity on clawed frog brain patterning during embryogenesis, noting that early frog embryos exhibit a characteristic hyperpolarization of cells lining the neural tube. Disruption of this spatial gradient of the transmembrane potential (V_{mem}) diminished or eliminated the expression of early brain markers in frogs, causing anatomical mispatterning, including absent or malformed regions of the brain. This effect was mediated by voltage-gated calcium signaling and gap-junctional communication. The authors hypothesized that voltage modulation is a tractable strategy for intervention in certain classes of birth defects in humans but they did not make the leap to potential environmental damage to other species from such ambient exposures.

In general, whether direct, indirect, or synergistic, to understand ambient effects to wildlife, one also needs to know if effects are cumulative, what compensatory mechanisms a species may have, and when or if homeostasis will deteriorate to the point of no return [205]. In looking at environmental contaminants, we have historically focused on chemicals for both direct and indirect effects such as endocrine disruption. But primary biological manifestation is more physical than chemical since the only thing that distinguishes one chemical from another on the Periodic Table is the amount of electrons being traded up and down on the scale. Chemicals are actually secondary manifestations of initial atomic principles, not the other way around. Plus, the synergistic effects of the Earth's natural fields can no longer be dismissed as an interesting artifact that is not biologically active or relevant. All living systems are first and foremost expressions of biological energy in various states of relationship.

For a Table of more low-level effects studies on DNA, see Part 2, Supplements 1 and 2.

What the studies show

The literature is voluminous on EMF effects to nonhuman species, going back at least to the 1930s using modern methods of inquiry. We have, after all, been using animal, plant, and microbial models in experiments for decades. We may in fact know *less* about effects to humans than to other species.

In this paper, we focused on exposures common in today's environment. In Part 1, Rising Background Levels, we defined low level RFR as power density of 0.001 mW/cm^2 (1 μW/cm^2), or a SAR of 0.001 W/kg. Part 2 Supplements 3 and 4 contain extensive tables with pertinent studies that apply to fauna and flora, respectively. The sections that follow in Part 2 on individual species include selected studies of particular interest to how EMF couples with, and potentially affects, wildlife. In most studies, as illustrated in Part 2, Supplement 3, the intensity of the incident EMF was provided in μW/cm^2 or V/m. To be consistent throughout the paper, we converted intensity in the studies to μW/cm^2. However, such conversion (i.e. V/m to μW/cm^2) tends to overestimate the exposure level and does not represent the full picture. Therefore where studies provided the amount of energy absorbed, e.g., the specific absorption rate (SAR), they were also included in Supplement 3 (in W/kg). Very low levels of energy absorption have shown effects in all living organisms studied.

Levitt and Lai [167] reported numerous biological effects from RFR at very low intensities and SARs comparable to far-field exposures within 197–492 ft (60–150 m) from cell towers. Included were *in vivo* and *in vitro* low-intensity RFR studies. Effects included genetic, growth and reproductive changes; increased permeability of the blood brain barrier; changes in stress proteins; behavioral responses; and molecular, cellular, genetic, and metabolic alterations. All are applicable to migratory birds, mammals, reptiles, and other wildlife and to plant communities, and to far-field exposures in general. (An update of that table appears in Part 2 Supplement 3.) It is apparent that environmental levels of RFR can elicit biological/health effects in living organisms. Although there are not enough data on low-intensity effects of static ELF-EMF to formulate a separate table, some effects of low-intensity static ELF-EMF are also described throughout this paper. ELF genotoxic effects can be found in Part 2, Supplement 2 and ELF in flora are also listed separately in Part 2, Supplement 4.

Effects, however, do not easily translate from the laboratory to the field. Cucurachi et al. [31] reported on 113 studies with a limited number of ecological studies. The majority were conducted in laboratory settings using bird embryos or eggs, small rodents, and plants. In 65% of the studies, effects from EMF (50% of the animal studies and about 75% of the plant studies) were found at both high and low intensities, indicating broad potential effects. But lack of standardization among the studies and limited sampling size made generalizing results from organism to ecosystem difficult. The researchers concluded that due to the number of variables, no clear dose–response relationship could be determined. Nevertheless, effects from some studies were well documented and can serve as predictors for effects to wild migratory birds and other wildlife.

As noted elsewhere throughout this paper, living organisms can sense and react to very low-intensity electromagnetic fields necessary for their survival as seen, for instance, in studies by Nicholls and Racey [206, 207] on bats and many others. Bats are already in serious trouble in North America from white-nosed syndrome and commercial wind turbine blade collisions. Due to the increased use of tracking radars for bird and bat studies, impacts will likely only increase [22, 23]. Presence of low levels of RFR from tracking radars could adversely affect bat foraging activity, which in turn could affect the composition of insect populations in the vicinity. Many insects, including honey bees (*Apis mellifera* var) and butterflies also depend on the Earth's electromagnetic fields for orientation and foraging. Presence of exogenous RFR can disturb these functions. This is particularly relevant for pollinator insects, such as bees and butterflies. Pollinators are essential in producing commercial crops for human consumption, including almonds, apples, pears, cherries, numerous berry crops, citrus fruits, melons, tomatoes, sunflowers, soybeans, and much more. The strongest disruptive effect to insect pollinators occurs at 1.2 MHz known as the Larmor frequency [208] which is related to radical pair resonance and superoxide radical formation. This is an important indication that effects from RFR are frequency-dependent.

Lai [77], citing Shepherd et al. [209], noted that EMF can disrupt the directional sense in insects. The fact that many animals are able to differentiate the north and south poles of a magnetic field known as the polarity compass [68, 73, 134, 210, 211] indicates they are susceptible to having that important sense impaired. These polarity compass traits confer survival competitiveness to organisms but are of particular concern since directional cues can be easily disturbed by man-made EMF [69, 134, 212].

Bird migration also depends on proper sensing and orientation to natural electromagnetic fields. A study by Engels et al. [213] showed that magnetic noise at 2 kHz–9 MHz (within the range of AM radio transmission) could disrupt magnetic compass orientation in migratory European Robins (*Erithacus rubecula*). The disruption can occur at a vanishingly low level of 0.01 V/m, or 0.0000265 μW/cm^2. Similar effects of RFR interference on magnetoreception have also been reported in a night-migratory songbird [214] and the European Robin [126]. Migration is already a taxing and dangerous activity for birds; adding another potential negative impact to bird survival is troubling.

Lai [77] also noted that another consideration is the “natal homing behavior” exhibited in some animals that return to their natal birth places to reproduce. These include sea turtles [89] eels [90]; and salmon [91]. Newborns of these animals are imprinted with the memory of the intensity and the inclination angle of the local geomagnetic field, later used to locate their place of birth when they return to breed. There are indications that man-made EMF can distort this imprinting memory to locate the site (see “Fish” and “Turtles”below). This has important consequences to the survival of particular species since it interrupts their reproductive processes.

It is clear that biological effects can occur at levels of man-made RFR in our present environment, thereby conceivably altering delicate ecosystems from a largely unrecognized danger.

Mammals

The majority of EMF laboratory research, some going back to the 1800s, has been conducted on a variety of mammal species using mice, rats, rabbits, monkeys, pigs, dogs, and others. (The second and third most used models are on insects and yeast respectively.) Thus, with varying degrees of confidence, we know a significant amount about how energy couples with, and affects, laboratory mammalian species across a range of frequencies. However, this evidence does not automatically transfer at the same confidence level regarding how this vast body of research applies to wildlife, including mammalian species.

There is unfortunately a dearth of field research on EMF effects to wildlife. Referenced below, however, are many potential indicator studies. The effects seen include reproductive, behavioral, mating, growth, hormonal, cellular, and others.

Rodents

Rodents are the most frequently used mammalian species in laboratory research across a range of frequencies and intensities. While studies are inconsistent, there are enough troubling indications regarding potential EMF implications for wildlife.

In the RFR range, there have been several reviews of fertility and other issues in rodent models with citations too numerous to mention here — see La Vignera e al. [215] and Merhi [216] — but some stand out as potentially pertinent to wildlife.

Magras and Xenos [217] investigated effects of RFR on prenatal development in mice, using RFR measurements and *in vivo* experiments at several locations near an "antenna park," with measured RFR power densities between 0.168 and 1.053 μW/cm^2. Divided into two groups were 12 pairs of mice, placed in locations of different power densities, and mated five times. One hundred eighteen newborns were collected, measured, weighed, and examined macro- and microscopically. With each generation, researchers found a progressive decrease in the number of newborns per dam ending in irreversible infertility. However, the crown-rump length, body weight, and number of lumbar, sacral, and coccygeal vertebrae, was improved in prenatal development of some newborns. RFR was below exposure standards and comparable to far-field exposures that mice could experience in the wild.

Aldad et al. [218], in a laboratory setting, investigated cell phone RFR (800–1,900 MHz, SAR of 1.6 W/kg) exposures in *in-utero* mouse models and effects on neurodevelopment and behavior. They found significant adult behavioral effects in prenatally exposed mice vs. controls. Mice exposed *in-utero* were hyperactive, had decreased memory and anxiety, and altered neuronal developmental programming. Exposed mice had dose-response impaired glutamatergic synaptic transmission onto layer V pyramidal neurons of the prefrontal cortex. This was the first evidence of neuropathology in mice from *in-utero* RFR at cell phone frequencies, now the most prevalent in the environment. Effects persisted into adulthood and were transmissible to next generations. Such changes can affect survival in wild populations.

Meral et al. [219] looked at effects in guinea pigs (*Cavia parcels*) from 900 MHz cell phone frequency exposures on brain tissue and blood malondialdehyde (MDA), glutathione (GSH), retinol (vitamin A), vitamin D(3) and tocopherol (vitamin E) levels, as well as catalase (CAT) enzyme activity. Fourteen male guinea pigs were randomly divided into control and RFR-exposed groups containing seven animals each. Animals were exposed to 890- to-915 MHz RFR (217 Hz pulse rate, 2 W maximum peak power, SAR 0.95 W/kg) from a cellular phone for 12 h/day (11 h 45 min stand-by and 15 min spiking mode) for 30 days. Controls were housed in a separate room without cell phone radiation. Blood samples were collected through cardiac puncture; biochemical analysis of brain tissue was done after decapitation at the end of the 30-day period. Results found MDA levels increased ($p<0.05$), and GSH levels and CAT enzyme activity decreased, while vitamins A, E and D(3) levels did not change significantly in the brain tissue of exposed animals. In blood samples of the exposed group, MDA, vitamins A, D(3) and E levels, and CAT enzyme activity increased ($p<0.05$), while GSH levels decreased ($p<0.05$). They concluded that cell phone radiation could cause oxidative stress in brain tissue of guinea pigs but more studies were needed to determine if effects are harmful and/or affect neural functions.

Lai et al. [220] found that Sprague-Dawley rats exposed to RFR during water maze testing showed spatial working memory deficits compared to controls. But similar studies [221–223] did not find performance effects in spatial tasks or alterations in brain development after similar exposures. However, subsequent studies in the last two decades have shown memory and learning effects in animals and humans after RFR exposure [224].

Several studies also investigated RFR behavioral effects in rodent models on learning, memory, mood disturbances, and anxiety behaviors with contradictory results. Daniels et al. [225] found decreased locomotor activity, increased grooming and increased basal corticosterone levels in rats exposed to RFR for 3 h per day at 840 MHz, but no significant differences were seen between controls and test animals in spatial memory testing or morphological brain assessment. The researchers concluded that RFR exposure may lead to abnormal brain functioning.

Lee et al. [226, 227] looked specifically at effects on pregnant mice and rat testicular function from combined RFR mobile network signal characteristics used in wideband code division multiple access (W-CDMA) or CDMA used in 3G mobile communications. Experiments showed no observable adverse effects on development, reproduction, or mutation in tested subjects. And no significant effects were seen by Poulletier de Gannes et al. [228] in *in-utero* and post-natal development of rats with wireless fidelity (WiFi) at 2,450 MHz. Also, Imai et al. [229] found no testicular toxicity from 1.95 GHz W-CDMA.

One extremely high frequency (EHF) study comparable to 5G on a mouse model by Kolomytseva et al. [230] looked at leukocyte numbers and the functional activity of peripheral blood neutrophils. In healthy mice, under whole-body exposures to low-intensity extremely-high-frequency electromagnetic radiation (EHF, 42.0 GHz, 0.15 mW/cm^2, 20 min daily) found that the phagocytic activity of peripheral blood neutrophils was suppressed by about 50% ($p<0.01$ as compared with the sham-exposed control) in 2–3 h after the single exposure. Effects persisted for 1 day and thereafter returned to normal within 3 days. But a significant modification of the leukocyte blood profile was observed in mice exposed to EHF for 5 days after exposure cessation. Leukocytes increased by 44% ($p<0.05$ as compared with sham-exposed animals). They concluded that EHF effects can be mediated via metabolic systems and further said results indicated whole-body low-intenstiy EHF exposure of healthy mice had a profound effect on the indices of nonspecific immunity. These low levels will be common near 5G infrastructure.

In well-designed non-rodent mammal field studies, Nicholls and Racey [206, 207], found that foraging bats showed aversive behavioral responses near large air traffic control and weather radars. Four civil air traffic control (ATC) radar stations, three military ATC radars and three weather radars were selected, each surrounded by heterogeneous habitat. Three sampling points were carefully selected for matched habitats, type, structure, altitude and surrounding land class at increasing distances from each station. Radar field strengths were taken at three distances from the source: close proximity (<656 ft/200 m) with a high EMF strength >2 V/m (1.06 μW/cm^2), an intermediate line-of sight point (656–1,312 ft/200–400 m) with EMF strength <2 V/m, and a control location out of radar sight (>1,312 ft/400 m) registering 0 V/m. Bat activity was recorded three times for a total of 90 samples, 30 within each field strength category. Measured from sunset to sunrise, they found that bat activity was significantly reduced in habitats exposed to an EMF greater than 2 V/m compared to 0 EMF sites, but such reduced activity was not significantly different at lower EMF levels within 400 m of the radar. They concluded that the reduced bat activity was likely due to thermal induction and an increased risk of hyperthermia. This was a large field study near commercial radar installations with mostly high intensity exposures but low-level effects cannot be excluded given known magneto-sensitivity in bats.

In another field study using a small portable marine radar unit significantly less powerful than their earlier measured field study, Nicholls and Racey [207] found the smaller signal could also deter bats' foraging behaviors. First, in summer 2007, bat activity was compared at 20 foraging sites in northeast Scotland during experimental trials with radar switched on, and in controls with no radar signal. After sunset, bat activity was recorded for a period of 30 min with the order of the trials alternating between nights. Then in summer 2008, aerial insects were sampled at 16 of the sites using two small light-suction traps, one with a radar signal, the other a control. Bat activity and foraging were found significantly reduced when the radar signal was unidirectional, creating a maximized exposure of 17.67–26.24 V/m (83–183 μW/cm^2). The radar had no significant effect on the abundance of insects captured by the traps despite reduced bat activity.

Balmori [231] also noted significantly reduced bat activity in a free-tailed bat colony (*Tadarida teniotis*) where the number of bats decreased when several cell towers were placed 262 ft (80 m) from the colony.

In the ELF range, Janać et al. [232] investigated ELF/MF effects — comparable to powerline and stray voltage ground current — on motor behavior patterns in Mongolian gerbils (*Meriones unguiculatus)* and found age-dependent changes in locomotion, stereotypy, and immobility in 3- and 10-month-old males. Animals were continuously exposed to ELF-MF (50 Hz; 0.1, 0.25 and 0.5 mT) for seven days with behavior monitored for 60 min in the open field after the 1st, 2nd, 4th, and 7th day (to capture immediate effects), as well as three days after exposure (to capture delayed effects). They found that exposure to 3-month-old gerbils increased motor behavior (locomotion and stereotypy), and therefore decreased immobility. In the 3-month old gerbils, ELF/MF also showed a delayed effect (except at 0.25 mT) on stereotypy and immobility. In 10-month-old gerbils, ELF/MF of 0.1, 0.25 and 0.5 mT induced decreased locomotion, a slight increase in stereotypy, and pronounced stimulation of motor behavior. Increased motor behavior was observed three days after exposure, indicating long lasting effects. Researchers concluded that in 3- and 10-month-old gerbils, specific temporal patterns of motor behavior changes were induced by ELF/MF due to age-dependent morpho-functional differences in brain areas that control motor behavior.

The above is a very small sample of rodent studies. See Part 2 Supplements 1 and 2 for more genetic effects to rodents, and Supplement 3 for additional studies.

Bovines

Due to domestication and easy accessibility, there are numerous studies of dairy cows (*Bos taurus*) which appear particularly sensitive to both natural and man-made EMFs. Fedrowitz [71] published a thorough review with citations too numerous to mention here. Noted in the review is the fact that bovines, although easily accessible, are difficult to study with precision due to their size, which creates handling and dosimetric complexities. Also noted are that bovines today are at their milk- and beef-production physiological limits, and that the addition of even a weak stressor may be capable of altering a fragile bovine physiological balance. It is clear in the Fedrowitz review that cows respond to environmental exposures from a broad range of frequencies and properties, even as some studies lack good exposure assessment. RFR exposure created avoidance behavior, reduced ruminating and lying times, and alterations in oxidative stress enzymes among other problems, while ELF-EMF found contradictory evidence affecting milk production, fat content, hormone imbalances and important changes in other physiological parameters. Cows have also been found sensitive to stray voltage and transient harmonics with problematic milk production, health, reproduction and behavioral effects.

The question is how much of this body of work could translate to other ruminants and large mammals on-field or in the wild such as deer/cervids — behaviorally, reproductively, and physiologically. Stray voltage and ELF-EMF near powerlines, and rural area RFR from both ground-based and satellite transmitters, for instance, may affect wild migratory herds and large ungulates in remote areas that go undetected.

Bovines and RFR

Loscher and Kas [233] observed abnormal behavior in a dairy herd kept in close proximity to a TV and radio transmitter. They found reduction in milk yield, health problems, and behavioral abnormalities. After evaluating other factors, they concluded the high levels of RFR were possibly responsible. They removed one cow with abnormal behavior to another stable 20 km away from the antenna, resulting in normalization of behavior within five days. Symptoms reappeared when the cow was returned to the stable near the antennas. In a later survey, Loscher [234] also found effects of RFR on the production, health and behavior of farm animals, including avoidance behavior, alterations in oxidative stress parameters, and ruminating duration.

Balode [59] obtained blood samples from female brown cows from a farm close to, and in front of, the Skrunda Radar – located in Latvia at an early warning radar system operating in the 156–162 MHz frequency range — and samples from cows in a control area. They found micronuclei in peripheral erythrocytes were significantly higher in the exposed cows, indicating DNA damage.

Stärk et al. [235] investigated short-wave (3–30 MHz) RFR on salivary melatonin levels in dairy cattle, with one herd at a farm located at 1,640 ft/500 m (considered higher exposure) and a second control herd located 13,123 ft/4,000 m from the transmitter (considered unexposed). The average nightly magnetic field strength readings were 21-fold greater on the exposed farm (1.59 mA/m) than on the control farm (0.076 mA/m). At both farms, after initially monitoring five cows' salivary melatonin concentrations at 2-h intervals during night dark phase for 10 consecutive days, and with the short-wave transmitter switched off during three of the 10 days (off phase), samples were analyzed using a radioimmunoassay. They reported that mean values of the two initial nights did not show a statistically significant difference between exposed and unexposed cows and concluded that chronic melatonin reduction was unlikely. But on the first night of re-exposure after the transmitter had been off for three days, the difference in salivary melatonin concentration between the two farms (3.89 pg/ml, CI: 2.04, 7.41) was statistically significant, indicating a two-to-sevenfold increase of melatonin concentration. They concluded that a delayed acute effect of EMF on melatonin concentration could not be excluded and called for further trials to confirm results.

Hässig et al. [95] conducted a cohort study to evaluate the prevalence of nuclear cataracts in veal calves near mobile phone base stations with follow-up of each dam and its calf from conception through fetal development and up to slaughter. Particular emphasis was focused on the first trimester of gestation (organogenesis). Selected protective antioxidants (superoxide dismutase, catalase, glutathione peroxidase [GPx]) were assessed in the aqueous humor of the eye to evaluate redox status. They found that of 253 calves, 79 (32%) had various degrees of nuclear cataracts, but only 9 (3.6%) of calves had severe nuclear cataracts. They concluded that a relationship between the location of veal calves with nuclear cataracts in the first trimester of gestation and the strength of antennas was demonstrated. The number of antennas within 328–653 ft (100–199 m) was associated with oxidative stress and there was an association between oxidative stress and the distance to the nearest base station. Oxidative stress was increased in eyes with cataract (OR per kilometer: 0.80, confidence interval 95 % 0.62, 0.93). But the researchers further concluded that it had not been shown that the antennas actually affected stress. Hosmer-Lemeshow statistics showed an accuracy of 100% in negative cases with low radiation, and only 11.11% accuracy in positive cases with high radiation. This reflected, in their opinion, that there are a lot of other likely causes for nuclear cataracts beside base stations and called for additional studies on EMF during embryonic development.

Hässig et al. [96] further examined a dairy farm in Switzerland where a large number of calves were born with nuclear cataracts after a mobile phone base station was erected near the barn. Calves showed a 3.5 times higher risk for heavy cataracts if born there compared to the Swiss average. All usual causes for cataracts could be excluded but they nevertheless concluded that the incidence remained unknown.

Bovines and swine: ELF-EMF, stray electric current

Bovines appear unusually sensitive to ELF-EMF from stray current caused by both normal industrial and faulty grounding methods near high tension transmission lines close to dairy farms. Stray current can cover large areas and occurs when current flows between the grounded circuit conductor (neutral) of a farm and the Earth through dairy housing equipment like metal grates. It typically involves small, steady power frequency currents [99], not high transient shocks, although that also can sometimes occur under wet weather conditions. According to Hultgren [236], dairy cattle can perceive alternating currents exceeding 1 mA between the mouth and all four hooves with behavioral effects in cows usually occurring above 3 mA. Stray current can act as a major physical stressor in cows and other animals [237]. This may also be happening in wild migratory species moving through such areas.

At the request of dairymen, veterinarians, and county extension agents in Michigan, U.S., Kirk et al. [238] investigated stray current on 59 Michigan dairy farms. On 32 farms, stray current sources were detected. Where voltage exceeded 1 V alternating current, increased numbers of dairy cows showed abnormal behavior in the milking facility and increased prevalence of clinical mastitis. Recovery from the stray current-induced abnormalities was related to the type of abnormality and the magnitude of the exposure voltage.

Burchard et al. [239] in a small but well-controlled alternating exposure study of non-pregnant lactating Holstein cows found a longer estrous cycle in cows exposed to a vertical electric field of 10 kV/m and a uniform horizontal magnetic field of 30 μT at 60 Hz, compared to when they were not exposed. Rodriguez et al. [240] also found that exposure to EMF may increase the duration of the bovine estrous cycle. Burchard et al. [241] evaluated effects on milk production in Holsteins exposed to a vertical electric field of 10 kV/m and a uniform horizontal MF of 30 μT at 60 Hz and found an average decrease of 4.97, 13.78, and 16.39% in milk yield, fat corrected milk yield, and milk fat, respectively in exposed groups, and an increase of 4.75% in dry matter food intake. And Buchard et al. [242] in two experiments investigated blood thyroxine (T4) levels in lactating pregnant and non-lactating non-pregnant Holstein cows exposed to 10 kV/m, 30 μT EMF and found a significant change depending on the time of blood sampling in exposed groups. They concluded that exposure of dairy cattle to ELF-EMF could moderately affect the blood levels of thyroxine.

Hillman et al. [93, 94] reported that harmonic distortion and power quality itself could be another variable in bovine sensitivity to stray current. They found behavior, health, and milk production were adversely affected by transients at the 3rd, 5th, 7th, and triplen harmonic currents on utility power lines after a cell tower was found charging the ground neutral with 10+ V, causing the distortion. After installing a shielded neutral isolation transformer between the utility and the dairy, the distortion was reduced to near zero. Animal behavior improved immediately and milk production, which had been suppressed for three years, gradually returned to normal within 18 months.

Swine (*Sus scrofa domesticus*) — like rats and mice — have demonstrated aversive behavior to ELF-EMF electric fields. Hjeresen et al. [243] found miniature pigs, exposed to 60-Hz electric fields (30 kV/m for 20 h/day, 7 days/week up to 6 months) preferred an absence of the field during a 23.5-h period by spending more time out of the electric field than in it during sleep periods. And Sikov et al. [244], as part of a broad study of Hanford Miniature swine on reproductive and developmental toxicology (including teratology) over three breeding cycles found a strong association between chronic exposure to a vertical uniform electric field (60-Hz, 30-kV/m, for 20 h/day, 7 days/week) and adverse developmental effects vs. control. They concluded that an association exists between chronic exposure to strong electric fields and adverse developmental effects in swine (75% malformations in exposed vs. 29% sham) in first generation with consistent results in two subsequent generations.

Avian

Birds are important indicators of ecosystem well-being and overall condition. Even subtle effects can be apparent due to their frequent presence in RFR areas. Their hollow feathers have dielectric and piezoelectric properties, meaning they are conductive and capable of acting as a waveguide directing external RFR energy directly and deeply into avian body cavities [245–249]. Their thin skulls have both magnetite and radical pair receptors (see "Mechanisms" above) and they are highly mobile — often traveling across great migratory distances of tens to as much as a hundred thousand kilometers round-trip per year, resulting in potential multi-frequency cumulative effects from chronic near, middle, and far-field exposures. Avian populations are declining worldwide, especially among migratory species. This means that birds may be uniquely sensitive to adverse effects from environmental RFR since their natural habitat is air and they often fly at lateral levels with infrastructure emissions, bringing them that much closer to generating sources.

Tower and building construction, as direct obstacles, are known hazards to birds. One tower at 150 feet (46 m) above ground level is thought to account for as many as 3,000 songbird deaths per month in migratory pathways during peak migration [250] and communication tower collisions have been documented to kill more than 10,000 migratory birds in one night at a TV tower in Wisconsin [251, 252]. It has been known for years that the songbird populations of North America and Europe are plummeting. Only recently were towers considered a significant factor. But is the problem solely due to obstacles in direct migratory pathways or is something else involved?

RFR from towers may be acting as an attractant to birds due to their singular physiology. Avian eyes and beaks are uniquely magnetoreceptive with both magnetite and cryptchrome radical pair receptors. One definitive study by Beason and Semm [253] demonstrated that the common cell phone frequency (900-MHz carrier frequency, modulated at 217 Hz) at nonthermal intensities, produced firing in several types of nervous system neurons in Zebra Finches (*Taeniopygia guttate*). Brain neurons of irradiated anesthetized birds showed changes in neural activity in 76% of responding cells, which increased their firing rates by an average 3.5-fold vs. controls. Other responding cells exhibited a decrease in rates of spontaneous activity. The Beason and Semm study [253] could explain why birds may be attracted to cell towers, a theoretical premise they previously observed with Bobolinks (*Dolichonyx oryzivorus*; [254]).

RFR may also act as an avian stressor/irritant. Early work by Wasserman et al. [255] in field studies on 12 flocks of migratory birds subjected to various combinations of microwave power density and duration under winter conditions at Monomet, MA, using birds from two additional flocks as controls, showed increased levels of aggression in some of the irradiated birds.

Other research indicated a range of effects capable of broad adverse environmental outcomes. Laboratory studies by Di Carlo et al. [256] found decreases in heat shock protein production in chick embryos. The researchers used 915-MHz RFR on domestic chicken embryos and found that exposure typical of some cell phone emissions reduced heat shock proteins (HSP-70) and caused heart attacks and death in some embryos. Controls were unaffected. In replicated experiments, similar results were found by Grigor'ev [257] and Xenos and Magras [258]. Batellier et al. [259] found significantly elevated embryo mortality in exposed vs. sham groups of eggs incubated with a nearby cell phone repeatedly calling a 10-digit number at 3-min intervals over the entire incubation period. Heat shock proteins help maintain the conformation of cellular proteins during periods of stress. A decrease in their production diminishes cellular protection, possibly leading to cancer, other diseases, heart failure, and reduction in protection against hypoxia and ultraviolet light.

Not all results are adverse. Tysbulin et al. [260, 261] investigated both short and prolonged GSM 900 MHz cell phone signal exposure on embryo development in Quail (*Coturnix coturnix japonica),* irradiating fresh fertilized eggs during the first 38 h and 14 days of incubation using a cell phone in connecting mode continuously activated through a computer system. Maximum intensity of incident radiation on the egg's surface was 0.2 mW/cm^2. Results found a significant ($p<0.001$) increase in differentiated somites in 38-h exposed embryos and a significant ($p<0.05$) increase in total survival of embryos in eggs after 14 days exposure. They also found the level of thiobarbituric acid (TBA) reactive substances was significantly (p 0.05–0.001) higher in the brains and livers of hatchlings from exposed embryos and hypothesized that a facilitating effect exists due to enhanced metabolism in exposed embryos via peroxidation mechanisms. They concluded low-level nonthermal effects from GSM 900 MHz to quail embryogenesis is possible and that effects can be explained via a hormesis effect induced by reactive oxygen species (ROS).

Signaling characteristics such as pulsing vs. continuous wave are also important. Berman et al. [262], in a multi-lab study of pulsed ELF magnetic fields found a highly significant incidence of abnormalities in exposed chick eggs vs. controls. And Ubeda et al. [263] found irreversible damage to chick embryos from weak pulsed ELF-EMF magnetic fields that are common in the environment today. Initial studies on freshly fertilized chicken eggs were exposed during the first 48 h of post-laying incubation to pulsed magnetic fields (PMFs) with 100 Hz repetition rate, 1.0 μT peak-to-peak amplitude, and 500 μs pulse duration. Two different pulse waveforms were used, with rise and fall times of 85 μs or 2.1 μs. A two-day exposure found significant increased developmental abnormalities. In follow-up research, after exposure, eggs were incubated for an additional nine days without PMFs. Embryos removed from eggs showed an excess of developmental anomalies in the PMF-exposed groups compared with the sham-exposed samples. There was a high rate of embryonic death in the 2.1 μs rise/fall time. Results indicate PMFs can cause irreversible developmental changes, confirming that a pulse waveform can determine embryonic response to ELF magnetic fields common today.

Between 1999 and 2005, Fernie et al. for the first time investigated various potential reproductive effects on a captive raptor species — the American Kestrel (*Falco sparverius*) — from ELF-EMF equivalent to that of wild nesting pairs on power transmission lines. In a series of studies, captive pairs were typically bred under control or EMF exposure over 1–3 breeding cycles. In 1999, Fernie et al. [264] investigated photo phasic plasma melatonin in reproducing adult and fledgling kestrels, finding that EMFs affected plasma melatonin in adult male kestrels, suppressing it midway through, but elevating it at the end of the breeding season. In long-term, but not short-term EMF exposure of adults, plasma melatonin was supressed in their fledglings too which could affect migratory success. Molt happened earlier in adult EMF-exposed males than in controls. EMF exposure had no effect on plasma melatonin in adult females. In avian species, melatonin is involved in body temperature regulation, seasonal metabolism, locomotor activity, feeding patterns, migration, and plumage color changes important for mate selection. Melatonin also plays a key role in the growth and development of young birds. The researchers concluded it is likely that the results are relevant to wild raptors nesting within EMF exposures.

In 2000 Fernie et al. [265] focused on reproductive success in captive American Kestrels exposed to ELF-EMF, again equivalent to that experienced by wild reproducing kestrels. Kestrels were bred one season per year for two years under EMF or controlled conditions. In some years but not others, EMF-exposed birds showed a weak association with reduced egg laying, higher fertility, larger eggs with more yolk, albumen, and water, but thinner egg shells than control eggs. Hatching success was lower in EMF pairs than control pairs but fledging success was higher than control pairs in one year. They concluded that EMF exposure such as what kestrels would experience in the wild was biologically active in a number of ways leading to reduced hatching success.

Also in 2000, Fernie et al. [266] further investigated behavioral changes in American Kestrels to ELF-EMF, again in captive birds comparable to nesting pairs that commonly use electrical transmission structures for nesting, perching, hunting, and roosting. The amount of EMF exposure time of wild reproducing American Kestrels was first determined at between 25 and 75% of the observed time. On a 24-h basis, estimated EMF exposure in wild species ranged from 71% during courtship, to 90% during incubation. Then effects of EMFs on the behavior of captive reproducing kestrels were examined at comparable exposures of 88% of a 24-h period. Additionally, captive kestrels were exposed to EMF levels experienced by wild kestrels nesting under 735-kV power lines. There appeared to be a stimulatory/stress effect. Captive EMF females were more active, more alert, and perched on the pen roof more frequently than control females during courtship. EMF females preened and rested less often during brood rearing. EMF-exposed male kestrels were more active than control males during courtship and more alert during incubation. The researchers concluded that the increased activity of kestrels during courtship may be linked to changes in corticosterone, but not to melatonin as found in earlier work [264], but said the behavioral changes observed were unlikely to result in previously reported effects in EMF-exposed birds as noted above. They added that behavioral changes of captive EMF-exposed kestrels may also be observed in wild kestrels, with uncertain results.

In 2001 Fernie and Bird [267] looked at ELF-EMF oxidative stress levels in captive American Kestrels using the same test parameters described above to see if ELF-EMF exposure elicited an immune system response. In captive male kestrels bred under control or EMF conditions equivalent to those experienced by wild kestrels, short-term EMF exposure (one breeding season) suppressed plasma total proteins, hematocrits, and carotenoids in the first half of the breeding season. It also suppressed erythrocyte cells and lymphocyte proportions, but elevated granulosa proportions at the end of the breeding season. Long-term EMF exposure (two breeding seasons) also suppressed hematocrits in the first half of the reproductive period. But results found that only short-term EMF-exposed birds experienced an immune response, particularly during the early half of the breeding season. The elevation of granulocytes and the suppression of carotenoids, total proteins, and melatonin [264] in the same kestrel species indicated that the short-term EMF-exposed male kestrels had higher levels of oxidative stress due to an immune response and/or EMF exposure. The researchers noted that long-term EMF exposure may be linked to higher levels of oxidative stress solely through EMF exposure. Oxidative stress contributes to cancer, neurodegenerative diseases, and immune disorders. And in 2005, Fernie and Reynolds [268] noted most studies of birds and EMF indicate changes on behavior, reproductive success, growth and development, physiology and endocrinology, and oxidative stress — with effects not always consistent or in the same direction under EMF conditions. The entire body of work by this research group has implications for all wild species that encounter a wide range of EMFs on a regular basis.

In field studies on wild birds in Spain, Balmori [269] found strong negative correlations between low levels of microwave radiation and bird breeding, nesting, roosting and survival in the vicinity of communication towers. He documented nest and site abandonment, plumage deterioration, locomotion problems, and death in Wood Storks (*Mycteria americana*), House Sparrows (*Passer domesticus*), Rock Doves (*Columba livia*), Magpies (*Pica pica*), Collared Doves (*Streptopelia decaocto)*, and other species. While these species had historically been documented to roost and nest in these areas, Balmori [269] did not observe these symptoms prior to construction and operation of the cell phone towers. Results were most strongly negatively correlated with proximity to antennas and Stork nesting and survival. Twelve nests (40% of his study sample) were located within 656 ft (200 m) of the antennas and never successfully raised any chicks, while only one nest (3.3%), located further than 984 ft (300 m) never had chicks. Strange behaviors were observed at Stork nesting sites within 328 ft (100 m) of one or several cell tower antennas. Birds impacted directly by the main transmission lobe (i.e., electric field intensity > 2 V/m) included young that died from unknown causes. Within 100 m, paired adults frequently fought over nest construction sticks and failed to advance nest construction (sticks fell to the ground). Balmori further reported that some nests were never completed and that Storks remained passively in front of cell site antennas. The electric field intensity was higher on nests within 200 m (2.36 ± 0.82 V/m; 1.48 μW/cm^2) than on nests further than 300 m (0.53 ± 0.82 V/m, 0.074 μW/cm^2). RF-EMF levels, including for nests <100 m from the antennas, were not intense enough to be classified as thermal exposures. Power densities need to be at least 10 mW/cm^2 to produce tissue heating of even 0.5 °C [270]. Balmori's results indicated that RFR could potentially affect one or more reproductive stages, including nest construction, number of eggs produced, embryonic development, hatching and mortality of chicks and young in first-growth stages.

Balmori and Hallberg [271] and Everaert and Bauwens [272] found similar strong negative correlations among male House Sparrows (*Passer domestics)* throughout multiple sites in Spain and Belgium associated with ambient RFR between 1 MHz and 3 GHz at various proximities to GSM cell base stations. House Sparrow declines in Europe have been gradual but cumulative for this species once historically well adapted to urban environments. The sharpest bird density declines were in male House Sparrows in relatively high electric fields near base stations, indicating that long-term exposure at higher RFR levels negatively affected both abundance and/or behavior of wild House Sparrows. In another review, Balmori [25] reported health effects to birds that were continuously irradiated. They suffered long-term effects that included reduced territorial defense posturing, deterioration of bird health, problems with reproduction, and reduction of useful territories due to habitat deterioration.

Birds have been observed avoiding areas with high and low-intensity EMF, in daylight as well as nocturnally. An early study by Southern in 1975 [273] observed that gull chicks reacted to the U.S. military's Project Sanguin ELF transmitter. Tested on clear days in the normal geomagnetic field, birds showed significant clustering with predicted bearing corresponding with migration direction, but when the large antenna was energized they dispersed randomly. He concluded that magnetic fields associated with such conductors were sufficient to disorient birds. Larkin and Sutherland [274] observed that radar tracking of individual nocturnal migrating birds flying over a large alternating-current antenna system caused birds to turn or change altitude more frequently when the antenna system was operating than when it was not. The results suggested that birds sense low-intensity alternating-current EMF during nocturnal migratory flight.

In a well-designed, multi-year avian study of magneto-disruption, Engels et al. [213] investigated environmental broadband electromagnetic 'noise' emitted everywhere humans use electronics, including devices and infrastructure. They found migratory birds were unable to use their magnetic compass in the presence of a typical urban environment today. European Robins (*E. rubecula),* exposed to the background electromagnetic 'noise' present in unscreened wooden huts at the University of Oldenburg campus, could not orient using their magnetic compass. But when placed in electrically grounded aluminum-screened huts, creating Faraday cages that attenuated electromagnetic 'noise' by approximately two orders of magnitude, their magnetic orientation returned. The researchers were able to determine the frequency range from 50 kHz to 5 MHz was the most disruptive. When grounding was removed, or additional broadband electromagnetic 'noise' was deliberately generated inside the screened and grounded huts, birds again lost magnetic orientation abilities. They concluded that RFR's magneto-disruption effects are not confined to a narrow frequency band. Birds tested far from sources of EMFs required no screening to orient with their magnetic compass. This work documented a reproducible effect of anthropogenic electromagnetic ambient 'noise' on the behavior of an intact vertebrate. The magnetic compass is integral to bird movement and migration. The findings clearly demonstrated a nonthermal effect on European Robins and serves as a predictor for effects to other migratory birds, especially those flying over urban areas. Such fields are much weaker than minimum levels expected to produce any effects and far below any exposure standards.

Intensity windows in different species have also been found where effects can be more extreme at lower intensities than at higher ones due to compensatory mechanisms such as cell apotosis. Panagopoulos and Margaritas [34] found an unexpected intensity window at thermal levels around 10 mW/cm^2 RFR — not uncommon near cell towers — where effects were more severe than at intensities higher than 200 mW/cm^2. This window appeared at a distance of 8–12 in (20–30 cm) from a cell phone antenna, corresponding to a distance of about 66–98 ft (20–30 m) from a base station antenna. This could be considered a classic nonlinear effect and would apply to far-field exposures. Since cell base station antennas are frequently located within residential areas where birds nest, often at distances 20–30 m from such antennas, migratory birds, non-migratory avifauna, and other wildlife may be exposed up to 24-h per day.

Concerns also apply to impacts from commercial radio signals on migratory birds. The human anatomy is resonant with the FM bands so exposure standards are most stringent in that range. High intensity (>6,000 W) commercial FM transmitters are typically located on the highest ground available to blanket a wider area. Low powered FM transmitters (<1,000 W) can be placed closer to the human population. High intensity locations, which can be multi-transmitter sites (colloquially called "antenna farms") for other services, also provide convenient perches and nest sites for migratory birds. FM digital signals, which simulate pulsed waves, pose additional health concerns to migratory birds. This creates a dangerous frequency potential for protected migratory birds such as Bald Eagles with wingspans that extend to about 6 ft (1.83 m) — a resonant match with the length of the FM signal — creating a potential full-body resonant effect for both humans and Bald Eagles. Birds could experience both thermal and non-thermal effects.

All migratory birds are potentially at risk, including Bald Eagles, Golden Eagles, birds of conservation concern [275], federal and/or state-listed bird species, birds nationally or regionally in peril, as well as birds whose populations are stable. Sadly, addressing these concerns — beginning with independent research conducted by scientists with no vested interest in the outcomes — has not been a priority for government agencies or the communications industry.

Insects and arachnids

Insects are the most abundant and diverse of all animal groups, with more than one million described species representing more than half of all known living species, and potentially millions more yet to be discovered and identified. They may represent as much as 90% of all life forms on Earth. Though some are considered pests to farm crops and others as disease vectors, insects remain essential to life and planetary health. Found in nearly all environments, they are the only invertebrates that fly, but adults of most insect species walk, while some swim.

Because of these different environmental adaptations, different species will encounter different EMF exposures in varying degrees. For instance, ground-based walking insects may be more susceptible to effects from 60 Hz stray current while flying insects may be more susceptible to wireless exposures. However, all species tested have been affected across a range of the nonionizing electromagnetic bands.

Most insects have an exoskeleton, three-part body consisting of a head, thorax, and abdomen, three pairs of jointed legs, compound eye structures capable to seeing many more colors, widths, and images than humans, and one pair of antennae capable of sensing subtle meteorological changes and Earth's geomagnetic fields. They live in close harmony with the natural environment for survival and mating purposes. The most diverse insect groups coevolved with flowering plants, many of which would not survive without them. Most insect species are highly sensitive to temperature variations and climate alterations as they do not dissipate heat efficiently.

Nearly all insects hatch from eggs that are laid in myriad ways and habitats. Growth involves a series of molts and stages (called instars) with immature stages greatly differing from mature insects in appearance, behavior, and preferred habitat. Some undergo a four-stage metamorphosis (with a pupal stage) and others a three-stage metamorphosis through a series of nyphal stages.

While most insects are solitary, some — like bees, termites and ants — evolved into social networks, living in "cooperative" organized colonies that can function as one unit as evidenced in swarming behaviors. Some even show maternal care over eggs and young. They communicate through various sounds, pheromones, light signals, and through their antennae such as during the bees' "waggle dance" (see below).

As far back as the 1800s, even though testing methods were primitive by today's standards, researchers were curious about electromagnetism's effect on insect development, particularly teratogenicity [276]. Research on EMF across frequencies and insect populations has been ongoing since at least the 1930s with an eye toward using energy as an insecticide and anti-contaminant in grain, typically at high intensity thermal exposures that would not exist in the natural environment. Mckinley and Charles [277] found that wasps die within seconds of high frequency exposure. But not all early work was strictly high intensity, or all effects observed due to thermal factors.

There were interesting theories introduced by early researchers regarding how energy couples with various insect species. Frings [278] found larval stages are more tolerant to heat than adult insects with appendages that can act as conducting pathways to the body, and that the more specialized the insect species, the more susceptible they appear to microwave exposure. Carpenter and Livingstone [279] studied effects of 10 GHz continuous-wave microwaves at 80 mW/cm^2 for 20 or 30 min, or at 20 mW/cm^2 for 120 min on pupae of mealworm beetles (*Tenebrio molitor*) — clearly within thermal ranges. In control groups, 90% metamorphosed into normal adult beetles whereas only 24% of exposed groups developed normally, 25% died, and 51% developed abnormally. Effects were assumed to be thermally induced abnormalities until they simulated the same temperature exposure using radiant heat and found 80% of pupae developed normally. They concluded that microwaves were capable of inducing abnormal effects other than through thermal damage.

Fruit flies

Insects at all metamorphic stages of development have been studied using RFR including egg, larva, pupa and adult stages. Much work has been done on genetic and other effects with fruit flies (*D. melanogaster*) because of their well-described genetic system, ease of exposure, large brood size, minimal laboratory space needed, and fast reproductive rates. Over several decades Goodman and Blank, using ELF-EMF on *Drosophila* models, found effects to heat shock proteins and several other effects ([201]; and see "Mechanisms" above). It is considered a model comparable to other insects in the wild approximating that size. *D. melanogaster* may be the most lab-studied insect on Earth, although honey and related bee species, due to their devastating losses over the last decade and significance to agriculture, are quickly catching up.

Michaelson and Lin [50] noted that RFR-exposed insects first react by attempting to escape, followed by disturbance of motor coordination, stiffening, immobility and eventually death, depending on duration of exposure and insect type. For example, *D. melanogaster* survived longer than 30 min while certain tropical insects live only a few seconds at the same field intensity. Also noted were concentration changes in many metabolic products and effects to embryogenesis — the period needed for a butterfly to complete metamorphosis — with accelerated gastrulation and larval growth [17]. Michaelson and Lin [50] cited several negative studies with *D. melanogaster* exposed with continuous-wave RFR between 25 and 2,450 MHz on larval growth [280, 281] and mutagenicity [282]. This was after Heller and Mickey [283] found a tenfold rise in sex-linked recessive mutations with pulsed RFR between 30 and 60 MHz. It was among the earliest studies that found pulsing alone to be a biologically active exposure.

As reported in Michaelson and Lin [50], Tell [284] looked at *D. melanogaster*'s physiological absorption properties and found that a group of 6-day old male wild-type flies, exposed to 2,450 MHz for 55 min at an intense field caused a dramatic 65% reduction in body weight. This was thought to be from dehydration. They then sought to calculate the fruit fly's absorption properties in relation to plane electromagnetic waves and found that a fly has only a 1/1,000th effective area of its geometric cross section and thus is an inefficient test species for absorbed microwave radiation. However, they concluded that fruit flies were responsive to absorbed energy at thermal levels as a black body resonator at a power density of 1.044×10^4 mW/cm^2, corresponding to a thermal flux density of 0.562×10^{-3} cal. These are levels found in close proximity to broadcast facilities and cell phone towers today.

More recent investigations of RFR by Weisbrot et al. [285] using GSM multiband mobile phones (900/1,900 MHz; SAR approximately 1.4 W/kg) on *D. melanogaster* during the 10-day developmental period from egg laying through pupation found that non-thermal radiation increased numbers of offspring, elevated heat shock protein-70 levels, increased serum response element (SRE) DNA-binding and induced the phosphorylation of the nuclear transcription factor, ELK-1. Within minutes, there was a rapid increase of hsp70, which was apparently not a thermal effect. Taken together with the identified components of signal transduction pathways, the researchers concluded the study provided sensitive and reliable biomarkers for realistic RFR safety guidelines.

Panagopoulos et al. [286] found severe effects in early and mid-stage oogenesis in *D. melanogaster* when flies were exposed *in vivo* to either GSM 900-MHz or DCS 1,800-MHz radiation from a common digital cell phone, at non-thermal levels, for a few minutes per day during the first 6 days of adult life. Results suggested that the decrease in oviposition previously reported [287–289] was due to degeneration of large numbers of egg chambers after DNA fragmentation of their constituent cells which was induced by both types of mobile phone radiation. Induced cell death was recorded for the first time in all types of cells constituting an egg chamber (follicle cells, nurse cells and the oocyte) and in all stages of early and mid-oogenesis, from germarium to stage 10, during which programmed cell death does not physiologically occur. Germarium and stages 7–8 were found to also be the most sensitive developmental stages in response to electromagnetic stress induced by the GSM and DCS fields. Germarium was also found to be more sensitive than stages 7–8. These papers, taken collectively, indicate serious potential effects to all insect species of similar size to fruit flies from cell phone technology, including from infrastructure and transmitting devices.

Fruit flies have also been found sensitive to ELF-EMF. Gonet et al. [290] found 50 Hz ELF-EMF exposure affected all developmental stages of oviposition and development of *D. melanogaster* females, and weakened oviposition in subsequent generations.

Savić et al. [291] found static magnetic fields influenced both development and viability in two species of *Drosophila* (*D. melanogaster and D. hydei*). Both species completed development (egg-to-adult), in and out of the static magnetic field induced by a double horseshoe magnet. Treated vials with eggs were placed in the gap between magnetic poles (47 mm) and exposed to the average magnetic induction of 60 mT, while control groups were kept far from the magnetic field source. They found that exposure to the static magnetic field reduced development time in both species, but only results for *D. hydei* were statistically significant. In addition, the average viability of both species was significantly weaker compared to controls. They concluded a 60 mT static magnetic field could be a potential stressor, influencing on different levels both embryonic and post-embryonic fruit fly development.

Beetles

Other insect species also react to both ELF-EMF and RF-EMF. Newland et al. [292] found behavioral avoidance in cockroaches (*Periplaneta americana*) to static electric fields pervasive in the environment from both natural and man-made sources. Such fields could exist near powerlines or where utilities ground neutral lines into the Earth. They found insect behavioral changes in response to electric fields as tested with a Y-choice chamber with an electric field generated in one arm of the chamber. Locomotor behavior and avoidance were affected by the magnitude of the electric fields with up to 85% of individuals avoiding the charged arm when the static e-field at the entrance to the arm was above 8–10 kV/m. Seeking to determine mechanisms of perception and interaction, they then surgically ablated the antennae and cockroaches were unable to avoid electric fields. They concluded that antennae are crucial in cockroach detection of electric fields that thereby helps them avoid such fields. They also noted that cockroach ability to detect e-fields is due to long antennae which are easily charged and displaced by such fields, not because of a specialized detection system. This leads to the possibility that other insects may also respond to electric fields via antennae alone.

Vácha et al. [208] found that cockroaches (*P. americana*) were sensitive to weak RFR fields and that the Larmor frequency at 1.2 MHz in particular had a "deafening effect" on magnetoreception. The parameter they studied was the increase in locomotor activity of cockroaches induced by periodic changes in geomagnetic North positions by 60°. The onset of the disruptive effect of a 1.2 MHz field was found between 12 and 18 nT whereas the threshold of a field twice the frequency (2.4 MHz) fell between 18 and 44 nT. A 7 MHz field showed no significant effect even at maximal of 44 nT. The results suggested resonance effects and that insects may be equipped with the same magnetoreception system as birds.

Prolić et al. [293] investigated changes in behavior via the nervous system of cerambycid beetles (*Morimus funereus*) in an open field before and after exposure to a 50 Hz ELF-MF at 2 mT. Experimental groups were divided into several activity categories. Results showed activity increased in the groups with medium and low motor activity, but decreased in highly active individuals. High individual variability was found in the experimental groups, as well as differences in motor activities between the sexes both before and after exposure to ELF-MF. They assumed activity changes in both sexes were due to exposure to ELF-MF. Only a detailed analysis of the locomotor activity at 1-min intervals showed some statistically significant differences in behavior between the sexes.

Ants

Ants are another taxa found sensitive to EMF. Ants comprise between 15 and 25% of the terrestrial animal biomass and thrive in most ecosystems on almost every landmass on Earth. By comparison, the total estimated biomass (weight) of all ants worldwide equates to the total estimated biomass of all humans. Their complex social organization in colonies, with problem-solving abilities, division of labor, and both individual and whole colony communication via complex behavioral and pheromone signaling may account for their success in so many environments. Some ant species (e.g., *Formica rufa*-group) are known to build colonies on active earthquake faults and have been found to change behavior hours in advance of earthquakes [294], thus demonstrating predictive possibilities. Ants can modify habitats, influence broad nutrient cycling, spread seeds, tap resources, and defend themselves. Ants co-evolved with other species which led to many different kinds of mutual beneficial and antagonistic relationships.

Ants (e.g., *Solenopsis invictus*) are long known to be sensitive to magnetic fields both natural and manmade [295]. Ants (e.g., *Atta colombica*), like birds, have been found to be sensitive to the Earth's natural fields and to use both a solar compass on sunny days as well as a magnetic compass when there is cloud cover [296]. Jander and Jander [297] similarly found that the weaver ant (*Oecophylla* spp*)* had a more efficient light compass orientation with a much less efficient magnetic compass orientation, suggesting that they switch from the former to the latter when visual celestial compass cues become unavailable. There is evidence from Esquivel et al. [298] that such magnetoreception is due to the presence of varying sized magnetite particles and paramagnetic resonance in fire ants (*Solenopsis* spp). But Riveros and Srygley [299] found a more complex relationship toward a magnetic compass rather than the presence of magnetite alone when leafcutter ants (*Atta columbica)* were subjected to a brief but strong magnetic pulse which caused complete disorientation regarding nest-finding. They found external exposures could interfere with ants' natural magnetic compass in home path integration, which indicated evidence of a compass based on multi-domain and/or superparamagnetic particles rather than on single-domain particles like magnetite.

Acosta-Avalos et al. [300] found that fire ants are sensitive to 60 Hz alternating magnetic fields as well as constant magnetic fields, changing their magnetic orientation and magnetosensitivity depending on the relation between both types of magnetic fields. Alternating current had the ability to disrupt ant orientation, raising the question of effects to wild species from underground wiring and the common practice of powerline utility companies using the Earth as a neutral return pathway to substations, creating stray current along the way [99].

Camelitepe et al. [301] tested black-meadow ants' (*Formica pratensis*) response under both natural geomagnetic and artificial earth-strength static EMFs (24.5 μT). They found that under the natural geomagnetic field, when all other orientational cues were eliminated, there was significant heterogeneity of ant distribution with the majority seeking geomagnetic north in darkness while under light conditions ants did not discriminate geomagnetic north. Under artificial EMF exposure, however, ant orientation was predominantly on the artificial magnetic N/S axis with significant preference for artificial north in both light and dark conditions. This indicated EMF abilities to alter ant orientation.

Ants are also shown to react to RFR [302, 303]. Cammaerts et al. [304] found that exposures to GSM 900 MHz at 0.0795 $\mu W/cm^2$ significantly inhibited memory and association between food sites and visual and olfactory cues in ants (*Myrmica sabuleti*) and eventually wiped out memory altogether. Subsequent exposure, after a brief recovery period, accelerated memory/olfactory loss within a few hours vs. a few days, indicating a cumulative effect even at very low intensity. The overall state of the exposed ant colonies eventually appeared similar to that exhibited by honey bee (*Apis mellifera*) colony collapse disorder. Although the impact of GSM 900 MHz radiation was greater on the visual memory than on the olfactory memory, the researchers concluded that such exposures — common to cell phones/towers — were capable of a disastrous impact on a wide range of insects using olfactory and/or visual memory, including bees. Many ant species (e.g., *Lasius neglectus, Nylanderia fulva, Camponotus* spp, *Hymenoptera formicidae, Solenopsis invicta,* among others*)* are attracted to electricity, electronic devices, and powerlines, thereby causing short circuits and fires. One hypothesis [305] is that the accumulation of ants in electrical equipment may be due to a few foraging "worker ants" seeking warmth and finding their way into small spaces, completing electrical contacts which then causes a release of alarm exocrine gland pheromones that attract other ants, which then go through the same cycle. In their study, they found that workers subjected to a 120 V alternating-current released venom alkaloids, alarm pheromones and recruitment pheromones that elicited both attraction and orientation in ants as well as some other unknown behavior-modifying substances. But given how ants are affected by EMFs in general it is likely that an attractant factor is also involved, not just warmth and small spaces.

There is evidence that ants use their antennae as "antennas" in two-way electrochemical communications. Over 100 hundred years ago, Swiss researcher Auguste Forel [306] removed the antennae of different species of ants and put them together in one place. What would have normally evoked aggressive behaviors among the different species did not occur and they got along as if belonging to the same colony. To Forel this indicated an ability of ant antennae to help different ant species identify each other.

Two mechanisms in ants have long been known for chemical receptivity as well as electromagnetic sensitivity. Recently Wang et al. [307] found evidence that chemical signals located specific to antennae vs. other body areas drew more attention from non-nest mates. When cuticular hydrocarbons (CHCs) were removed by a solvent from antennae, non-nest mates responded less aggressively than to other areas of the body, indicating that antennae reveal nest-mate identity, conveying and receiving social signals. Regarding magnetoreception, magnetic measurements [308–310] found the presence of biogenic magnetite was concentrated in antennae and other body parts of the ant *Pachycondyla marginata*. De Oliveira et al. [311] also found evidence of magnetite and other magnetic materials imbedded in various locations of antennae tissue in *P. marginata* indicating that antennae function as magnetoreceptors. The amount of magnetic material appeared sufficient to produce a magnetic-field-modulated mechanosensory output and therefore demonstrated a magnetoreception/transduction sense in migratory ants.

Ticks

Ticks are members of the order Arachnida, shared with scorpions and spiders. Recent papers in a tick species (*Dermacentor reticulates*) mirrors an attraction to some frequencies but not others. Vargová et al. [312, 313] found that exposure to RFR may be a potential factor altering both presence and distribution of ticks in the environment. Studies were conducted to determine potential affinity of ticks for RFR using radiation-shielded tubes (RST) under controlled conditions in an electromagnetic compatibility laboratory in an anechoic chamber. Ticks were irradiated using a Double-Ridged Waveguide Horn Antenna to RF-EMF at 900 and 5,000 MHz; 0 MHz served as control. Results found that 900 MHz RFR induced a higher concentration of ticks on the irradiated arm of RST whereas at 5,000 MHz ticks escaped to the shielded arm. In addition, 900 MHz RFR had been shown to cause unusual specific sudden tick movements during exposure manifested as body or leg jerking [312]. These studies are the first experimental evidence of RFR preference and behavioral changes in *D. reticulates* with implications for RFR introduced into the natural environment by devices and infrastructure. In a further study, Frątczak et al. [314] reported that *Ixodes ricinus* ticks were attracted to 900 MHz RFR at 0.1 $\mu W/cm^2$, particularly those infected with Rickettsia (spotted fever).

RFR may be a new factor in tick distribution, along with known factors like humidity, temperature and host presence, causing concentrated non-homogenous or mosaic tick distribution in natural habitats. Tick preference for 900 MHz frequencies common to most cell phones has possibly important ecological and epidemiological consequences. Increasing exposures from use of personal devices and infrastructure in natural habitats where ticks occur may increase both tick infestation and disease transmission. Further studies need to investigate this work, given the ubiquity of ticks today, their northward spread due to climate change in the Northern Hemisphere, and the increasing and sometimes life-threatening illnesses they transmit to humans, pets, and wildlife alike.

Monarch butterflies

The American Monarch butterfly (*D. plexippus)* has fascinated researchers for over 100 years as it is the only insect known to migrate in multi-generational stages [315–319], with the ability to find their exact birthplace on specific milkweed plants (*Asclepias* spp.) at great distances across land and oceans.

Monarchs (*D. plexippus*), found across Southern Canada, the United States, and South America, are generally divided by the Rocky Mountains into eastern and western migratory groups. Their population has precipitously declined by 99.4% since the 1980s (85% of that since 2017) and by 90% in the past two decades in both western and eastern populations [13, 15]. These steep declines are from numerous anthropogenic causes and may have already crossed extinction thresholds, thereby leaving us bereft not only of their beauty and inspiration, but also the perfect model for long-distance animal migration study in general.

Monarch butterflies are among North America's most beloved invertebrates. They have for centuries navigated thousands of miles/kilometers in an iconic fall migration from southern Canada and the mid- and northeastern U.S. to a small area of about 800 square miles (2,072 square kilometers) in Central Mexico where they once wintered over in the millions in small remote oyamel fir forests. By the time they reach their final destination, some will have traveled distances exceeded only by some migratory seabird species. The monarch is the only insect known to migrate annually over 3,000 miles (4,828 km) at ~ 250 miles (402 km) per day in the fall from the Canadian border to Mexico, and in the springtime back again. Similar to some bird species, it is the only butterfly known to have a two-way migration pattern. Monarchs are only followed by army cutworm moths (*Euxoa auxiliaris*) which may migrate several thousand kilometers to high elevation sites in the Rocky Mountains to escape lowland heat and drought.

But monarchs are more interesting than for this one amazing migrational feat alone. How they do this is a long-standing mystery since their entire lifecycle, including their two-stage spring return migration, is multi-generational indicating genetic factors in directional mapping since the final return fall migration south cannot be considered "learned." Several multifaceted mechanisms must come into play, as well as little understood complexities in how those mechanisms cooperate and trade off with each other under different environmental circumstances. Monarchs also go from solitary insects during early developmental stages confined to specific locations, then exhibit social insect behaviors after the third generation has reached northern latitudes and turned south during the final fall migration. And all of this happens in a brain the size of a grain of sand.

Reppert et al. [320] published an excellent review in 2010 on the complexities of monarch migration, noting "… recent studies of the fall migration have illuminated the mechanisms behind the navigation south, using a time-compensated sun compass. Skylight cues, such as the sun itself and polarized light, are processed through both eyes and likely integrated in the brain's central complex, the presumed site of the sun compass. Time compensation is provided by circadian clocks that have a distinctive molecular mechanism and that reside in the antennae. Monarchs may also use a magnetic compass, because they possess two cryptochromes that have the molecular capability for light-dependent magnetoreception. Multiple genomic approaches are being utilized to ultimately identify navigation genes. Monarch butterflies are thus emerging as an excellent model organism to study the molecular and neural basis of long-distance migration." Reppert and de Roode [321] updated that information in 2018.

Although it has been known for some time that monarchs use a circadian rhythm time-compensated directional sun compass [316, 322–338], many questions remain about its dynamics and concerns regarding effects from radiation.

Monarch antennae are known to contain magnetite [339, 340] and cryptochromes [335, 336, 341, 342] — both understood to play a role in magnetoreception (see "Mechanisms"above). One early study by Jones and MacFadden [343] found magnetic materials located primarily in the head and thorax areas of dissected monarchs. More recently, Guerra et al. [16] found convincing evidence that monarchs use a magnetic compass to aid their longest fall migration back to Mexico. Those researchers used flight simulator studies to show that migrants possess an inclination magnetic compass to assist fall migration toward the equator. They found this inclination compass is light-dependent, utilizing ultraviolet-A/blue light between 380 and 420 nm and noted that the significance of light (<420 nm) for an inclination compass function had not been considered in previous monarch studies. They also noted that antennae are important for an inclination compass since they contain light-sensitive magnetosensors. Like some migratory birds, the presence of an inclination compass would serve as an orientation mechanism when directional daylight cues are impeded by cloudy or inclement weather or during nighttime flight. It may also augment time-compensated sun compass orientation for appropriate directionality throughout migration. The inclination compass was found to function at earth-strength magnetic fields, an important metric.

The question remains: Can the magnetic compass in monarchs be disrupted by anthropogenic EMF like it does with geomagnetic orientation in migratory birds [213]. There is some indication this is possible. Perez et al. [330] found monarchs completely disorient after exposure to a strong magnetic field (0.4-T MF for 10 s, or approximately 15,000 times the Earth's magnetic field) immediately before release vs. controls. This is a high exposure but within range of man-made exposures today very close to powerlines.

Bees, wasps, and others

Pollinators, bees in particular, are keystone species without which adverse effects would occur throughout food webs and the Earth's entire biome were pollinators to disappear. Because of their central role and accessibility for research, bee studies have created a wealth of information, including regarding anthropogenic EMFs.

Bees — especially honey and bumble bees — are another iconic insect species beloved for their role in pollination; honey, propolis, royal jelly and beeswax production; their critical importance to our food supply; and their crucial role in global ecological health and stability. Found on every continent except Anarctica wherever there are flowering plants requiring insect pollination, there are over 16,000 known species of bees in seven different biological families, consisting of four main branches. Some species live socially in colonies while others are solitary. The western honey bee (*Apis mellifera*) is the best known and most studied due in part to its central role in agriculture. Bees feed on nectar for energy and pollen for protein/nutrients, and have co-evolved with many plant species in astoundingly complex ways. They are also highly sensitive to both natural and anthropogenic EMFs. Beeswax itself has electrical properties [50].

Human apiculture has been practiced since the time of ancient Egyptian and Greek cultures and bees have been closely studied since the 1800s. Almost all bee species, including commercially raised and wild species, are under decades-long multiple assaults. These include from pesticides, herbicides, climate change, various bacterial/viral diseases, infestations from parasitic mite species — particularly *Apis cerana*, *Varroa destructor* and *Varroa jacobsoni* beginning in the mid-1980s — and predation from introduced species that attack bees directly (e.g., the invasive giant bee-eating hornet *Vespa mandarinia*), as well as alter plant ecology over time to adversely affect bee food supply. Some have suggested that vanishing bees may also have to do with premature aging due to environmentally caused shortened telomeres [344].

Whole colony collapse disorder (CCD) is the most dramatic manifestation of domesticated bee demise in which worker bees abruptly disappear from a hive without a trace, resulting in an empty hive with perhaps a remaining queen and a few worker bees despite ample resources left behind. Few, if any, dead bees are ever found near the hive. CCD was first described in the U.S. in 2006 in Florida in commercial western honey bee colonies. Van Englesdorp et al. [345] quantified bee losses across all beekeeping operations and estimated that between 0.75 and 1.00 million honey bee colonies died in the United States over the winter of 2007–2008. Up until that survey, estimates of honey bee population decline had not included losses occurring during the wintering period, thus underestimating actual colony mortality.

The same phenomenon had been described by beekeepers in France in 1994 [346] — later attributed to the timing of sunflower blooming and the use of imidacloprid (IMD), a chlorinated nicotine-based insecticide or "neonicotinoid" being applied to sunflowers for the first time there [347]. Similar to DDT but considered safer for mammals including humans, neonicotinoids are a slow-release class of neurotoxins that block insect nervous systems via acetylcholine receptors, interfering with neuronal signaling across synapses. Sublethal doses can interfere with bee navigation.

Since then similar phenomena have been seen throughout Europe [348] and some Asian countries. Causal hypotheses included all of the above factors with varying foci on pesticide classes like neonicotinoids and genetically modified crops, but no single agent adequately explains CCD. Bromenshenk et al. [349] however, identified pathogen pairing/co-infection with two previously unreported RNA viruses — *V. destructor*-1, and Kakugo viruses, and a new irridescent virus (IIV) (*Iridoviridae*) along with *Nosema ceranae* — in North American honey bees that were associated with all sampled CCD colonies. The pathogen pairing was not seen in non-CCD colonies. Later cage trials with IIV type-6 and *N. ceranae* confirmed that co-infection with those two pathogens was more lethal to bees than either pathogen alone. Still many questions remain.

There are two national surveying groups in the U.S. — the U.S. Department of Agriculture (USDA) which began surveying managed bee populations in 2015 but funding was cut in late 2019; and the Bee Informed Partnership (BIP), a non-profit that coordinates with research facilities and universities. Prior to USDA's funding cuts, managed colonies decreased from CCD by 40% [350] with an additional 26% over the same quarter in 2019 [351]. BIP's survey period for April 1, 2018 through April 1, 2019 found U.S. beekeepers lost an estimated 40.7% of their managed honey bee colonies. The previous year had similar annual losses of 40.1%. The average annual rate of loss reported by beekeepers since 2010–11 was 37.8% [352].

Also in the U.S., for the first time in 2016, seven species of Hawaiian yellow-faced bees (*Hylaeus anthracinus*, *Hylaeus longiceps*, *Hylaeus assimulans*, *Hylaeus facilis*, *Hylaeus hilaris*, *Hylaeus kuakea*, and *Hylaeus mana*) were added to the federal endangered species list, as well as the rusty patched bumble bee (*Bombus affinis*) which, prior to the late 1990s, had been widely dispersed across 31 U.S. states [353]. Mathiasson and Rehan [354] examined 119 species in museum specimens in New Hampshire going back 125 years and concluded that 14 species found across New England were on the decline by as much as 90%, including the lesser studied leafcutter and mining bees that nest in the ground, unlike honeybees that nest in commercial hives or in trees, shrubs, and rock crevices in the wild.

Worldwide, many bee and other pollinator populations have also declined over the last two decades. Managed honey bee (*Apis mellifera*) colonies decreased by 25% over 20 years in Europe and 59% over 58 years in North America, with many wild bumble bee populations in Europe and North America having gone locally extinct [355–358]. But while dramatic range contractions have been seen, not all bees in all places are declining; some populations are growing depending on opportunistic and species-adaptability factors. For many species data are still insufficient, of poor quality, or nonexistent [359]. In addition, bee declines can affect flora survival. Miller-Struttmann et al. [360] recorded flower declines of 60% with 40 years of climate warming in alpine meadows — areas largely protected from land-use changes. Insects are highly sensitive to temperature changes.

A comprehensive UK survey of pollinator species [361] found that of 353 wild bee and hoverfly species across Britain from 1980 to 2013, 25% had disappeared from the places they had inhabited in 1980. Further estimates found a net loss of over 2.7 million in 0.6 mi (1 km) grid cells across all species. Declining pollinator evenness suggested losses were concentrated in rare species. Losses linked to specific habitats were also identified, with a 55% decline among wild upland species while dominant crop pollinators increased by 12%, possibly due to agricultural business interventions. The general declines found a fundamental deterioration in both wider biodiversity and non-crop pollination services.

There is no question that the huge diversity of pollinator species across the planet is suffering and that losses could be catastrophic with an estimated 90% of wild plants and 30% of world crops in jeopardy [362].

There is a likelihood that rising EMF background levels play a role. Bees have been known for decades to have an astute sense of the Earth's DC magnetic fields [363, 364] and rely on that perception for survival. For centuries beekeepers had noticed curious movements in bee hives but Austrian ethologist Karl von Frisch finally interpreted that activity in the 1940s, winning the Nobel Prize in 1973 for what came to be known as the honey bee "waggle dance." Through complex circles and waggle patterns, bees communicate the location of food sources to other members of the hive, using the orientation of the sun and the Earth's magnetic fields as a gravity vector, "dancing" out a map for hive members to follow like nature's own imbedded GPS. Bees also detect the sun's direction through polarized light and on overcast days use the Earth's magnetic fields, likely through the presence of magnetite in their abdominal area, and employ complex associative learning and memory [365].

Building on the earlier work of Gould et al. [119], Kobayashi and Kirschvink [52] noted that biogenic magnetite in honey bees is located primarily in the anterior dorsal abdomen. When small magnetized bits of wire were glued over those areas, it interfered with bees' ability to learn to discriminate magnetic anomalies in conditioning experiments, while nonmagnetized wire used in controls did not interfere [366]. Kirschvink and Kobayashi [367] found that when pulse-remagnetization techniques were used on bees trained to exit from a T-maze, that north-exiting bees could be converted to a south-exiting direction similar to what was observed in magnetobacteria and artificial reorientation by Blakemore [113]. Honeybees could also be trained to respond to very small changes in the geomagnetic field intensity [368]. Valkova and Vacha [369] discussed the possibility that honey bees use a combination of both radical pair/cryptochromes and magnetite to detect the geomagnetic field and use it for direction like many birds.

Given these sensitivities, bees may be reacting negatively through muti-sensory mechanisms to numerous sources of anthropogenic multi-frequency interference. Bumble bees (*Bombus terrestris*), a solitary species, and honey bees (*Apis mellifera*), a social hive species, are known to detect weak electric fields in different behavioral contexts, using different sensory mechanisms. Bumble bee e-field detection is likely through mechanosensory hairs [370–372] while honey bees reportedly use their antennae [373] that are electro-mechanically coupled to the surrounding e-field, taking place in the antennal Johnston's organ. Greggers et al. [373] found that honey bee antennae oscillate under electric field stimulation that can then stimulate activity in the antennal nerve. The latter occurs due to bees being electrically charged, and thus subject to electrostatic forces. Erickson [374] found different surface potentials in bees when leaving or entering hives, and Colin et al. [375] found seasonal variability between positive and negative charges in resting bees. It has also been shown that honey bees with removed or fixed antennae are less able to associate food reward with electric field stimuli and that bees emanate modulated electric fields when moving their wings (at about 230 Hz) and body (at about 16.5 Hz) during the waggle dance [373].

Electro-ecological interplay between flowers and pollinators has also been known since the 1960s and is critical to pollen transfer from flowers to bees [376–378]. It is known that as bees fly through the air, they accumulate a positive charge. Flowers, on the other hand, which are electrically grounded through their root systems, tend to have a negative charge in their petals created by surrounding air that carries around 100 V for every meter above ground. The accumulating positive charge around the flower induces a negative charge in its petals which then interacts with the positive charge in bees. In fact, bees do not even need to land on flowers for pollen transfer to occur; pollen can "jump" from the flower to the bee as the bee approaches due to charge differentials between the two. Thus, it appears that bees and flowers have been "communicating" via electric fields all along [379]. Bees can also learn color discrimination tasks faster when color cues are paired with artificial electric field cues similar to those surrounding natural flowers, but did not learn as readily in an electrically neutral environment [370].

This evidence points to floral e-fields being used in a co-evolutionary symbiotic relationship with bees. Clarke et al. [370, 371] even found that bumblebees can distinguish between flowers that give off different electric fields as floral cues to attract pollinators. Like visual cues, floral electric fields exhibit complex variations in pattern and structure that bumblebees can distinguish, contributing to the myriad complex cues that create a pollinator's memory of floral food sources. And because floral electric fields can — and do — change within seconds of being visited by pollinators, this sensory ability likely facilitates rapid and dynamic "information exchange" between flowers and their pollinators. Bumblebees can even amazingly use electric field information to discriminate between nectar-rewarding and unrewarding flowers [370].

Bees, locusts: ELF-EMF

Bees are also known to be sensitive to anthropogenic ELF-EMF. In 1973,Wellenstein [380] found that high tension powerlines adversely affected honey bees in wooden hives. This in part prompted the Bonneville Power Administration, an American federal agency operating in the Pacific Northwest under the U.S. Department of Energy (U.S. DOE), to investigate in 1974 [381–384] the effects of transmission lines on people, plants, and animals, including honey bees. The industry group, Electric Power Research Institute, also followed up on bee research [385, 386]. Both of those studies confirmed that transmission line electric fields can affect honey bees inside wooden hives as wood is a poor insulator and current can be induced when hives are placed in electric fields whether metal is present or not. The strength of the current inside the hive was influenced by the electric field strength, hive height, and moisture conditions with effects noticeable when induced current exceeded 0.02–0.04 mA. Depending on hive height, this occurred in field strengths between 2 and 4 kV/m. Effects included increased motor activity with transient increase in hive temperature, excessive propolis production (a resinous material used by bees as a hive sealer), decreased colony weight gains, increased irritability and mortality, abnormal production of queen cells, queen loss, decreased seal brood, and poor over-winter colony survival [387]. Impacts were most likely caused by electric shocks inside the hives [386, 388]. Effects were mitigated with grounded metal screen/shielding of hives [385]; however, bees appeared unaffected by magnetic fields which permeate metal shielding. The authors concluded that the shielding results indicated that bees were unaffected by flying through an external electric field up to 11 kV/m but noted that the study design could not reveal if subtle effects were occurring.

A more recent study of electric fields by Migdał [389] focused on honey bee behavioral effects on walking, grooming, flight, stillness, contact between individuals, and wing movement. They found that the selected frequency, intensity, and duration of exposure effects bees' behavioral patterns. Bees were exposed for 1, 3 and 6 h to E-fields at 5.0 kV/m, 11.5 kV/m, 23.0 kV/m, or 34.5 kV/m (with controls under E-field <2.0 kV/m). Within the exposed groups, results showed that exposure for 3 h caused decreased time that bees spent on select behaviors as well as the frequency of behaviors, whereas after both 1 and 6 h, the behavioral parameters increased within the groups. The researchers concluded that a barrier allowing behavioral patterns to normalize for some periods was indicated although none of the exposed groups returned to reference values in controls which adhered to normal behavioral patterns. Bees may have compensatory windows that appear to be both time and intensity dependent for E-fields. The significance of this study is that bees must accomplish certain activities — like flight frequency and the honey bee 'waggle dance' noted above — that are critical for life expectancy and survival. Even slight sequential disturbances may have cascading effects.

In an early-1988 study, Korall et al. [390] also found effects to bees from magnetic fields (MF). Bursts comparable to some of today's pulsed exposures of artificial MF at 250 Hz — the frequency of buzzing during the waggle dance — were applied parallel to natural EMF field lines and induced unequivocal 'jumps' of misdirection by up to +10° in bees during the waggle dance. This alone could cause directional confusion in hives. Continuous fields of 250 Hz with bursts perpendicular to the static MF however caused no effects. They concluded that a resonance relationship other than classic resonance models was indicated (see "Mechanisms" above). This early work has implications for subsequent digital pulsing and all wireless broadband technology.

More recent work on honey bees and ELF-EMF by Shepherd et al. [209] in 2018 found that acute exposure to 50 Hz fields at levels from 20–100 μT (at ground level underneath powerline conductors), to 1,000–7,000 μT (within 1 m of the conductors), reduced olfactory learning, foraging flight success toward food sources and feeding, as well as altered flight dynamics. Their results indicated that 50 Hz ELF-EMFs from powerlines is an important environmental honey bee stressor with potential impacts on cognitive and motor abilities.

Some wasp species have also been found sensitive to ELF-EMF. Pereira-Bomfim et al. [391] investigated the magnetic sensitivity of the social paper wasp (*Polybia paulista*) by analyzing wasp behavior in normal geomagnetic fields and in the presence of external magnetic fields altered by either permanent magnets (DC fields) or by Helmholtz coils (AC fields). They evaluated the change in foraging rhythm and colony behavior, as well as the frequency of departing/homeward flights and the behavioral responses of worker wasps located on the outer nest surface. They found that the altered magnetic field from the DC permanent magnet produced an increase in the frequency of departing foraging flights, and also that wasps grouped together on the nest surface in front of the magnet with their heads and antennae pointing toward the perturbation source, possibly indicating a response to a potential threat as a defense strategy. Controls showed no such grouping behavior. The AC fields created by the Helmholtz coils also increased foraging flights, but individuals did not show grouping behavior. The AC fields, however, induced wasp workers to perform "learning flights." They concluded that for the first time, *P. paulista* demonstrated sensitivity to an artificial modification of the local geomagnetic field and that mechanisms may be due to both cryptochrone/radical pairs and magnetite.

Another flying insect model — desert locust (*Schistocerca gregaria*) — was found susceptible to entrainment by ELF-EMF. In a complex study, Shepherd et al. [392] analyzed acute exposure to sinusoidal AC 50 Hz EMF (field strength range: 10 to 10,000 μT) vs. controls on flights of individual locusts tethered between copper wire coils generating EMFs at various frequencies and recorded on high-speed video. Results found that acute exposure to 50 Hz EMFs significantly increased absolute change in wingbeats in a field-strength-dependent manner. Applying a range of ELF-EMF close to normal wingbeat occurance, they found that locusts entrained to the exact frequency of the applied EMF. They concluded that ELF exposure can lead to small but significant changes in locust wingbeats, likely due to direct acute effects on insect physiology (vs. cryptochrome or magnetite-based magnetoreception) and/or behavioral avoidance responses to molecular/physiological stress. Wyszkowska et al. [393] also found effects on locusts — exposure to ELF-EMF above 4 mT led to dramatic effects on behaviour, physiology and increased Hsp70 protein expression. Such higher exposures may be found near high tension lines.

Bees: RF-EMF

The effects of RF-EMF on bees is of increasing interest since that is the fastest rising EMF environmental exposure of the past 30 years [369]. Beginning in the early 2000s, studies of cell phones placed in the bottom of hives began to appear. Honey bees showed disturbed behavior when returning to hives after foraging and under various RFR exposures [394–396]. Early methodologies, however, were not well designed or controlled. For instance, Favre [397] found increased piping — a distress signal that honey bees give off to alert hive mates of threats and/or to announce the swarming process. Both active and inactive mobile phone handsets were placed in close proximity to honey bees with sounds recorded and analyzed. Audiograms and spectrograms showed that active phone handsets had a dramatic effect on bee behavior in induced worker piping. This study was criticized by Darney et al. [398] for using music in the active RFR exposure which may have introduced a variable capable of affecting bee piping in response to the added sound alone.

In a complex study, Darney et al. [398] tested high frequency (HF) and ultra high frequency (UHF) used in RFID technology in order to develop a method to automatically record honey bees going in and out of hives. They glued RFID tags onto individual bee dorsal surfaces that were detected at the hive entrance by readers emitting HF radio waves. They then looked for possible HF adverse effects on honey bees' survival. Eight-day-old honey bees were exposed to HF 13.56 MHz or UHF 868 MHz RFR for 2 h split into ON and OFF periods of different durations. Dead bees were counted daily with cumulative mortality rates of exposed and non-exposed honey bees compared seven days after exposure. Two out of five experimental conditions found increased mortality, once after HF and once after UHF exposure, with OFF duration of 5 min or more, after which they recommended limiting honey bee exposure to RFR to less than 2 h per day. They also curiously concluded that the RFID parameters they used for monitoring hive activity presented no adverse effects but the multifrequency peak exposures and RFID attachments need further study in light of other works on RFID effects (see Part 1 for discussion of RFID.)

In another study using an active cell phone attached to hive frames, Odemer and Odemer [399] investigated RFR effects on honey bee queen development and mating success. Control hives had an inactive cell phone attached. After exposing honey bee queen larvae to GSM 900 MHz RFR during all stages of pre-adult development (including pupation), hatching of adult queens was assessed 14 days after exposure and mating success after an additional 11 days. They found that chronic RFR exposure significantly reduced honey bee queen hatching; that mortalities occurred during pupation but not at the larval stages; that mating success was not adversely affected by the irradiation; and that after exposure, surviving queens were able to establish intact colonies. They therefore determined that mobile phone radiation had significantly reduced the hatching ratio but not mating success if queens survived, and if treated queens successfully mated, colony development was not adversely affected. Even though they found strong evidence of mobile phone RFR damage to pupal development, they cautioned its interpretation, noting that the study's worst-case exposure scenario was the equivalent of a cell phone held to a user's head, not at a level found in typical urban or rural hive settings. They concluded that while no acute negative effects on bee health were seen in the mid-term, they also could not rule out effects on bee health at lower chronic doses such as found in ambient environments, and urgently called for long term research on sublethal exposures present in major city environments.

Sharma and Kumar [400] found similar abnormalities in honey bee behavior when they compared the performance of honey bees in RFR exposed and unexposed colonies. Two of four test colonies were designated and each equipped with two functional cell phones — a high exposure — placed on two different hive side walls in call mode at GSM 900 MHz. The average RFR power density was measured at 8.549 μW/cm^2 (56.8 V/m, electric field). One control colony had a dummy phone; the other had no phone. Exposure was delivered in 15 min intervals, twice per day during the period of peak bee activity. The experiment was performed twice a week during February to April. It covered two brood cycles with all aspects of hive behavior observed, including brood area comprising eggs, larvae and sealed brood; queen proficiency in egg-laying rate; foraging, flight behavior, returning ability; colony strength including pollen storage; and other variables. Results included a significant decline in colony strength and egg laying and reduced foraging to the point where there was no pollen, honey, brood, or bees by the end of the experiment. One notable difference in this study was that the number of bees leaving the hive decreased following exposure. There was no immediate exodus of bees as a result of exposure — instead bees became quiet, still, and/or confused "…as if unable to decide what to do…" the researchers said. Such a response had not been reported before. The authors concluded that colony collapse disorder is related to cell phone radiation exposures.

Vilić et al. [401] investigated RFR and oxidative stress and genotoxicity in honey bees, specifically on the activity of catalase, superoxide dismutase, glutathione *S*-transferase, lipid peroxidation levels and DNA damage. Larvae were exposed to 900 MHz RFR at field levels of 10, 23, 41 and 120 V m^{-1} for 2 h. At a field level of 23 V m^{-1} the effect of 80% AM 1 kHz sinusoidal and 217 Hz modulation were also investigated. They found that catalase activity and the lipid peroxidation levels significantly decreased in larvae exposed to the unmodulated field at 10 V m^{-1} (27 μW/cm^2) compared to the control. Superoxide dismutase and glutathione *S*-transferase activity in honey bee larvae exposed to unmodulated fields were not statistically different compared to the control. DNA damage increased significantly in larvae exposed to modulated (80% AM at 1 kHz) field at 23 V m^{-1} (140 μW/cm^2) compared to control and all other exposure groups. Their results suggested that RFR effects in honey bee larvae manifested only after certain EMF exposure conditions. Interestingly, they found that increased field levels did not cause a linear dose-response in any of the measured parameters, while modulated RFR produced more negative effects than the corresponding unmodulated field. They concluded that while honey bees in natural environments would not be exposed to the high exposures in their experiments, the results indicated additional intensive research is needed in all stages of honey bee development since the cellular effects seen could affect critical aspects of bee health and survival.

Kumar et al. [402] also found biochemical changes in worker honey bees exposed to RFR. A wooden box was designed with glass on the front and back and wire gauze for ventilation on two sides for both exposed bees and controls. Cell phones (same make, model, and network connection) were kept in listen-talk mode for 40 min. At intervals of 10, 20 and 40 min, 10 exposed and 10 control bees were collected at the same times. Hemolymph was then extracted from the inter-segmental region of bee abdomens and analyzed. Results included increased concentration of total carbohydrates in exposed bees in the 10 min exposure period compared to unexposed bees. Increasing the exposure time to 20 min resulted in a further increase in the concentration, but exposure at 40 min had a reverse effect with declines in carbohydrate concentration although it was still higher than controls. Hemolymph glycogen and glucose content also showed the same exposure pattern — increase in content up to 20 min after which a slight decline that was still higher than controls. Changes in total lipids/cholesterol — the major energy reserves in insects — can affect numerous biological processes. Some lipids are crucial membrane structure components while others act as raw materials in hormones and pheromones. Changes in these parameters are significant to every biological activity, including reproduction. Also of interest in this study was that as exposure time increased, the bees appeared to have identified the source of disturbance. There was a large scale movement of workers toward the talk-mode (with higher RFR exposure during transmission function) but not the listening mode. Bees also showed slight aggression and agitation with wing beating. The researchers hypothesized that this increased activity could be responsible for increased energy use thereby accounting for the decrease in concentration of carbohydrates and lipids in the 40 min exposed sample. The researchers concluded that cell phone radiation influences honey bee behavior and physiology. Sharma [403] had also reported increased glycogen and glucose levels in exposed honey bee pupa.

It must be pointed out that the cell phone emission conditions used in some experiments are questionable, in particular where there was no detail regarding how the phones were activated to achieve emission.

Not all studies demonstrated adverse effects. Mall and Kumar [404] found no apparent RFR effects on brood rearing, honey production or foraging behavior in honey bees in hives with cell phones inside or near a cell tower; and Mixon et al. [405] also found no effects of GSM-signal RFR on increased honey bee aggression. They concluded that RFR did not impact foraging behavior or honey bee navigation and therefore was unlikely to impact colony health.

Although there are several anectodal reports of insect losses near communication towers, there are only a handful of ambient RFR field studies conducted on invertebrates thus far. In the first large survey of wild pollinating species at varying distances from cell towers, Lázaro et al. [406] found both positive and negative effects from RFR in a broad range of insects on two islands (Lesvos and Limnos) in the northeastern Aegean Sea near Greece. Measured ambient RFR levels included all frequency ranges used in cell communications; broadcast RFR is absent on the islands. RFR values did not significantly differ between islands (Lesvos: 0.27 ± 0.05 V/m; Limnos: 0.21 ± 0.04 V/m; v3 2 = 0.08, p=0.779) and did not decrease with the distance to the antenna, possibly, they hypothesized, because some sampling points near the antenna may have been outside or at the edge of the emission lobes. They measured RFR at four distances of 50, 100, 200 and 400 m (164, 328, 656, and 1,312 ft, respectively) from 10 antennas (5 on Lesvos Island and 5 on Limnos Island) and correlated RFR values with insect abundance (numbers of insects) and richness (general health and vitality) — the latter only for wild bees and hoverflies. The researchers conducted careful flowering plant/tree- and- insect inventories in several low-lying grassland areas, including for wild bees, hoverflies, bee flies, other remaining flies, beetles, butterflies, and of various types. Honey bees were not included in this study as they are a managed species subject to beekeeper decisions and therefore not a wild species. On Lesvos 11,547 insects were collected and on Limnos 5,544. Varied colored pan traps for both nocturnal and diurnal samples were used. Results found all pollinator groups except butterflies were affected by RFR (both positively and negatively) and for most pollinator groups effects were consistent on both islands. Abundance for beetles, wasps, and hoverflies significantly decreased with RFR but overall abundance of wild bees and bee flies significantly increased with exposure. Further analysis showed that only abundance of underground-nesting wild bees was positively related to RFR while wild bees nesting above ground were not affected. RFR effects between islands differed only on abundance of remaining flies. On species richness, RFR tended to only have a negative effect on hoverflies in Limnos. Regarding the absence of effects seen in butterflies, they hypothesized that the pan trap collection method is not efficient for collecting butterflies (butterflies accounted for only 1.3 % of total specimens), and that a different sampling method might produce a different result. They concluded that with RFR's negative effects on insect abundance in several groups leading to an altered composition of wild pollinators in natural habitats, it was possible this could affect wild plant diversity and crop production. They further said the negative relationship between RFR on the abundance of wasps, beetles and hoverflies could indicate higher sensitivity of these insects to EMFs. Potentially more EMF-tolerant pollinators, such as underground-nesting wild bees and bee flies, may fill the vacant niches left by less tolerant species, thus resulting in their population increases. Another possible explanation is that EMFs may have particularly detrimental effects on more sensitive larval stages, and if so, larvae developing above ground (many beetles, wasps, hoverflies) may be more vulnerable than those developing underground since the former could be exposed to higher radiation levels.

In another field study, Taye et al. [407] placed five hives from December to May at varying distances of 1,000, 500, 300, 200 and 100 m (3,280, 1,640, 984, 656 and 328 ft, respectively) from a cell tower in India to measure flight activity, returning ability, and pollen foraging efficiency in honey bees (*Apis cerana* F). They found most effects closest to towers with the least returning bees at 100 m distance from the tower. Maximum foraging and return ability to the colonies was seen at 500 m, followed by 1,000 m and in descending order at 300 and 200 m, with the fewest returning bees at 100 m from the tower. The study also found that if bees returned, the pollen load per minute was not significantly affected.

Vijver et al. [408] however challenged the accuracy of distance from towers that is often used as a proxy for EMF gradients such as the study above. In a field study in The Netherlands, the researchers tested exposure to RFR from a cell base station (GSM 900 MHz) on the reproductive capacity of small virgin invertebrates during the most sensitive developmental periods spanning preadolescent to mating stages when reproductive effects would most likely be seen. Careful RFR field measurements were taken to determine null points in order to see if distance from emitters is a reliable RFR exposure model in field studies. They exposed four different invertebrate hexapod species. Springtails (*Folsomia candida*), predatory 'bugs' (*Orius laevigatus)*, parasitic wasps (*Asobara japonica)*, and fruitflies (*D. melanogaster*) were placed in covered pedestal containers within the radius of approximately 150 m of a 900 MHz mobile phone base station for a 48-h period. Six control groups were placed within 6.6 ft (2 m) of the treatment groups and covered in Farady cages. After exposure, all groups were brought to the laboratory to facilitate reproduction with resulting fecundity and number of offspring then analyzed. Results showed that distance was not an adequate proxy to explain dose-response regressions. After complex data synthesis, no significant impact from the exposure conditions, measures of central tendency, or temporal variability of EMF on reproductive endpoints were found although there was some variability between insect groups. As seen in other studies, distance is often used to create a gradient in energy exposures in studies but this study found the intensity of the transmitter and the direction of transmission to be more relevant, as did Bolte and Eikelboom [409, 410]. The direction and tilt of the transmitter determines whether the location of interest in field studies is in the main beam. In some instances, the closer promixity to the transmitter provided lower readings than further away, which they found between two locations. They also noted that the organisms selected in the study were small in size; springtails have a body length on average of 2 mm; wasps are about 3 mm, insect sizes from 1.4 to 2.4 mm, with the largest organisms tested being female fruit flies at about 2.5 mm length and males slightly smaller. Due to size, limited absorption and little energy uptake capacity, none of these insects are efficient whole-body receptors for 900 MHz waves with a wavelength of approximately 13 in (33 cm). But they further noted that this was a linear regression study and that biological effects are often non-linear. However, finding no distinct effects did not exclude physiological changes. They concluded that because of RFR exposure's increasing ubiquity, urgent attention to potential effects on biodiversity is needed.

The issue of insect size, nonlinearity, and antenna tilt/direction are factors of critical importance with 5G radiation which will create extremely complex near- and- far-field ambient exposures to species in urban and rural environments alike, not only from a densification of small cell antennas close to the ground but also from increased satellite networks circling in low Earth orbits (see Part 1). The range of frequencies used for wireless telecommunication systems will increase from below 6 GHz (2G, 3G, 4G, and WiFi) to frequencies up to 120 GHz for 5G which, due to smaller wavelengths, is therefore a better resonant match for small insects. An alarming study by Thielens et al. [411], drawing on numerous robust studies of RFR's decades-long use as a thermal insecticide, modeled absorbed RFR in four different types of insects as a function of frequency alone from 2 to 120 GHz. A set of insect models was obtained using novel Micro-CT (computer tomography) imaging and used for the first time in finite-difference time-domain electromagnetic simulations. All insects showed frequency-dependent absorbed power and a general increase in absorbed RFR at and above 6 GHz, in comparison to the absorbed RFR power below 6 GHz. Their simulations showed that a shift of 10% of the incident power density to frequencies above 6 GHz would lead to an increase in absorbed power between 3–370% — a large differential of serious potential consequence to numerous insect species.

Using a similar approach, Thielens et al. [412] focused on the western honey bee (*Apis mellifera*) with RF-EMF, using a combination of *in-situ* exposure measurements near bee hives in Belgium and numerical simulations. Around five honey bee models were exposed to plane waves at frequencies from 0.6 to 120 GHz — frequencies carved out for 5G. Simulations quantified whole-body averaged RFR absorbed as a function of frequency and found that the average increased by factors of 16–121 (depending on the specimen) when frequency increased from 0.6 to 6 GHz for a fixed incident electric field strength. A relatively small decrease in absorption was observed for all studied honey bees between 12 and 120 GHz due to interior attenuation. RFR measurements were taken at 10 bee hive sites near five different locations. Results found average total incident RFR field strength of 0.06 V/m; those values were then used to assess absorption and a realistic rate was estimated between 0.1 and 0.7 nW. They concluded that with an assumed 10% incident power density shift to frequencies higher than 3 GHz, this would lead to an RFR absorption increase in honey bees between 390 and 570% — a frequency shift expected with the buildout of 5G.

The two previous studies alone should give pause regarding environmental effects to invertebrates in these higher 5G frequency ranges.

Kumar [413] noted that RFR should be included as causal agents of bee CCD and that test protocols need to be standardized and established. Standardization is critical since many studies conducted with cell phones in hives are of very uneven quality and only indicative of potential effects. Placing cell phones in hives and assuming that RFR is the only exposure is inaccurate and misleading. ELF-EMFs are always present in all telecommunications technology, using pulsed and modulated signals [414]. All of these characteristics have been found to be highly biologically active apart from frequency alone. Such studies are likely capturing ELF effects without identifying them. All aspects of transmission, including transmission engineering itself from towers, need to be considered to determine accurate exposures and delineate causative agents. Vibration and heat must also be considered — cell phones in transmission mode could raise hive temperature quickly and bees are highly temperature sensitive. Due to "waggle dance" specifics in creating foraging "roadmaps," bees should not be artificially relocated from hives to determine return ability after EMF exposure. They may be confused by relocation alone, adversely affecting their return abilities. Such tests also involve only one stressor when there are multiple stressors on insect species today. Understanding such cofactors is critical in determining accurate data and outcomes [415, 416]. Translating laboratory studies to field relevance has always been problematic but understanding EMF effects to insects has become urgent with ever increasing low-level ambient exposure from devices and infrastructure, especially in light of the new 5G networks being built. There are numerous variables that studies have yet to factor in. All of the above indicates a critical need to standardize experimental protocols and to take electroecology far more seriously, especially regarding aerial species in light of 5G.

Aquatic environments

There are fundamental electrical differences in conductivity (how well a material allows electric current to flow) and resistivity (how strongly a material opposes the flow of electric current) between air and water. Through water, EMF propagation is very different than through air because water has higher permittivity (ability to form dipoles) and electrical conductivity. Plane wave attenuation (dissipation) is higher in water than air, and increases rapidly with frequency. This is one reason that RFR has not traditionally been used in underwater communication while ELF has been. Conductivity of seawater is typically around 4 S/m, while fresh water varies but typically is in the mS/m range, thus making attenuation significantly lower in fresh water than in seawater. Fresh water, however, has similar permittivity as sea water. There is little direct effect on the magnetic field component in water mediums; propagation loss is mostly caused by conduction on the electric field component. Energy propagation continually cycles between electric and magnetic fields and higher conduction leads to strong attenuation/dissipation of EMF [98].

Because of these essential medium differences, electroreceptor mechanisms in aquatic species may be very different than those previously described in aerial species since air is a less conductive and resistive medium with less attenuation. That is why RFR travels more easily and directly through air. In aquatic species electroreception may be a result of transmission via water directly to the nervous system through unique receptor channels called Ampullae of Lorenzini [371]. In frogs, amphibians, fish, some worm species and others, receptor channels may be through the skin as well as via mechanisms more common in aerial species such as in the presence of magnetite (see "Mechanisms" above). There can be great variation in electroreceptive sensitivities in species inhabiting the two fundamentally different environments. Some amphibian species, however, have physical characteristics that span both mediums and therefore varied magnetoreception mechanisms.

Amphibians: frogs, salamanders, reptiles: regeneration abilities

Amphibians are the class of animals that include frogs, toads, salamanders, newts, some reptiles, and caecilians. The common term ‘frog’ is used to describe thousands of tailless amphibian species in the Order *Anura*. There are over 6,300 anuran species recorded thus far, with many more likely disappearing today due to climate change and other factors before we even knew they existed. Informal distinctions are made between frogs (thin-skinned species) and toads (thick, warty skins) but such distinctions are not used for taxonomic reasons. While the greatest concentration of diverse frog species is in tropical rainforests, they are widely found all over the world from the tropics to subarctic regions. Most adult frogs live in fresh water and/or on dry land while some species have adapted to living in trees or underground. Their skin varies in all manner of colors and patterns, from gray/green and brown/black to bright reds/yellows.

Frog skin is smooth and glandular — something of concern given nascent 5G technology (see Part 1) — and can secrete toxins to ward off predators. Frog skin is also semi-permeable which makes them highly susceptible to dehydration and pollutants. With radical weather shifts due to climate change and unpredictable swings between abnormal droughts followed by flooding in previously weather-stable regions, environmentally sensitive amphibians like frogs are considered bell-weather species. Frequently, time may be insufficient for some local/regional species to regenerate in between radical weather cycles, leading to population collapse.

Since the 1950s, there has been a significant decline in frog populations with more than one third of species today considered threatened with extinction while over 120 species are already believed to have gone extinct since the 1980s [10, 417, 418]. This amphibian decline is considered part of an ongoing global mass extinction, with population crashes as well as local extinctions creating grave implications for planetary biodiversity [419]. Amphibian extinction results are from climate change [420–422]; habitat loss/destruction [423, 424]; introduced species [425]; pollution [426], parasites [423, 427]; pesticides, herbicides and fungicides [428–430]; disease [431–435]; and increased ultraviolet-B radiation [436–439] among others. Anthropogenic sound pollution may also affect amphibian call rates and therefore impact reproduction [440] and artificial night lights affect male green frog (*Rana clamitaus melanota*) breeding [441]. Nonionizing electromagnetic fields may also play a role [442].

McCallum [443] calculated that the current extinction rate of amphibians could be 211 times greater than their pre-anthropogenic natural “background extinction” rate with the estimate rising 25,000–45,000 times if endangered species are also included in the computation. Today, declining amphibian populations are seen in thousands of species across numerous ecosystems, including pristine forested areas [418] and declines are now recognized among the most severe impacts of the anthropocene era [417, 442].

In addition, the number of frogs with severe malformations often incompatible with survival has risen sharply. Deformities are a complex issue related to physiology, anatomy, reproduction, development, water quality, changing environmental conditions, and ecology in general. Any time deformities are observed in large segments of wildlife populations there are indications of serious environmental problems [442]. Amphibian malformations are presumed due to an aggressive infectious fungal disease called Chytridiomycosisy, caused by the chytrid fungi *Batrachochytrium dendrobatodis* and *Batrachochytrium salamandrivorans* [432–435], and by parasites like *Ribeiroia ondatrae* [427]. Chytridiomycosis has been linked to dramatic amphibian declines and extinctions in North, Central, and South America, across sections of Australia and Africa and on Caribbean islands like Dominica and Montserrat. First identified in the 1970s in Colorado, U.S., it continues to spread globally at an alarming rate. Some populations witness sporadic deaths while others experience 100% mortality. There is no effective measure to control the disease in wild populations. Herbicides like glyphosate used in Roundup™ and atrazine, an endocrine disruptor, have also been found to cause severe malformations in both aquatic and land amphibian species from farmland pesticide/herbicide/fungicide runoff [428–430].

Frogs are known to be highly sensitive to natural and manmade EMF. Much research into the electrophysiology of frogs has been conducted because they are good lab models for human nervous system research, readily available, and easily handled. As far back as 1780, the Italian physicist Luigi Galvani discovered what we now understand to be the electrical basis of nerve impulses while studying static electricity (the only kind then known) when he accidentally made frog leg muscles contract while connected to the spinal cord by two different metal wires [444]. Galvani thought he had discovered "animal magnetism” but had actually discovered direct current and what later became known as a natural “current of injury”—the process by which an injured limb, for instance, produces a negative charge at the injury site that will later turn to a positive charge at the same site in some species as discovered in the 1960s by Robert O. Becker [444–451]. The earliest curiosity about natural current continued throughout the 1800s on various aspects of EMF and later throughout the 1920s to 1940s in pioneering researchers Elmer J. Lund [452–454] and Harold Saxon Burr [455–457] who worked to establish the first unified electrodynamic field theory of life, using hydra, frog, and salamander models among several others because of their morphogenic properties [458]. While frogs do not regenerate limbs the way salamanders do, both are so similar in taxonomy that curiosity was high in the early pioneers cited above throughout the 1960s to 1990s about what fundamentally allowed limb regeneration in one species, by not the other. Much was learned in the process about amphibian electrophysiology and cellular microcurrent in wound healing, as well as the electrophysiological properties of cellular differentiation, and eventually dedifferentiation pertinent to all contemporary stem cell research. Today the implications of this early work have gained new interest and targeted research regarding endogenous microcurrent and limb regeneration potential in humans, as well as dediffentiation/stem cell/morphogenesis in general for cancer treatment and other healing modalities. For a thorough review of studies on morphogenesis see Levin [459].

Ubiquitous low-level ambient EMFs today match some of the natural low-level microcurrent found critical to the fundamental processes of amphibian growth, reproduction, morphogenesis, and regeneration, lending new meaning to the early research that defined amphibian electrophysiology. We just need to make far better use of it to understand what role, if any, today's ambient exposures may be contributing to amphibian losses. (To compare tables between rising ambient EMF levels and low level effects in wildlife, see Part 1, Supplement 1; and Part 2, Supplement 3.)

Amphibian and reptile magnetoreception

How amphibians perceive natural and manmade EMF is similar to other species reviewed above and for amphibian mechanism reviews see Phillips et al. [460, 461]. Like many bird and insect species, evidence indicates that amphibians perceive the Earth's geomagnetic fields by at least two different biophysical magnetoreception mechanisms: naturally occurring ferromagnetic crystals (magnetite), and light-induced reactions via specialized photo-receptor cells (cryptochromes) that form spin-correlated radical pairs. Like birds, both mechanisms are present in some amphibians. Cryptochromes provide a directional 'compass' and the non-light-dependent magnetite provides the geographical 'map.'

In a thorough discussion of many magnetoreception studies in anura and urodela species, Diego-Rasilla et al. [462] found evidence that Iberian green frog tadpoles (*Pelophylax perezi*) had a light-dependent magnetic compass, and Diego-Rasilla et al. [463] also found that tadpoles of the European common frog (*Rana temporaria*) are capable of using the Earth's magnetic field for orienting along a learned y-axis. In these studies, they investigated if this orientation is accomplished using a light-dependent magnetic compass similar to that found in the earlier experiments with other species of frogs and newts [460, 462–470] or from some other factor. They concluded that the magnetic compass provided a reliable source of directional information under a wide range of natural lighting conditions. They also compared their findings to studies [470] that showed the pineal organ of newts to be the site of the light-dependent magnetic compass, as well as to recent neurophysiological evidence showing magnetic field sensitivity located in the frog frontal organ which is an outgrowth of the pineal gland. They hypothesized this work could indicate a common ancestor as long ago as 294 million years.

To determine if orientation using Earth's magnetic fields changed according to seasonal migration patterns, Shakhparonov and Ogurtsov [471] tested marsh frogs (*Pelophylax ridibundus*) in the laboratory to see if frogs could determine migratory direction between the breeding pond and their wintering site according to magnetic cues. Adult frogs (n=32) were tested individually in a T-maze 127 cm long inside a three-axis Helmholtz coil system (diameter 3 m). Maze arms were positioned parallel to the natural migratory route and measured in accordance with the magnetic field. Frogs were tested in the breeding migratory state and the wintering state, mediated by a temperature/light regime. Frog choice in a T-maze was evident when analyzed according to the magnetic field direction. They moved along the migratory route to the breeding pond and followed the reversion of the horizontal component of the magnetic field. The preference was seen in both sexes but only during the breeding migratory state. They concluded that adult frogs obtained directional information from the Earth's magnetic field.

Diego-Rasilla et al. [472] found similar evidence in two species of lacertid lizards (*Podarcismuralis and Podarcis lilfordi*) that exhibited spontaneous longitudinal body axis alignment relative to the Earth's magnetic field during sun basking periods. Both species exhibited a highly significant bimodal orientation along the north-northeast and south-southwest magnetic axis. Lizard orientations were significantly correlated over a five-year period with geomagnetic field values at the time of each observation. This suggested the behavior provides lizards with a constant directional reference, possibly creating a spacial mental map to facilitate escape. This was the first study to provide spontaneous magnetic alignment behavior in free-living reptiles although studies of terrapins have also found such spontaneous magnetic alignment [92, 323, 473]. Nishimura et al. [474, 475] also found sensitivity to ELF-EMF (sinusoidal 6 and 8 Hz, peak magnetic field 2.6 μT, peak electric field (10 V/m) in a lizard species (*Pogona vitticeps*) as demonstrated by significant increased tail lifting — a reproductive behavior. Interestingly, this tail-lifting response to ELF-EMF disappeared when the parietal eye was covered, suggesting that the parietal eye contributes to light-dependent magnetoreception and that exposure to ELF-EMFs may increase magnetic-field sensitivity in the lizards. A further experiment [476] showed that light at a wavelength lower than 580 nm was needed to activate the light-dependent magnetoreception of the parietal eye.

Amphibians: RF-EMF

Most frogs spend significant time on land but lay eggs in water where they hatch into tadpoles with tails and internal gills. However, some species bypass the tadpole stage and/or deposit eggs on land. Frogs are thus subject to exposures from both land-based and aquatic environments. A frog's life cycle is complete when metamorphosis into an adult form occurs. Many adverse effects do not appear until after metamorphosis is completed but problems have been found throughout the entire life cycle after exposures to both ELF-EMF and RFR.

Most early research on frogs (other than the Becker et al. regeneration inquiries noted above) was conducted at high thermal levels rarely encountered in the environment but some are included here because they helped delineate amphibian electrophysiology with effects later supported in low-level research. Some early work did use frog models to investigate cardiac effects with lower intensity exposures. Levitina [477] found that intact frog whole-body exposure caused a decrease in heart rate, while irradiation of just the head caused an increase. Using VHF frequency RFR at a power density of 60 $\mu W/cm^2$, A=12.5 cm, Levitina attributed the cardiac changes to peripheral nervous system effects but according to Frey and Siefert [478], because of the wavelengths used in that study, little energetic body penetration would be expected. They said a skin receptor hypothesis was therefore reasonable.

Following on Levitina's work, Frey and Seifert [478] — using isolated frog hearts, UHF frequencies that penetrate tissue more efficiently and low intensity pulse modulation — found that pulsed microwaves at 1,425 GHz could alter frog heart rates depending on the timing of exposure between the phase of heart action and the moment of pulse action. Twenty-two isolated frog hearts were irradiated with pulses synchronized with the P-wave of the ECGs; pulses were of 10 s duration triggered at the peak of the P-wave. Two control groups were used without RFR exposures with no effects noted. They found heart rate acceleration occurred with pulsing at about 200 ms after the P-wave. But if the pulse occurred simultaneously with the P-wave, no increases were induced. Arrhythmias occurred in half the samples, some resulting in cardiac cessation. Clearly from this study, RFR affected frog heart rhythm and could cause death.

A more recent work by Miura and Okada [479] found severe vasodilation in frog foot webs from RFR. In a series of three experiments using 44 anesthetized frogs (*X. laevis*) at thermal and non-thermal intensities, researchers exposed foot webs to pulsed RFR in three parameters with the monitor coil set at 1 V peak-to-peak: 100 kHz 582-3 mG and 174.76 V cm^{-1}; 10 MHz 7.3 mG and 2.19 V cm^{-1}; 1 MHz 539 mG and 16.11 V cm^{-1}. They found not only dilated arterioles of the web which had already been re-constricted with noradrenaline, but also dilated arterioles under non-stimulated conditions. Vasodilatation increased slowly and reached a plateau 60 min after radiation's onset. After radiation ceased, vasodilation remained for 10–20 min before slowly subsiding. Vasodilation was optimum when pulsation was applied 50% of the total time at a 10 kHz burst rate at 10 MHz. Effects were non-thermal. The pattern of vasodilation induced by warm Ringer solution was different from the vasodilatory effect of weak RFR, involving the level of intracellular Ca^{2+}. They hypothesized that since Ca^{2+} ATPase is activated by cyclic GMP which is produced by the enzymatic action of guanylate cyclase, RF-EMF may activate guanylate cyclase to facilitate cyclic GMP production. They concluded the study indicates for the first time that RFR dilates peripheral resistance vessels by neither pharmacological vasodilator agents nor physical thermal radiation, but that the precise mechanisms of activation of guanylate cyclase by RFR at the molecular level required further study. Vasodilation and constriction affects every part of the body and can affect all organ systems.

Prior to this, Schwartz et al. [480] found changes in calcium ions in frog hearts in response to a weak VHF field that was modulated at 16 Hz. This would be an exposure common in the environment. Calcium ions are critical to heart function.

Balmori [24–30, 442] and Balmori and Hallberg [271] have focused widely on EMF effects to wildlife, with two papers on amphibians. Balmori [442], in a review, noted that RFR in the microwave range is a possible cause for deformations and decline of some amphibian populations, and Balmori [481] in 2010 found increased mortality in tadpoles exposed to RFR in an urban environment. In the 2010 study, tadpoles of the common frog (*Rana temporaria*) were exposed to RFR from several mobile phone towers at a distance of 459 ft (140 m). Two month exposures lasted through egg phase to advanced tadpole growth prior to metamorphosis. RF and MW field intensity between 1.8 and 3.5 V/m (0.86–3.2 μW/cm^2) were measured with three different devices. Results determined that the exposed group (n=70) had low coordination of movements and asynchronous growth that resulted in both large and small tadpoles, as well as a disturbing 90% high mortality rate. In the control group (n=70) a Faraday cage was used under the same conditions. Controls found movement coordination to be normal and development synchronous with mortality rate at a low 4.2%. These results indicated that RFR from cell towers in a field situation could affect both development and mortality of tadpoles. Prior to this study, Grefner et al. [482] also found increased death in tadpoles (*Rana temporaria* L.) exposed to EMF, as well as higher mortality rates, and slower less synchronous development.

Mortazavi et al. [483] found changes in muscle contractions in frogs exposed to 900-MHz cell phone radiation for 30 min; gastrocnemimus muscles were then isolated and exposed to a switched on/off mobile phone radiation for three 10-min intervals. The authors reported RFR-induced effects on pulse height and latency period of muscle contractions. SARs of the nerve-muscle preparation were calculated to be 0.66 (muscle) and 0.407 (nerve) W/kg.

Rafati et al. [484] investigated the effects of RFR on frogs from mobile phone jamming equipment emitting RFR in the same frequencies as mobile phones. (Although illegal in many countries, jammers are nevertheless used to interfere with signals and stop communication.) The study sought to follow up on reports of non-thermal effects of RFR on amphibians regarding alterations of muscle contraction patterns. They focused on three parameters: the pulse height of leg muscle contractions, the time interval between two subsequent contractions, and the latency period of frog's isolated gastrocnemius muscle after stimulation with single square pulses of 1 V (1 Hz). Animals in the jammer group were exposed to RFR at a distance of 1 m from the jammer's antenna for 2 h while the control frogs were sham exposed. All were then sacrificed and isolated gastrocnemius muscles were exposed to on/off jammer radiation for three subsequent 10 min intervals (SAR for nerve and muscle of the different forms of jammer radiation was between 0.01 and 0.052 W/kg). Results showed that neither the pulse height of muscle contractions nor the time interval between two subsequent contractions were affected, but the latency period (time interval between stimulus and response) was statistically significantly altered in the RFR-exposed samples. They concluded the results supported earlier reports of non-thermal effects of EMF on amphibians including the effects on the pattern of muscle contractions. Control sham exposed samples showed no effects.

Amphibians, reptiles: ELF-EMF

Amphibians are highly sensitive to ELF-EMF. An early-1969 study by Levengood [485] using a magnetic field probe found increased high rates of teratogenesis in frogs (*Rana sylvatica*) and salamanders *(Ambystoma maculatum*). Two identical probes using different field strengths were employed — both operated in the kilogauss region with high field gradients. Amphibian eggs and embryos were exposed at various stages of development with gross abnormalities found in developing larvae vs. control. At the hatching stage severe abnormalities were noted in both anuran and urodele larvae from probe-treated eggs. Hatching abnormalities included microcephaly, altered development, and multiple oedematous growths. In probe-treated frogs there was a delay in the appearance of a high percentage of malformations until the climax stage of metamorphosis. Until that stage, the larvae were of the same appearance as control specimens, thus camouflaging the damage after just a brief treatment of early embryos. The frog abnormalities at metamorphosis differed from those in the hatching tadpoles and consisted mainly of severe subepidermal blistering and leg malformations including formation of multiple deformed limbs incompatible with life. Over 90% of the morphological alterations at metamorphosis climax were also found to be associated with deformed kidneys. The gastrula stages of development appeared to be the most sensitive in the delayed-effects category. While this was a high-field exposure experiment, it is an intensity that is found in some environments today especially near high tension lines and in abnormal ground current situations.

Neurath [486] also found strongly inhibited early embryonic growth of the common leopard frog (*Rana pipiens*) by a high static magnetic field with a high gradient (1T) — an exposure sometimes found in the environment — while Ueno and Iwasaka [487] found abnormal growth and increased incidence of malformations in embryos exposed to magnetic fields up to 8T but exposures that high are typically near industrial sites and rarely found in nature.

Severini et al. [488] specifically addressed whether weak ELF magnetic fields could affect tadpole development and found delayed maturation in tadpoles. Two cohorts of *X. laevis laevis* (Daudin) tadpoles were exposed for 60 days during immaturity to a 50 Hz magnetic field of 63.9–76.4 μT rms (root mean square, average values) magnetic flux density in a solenoid. Controls were two comparable cohorts remotely located away from the solenoid. The experiment was replicated three times. Results showed reduced mean developmental rate of exposed cohorts vs. controls (0.43 vs. 0.48 stages/day, $p< 0.001$) beginning from early larval stages; exposure increased the mean metamorphosis period of tadpoles by 2.4 days vs. controls ($p < 0.001$); and during the maturation period, maturation rates of exposed vs. control tadpoles were altered. No increases in mortality, malformations, or teratogenic effects were seen in exposed groups. The researchers concluded that relatively weak 50 Hz magnetic fields can cause sub-lethal effects in tadpoles via slowed larval development and delays in metamorphosis. Such exposures are found in the environment today in some locations and even though the changes were small, coupled with climate change, such sub-lethal effects may impact some wildlife populations in some environments.

In similar followup work, Severini and Bosco [489] found sensitivity to small variations of magnetic flux density (50 Hz, 22-day continuous exposure, magnetic flux densities between 63.9 and 76.4 μT) in tadpoles exposed to a stronger field vs. controls exposed to a weaker field. A significant delay in development of 2.5 days was found in exposed vs. controls. They concluded the delay was caused by the slightly different magnetic flux densities with results suggesting a field threshold around 70 μT in controlling the tadpole developmental rate.

Schlegel in 1997 found European blind cave salamanders (*Proteus anguinus*) and Pyrenean newts (*Euproctus asper)* to be sensitive to low level electric fields in water [490]. And Schlegel and Bulog [491] in followup work found thresholds of overt avoidance behavior to electric fields as a function of frequency of continuous sine-waves in water. Nine salamanders from different Slovenian populations of the urodele (*P. anguinus)* that included three specimens of its 'black' variety (*P. anguinus parkelj*) showed thresholds between 0.3 mV/cm (ca 100 nA/cm^2) and up to 2 mV/cm (670 nA/cm^2), with the most reactive frequencies around 30 Hz. Sensitivity included a total frequency range below 1 Hz (excluding DC) up to 1–2 kHz with up to 40 dB higher thresholds. These are ranges that may be found in the wild near high tension lines and utility grounding practices near water, by some underwater cabling, and by some RFR transmitters.

Landesman and Douglas in 1990 [492] found some newt species showed accelerated abnormal limb growth when pulsed electromagnetic fields were added to the normal limb regeneration process. While normal limb regeneration found normal regrowth patterns in 72% of specimens, 28% were abnormal. Abnormalities included loss of a digit, fused carpals, and long bone defects which occurred singly or in combination with one another. When exposure to a PEMF was added for the first 30 days post-amputation, followed by a 3–4 month postamputation period, a group of forelimbs with unique gross defects increased by an additional 12%. Defects (singly or in combination) included the loss of two or more digits with associated loss of carpals, absence of the entire hand pattern, and abnormalities associated with the radius and ulna. The researchers offered no explanation. Exposure intensities were similar to those used to facilitate non-juncture fracture healing in humans.

Komazaki and Takano in 2007 [493] found accelerated early development growth rates with 50 Hz, 5–30 mT alternating current exposures in the fertilized eggs of Japanese newts (*Cynops pyrrhogaster*). The period of gastrulation was shortened via EMF-promoted morphogenetic cell movements and increased $[Ca^{2+}]_i$. They said their results indicated that EMF specifically increased the $[Ca^2]_i$ of gastrula cells, thereby accelerating growth. This study only observed through the larval stages and they did not see any malformations under EMF exposures, which they attributed to possible differences in the intensity and mode of EMF.

With amphibians and some reptiles demonstrating high sensitivity to natural background EMF for important breeding and orientation needs, amphibians living in aquatic, terrestrial, and aerial environments (i.e. tree frog species) may be affected from multi-frequency anthropogenic EMF in ways we do not fully understand. There are potential effects — especially from 5G MMW that couple maximally with skin — to all aspects of their development and life cycles, including secondary effects.

Fish, marine mammals, lobsters, and crabs

Aquatic animals are exquisitely sensitive to natural EMF and therefore potentially to anthropogenic disturbance. The Earth's dipole geomagnetic field yields a consistent though varying source of directional information in both land and aquatic species for use in homing behavior, orientation during navigation and migration. This information is used both as a 'map' for positional information as well as a 'compass' for direction [494–497]. Aquatic species are known to be sensitive to static geomagnetic fields, atmospheric changes and sunspot activities [498]. For recent comprehensive reviews on magnetic field sensitivity in fish and effects on behavior, see Tricas and Gill [36] and Krylov et al. [33]. Some biological 'magnetic maps' may be inherited [499]. And for a recent extensive discussion of the Earth's natural fields and magnetoreception in marine animals with a focus on effects from electromagnetic surveys that use localized strong EMFs to map petroleum deposits under seabeds, see Nyqvist et al. [498] and below.

As mentioned above, because of the difference in conductivity of water and other factors, the way some aquatic species sense EMF may rely on unique modes of physiological perception, as well as those employed by terrestrial animals. There may also be sensory combinations not yet understood in some aquatic and semi-aquatic species. For instance, what role does the neural conductivity of whiskers (vibrissae) in seals, sea lions and walrus play other than for food finding? Aquatic species' dense network of whiskers is larger with greater blood flow than terrestrial species and can contain 1,500 nerves per follicle vs. cats at 200 per follicle. Seal whiskers also vary geometrically from terrestrial species and the largest part of the seal brain is linked to whisker function. Seals use whiskers to map the size, shape and external structure of objects and can find prey even when blindfolded. Their whiskers are also sensitive to weak changes in water motion [100]. But are they also using them as a location or directional compass in relation to the geomagnetic field? That has yet to be studied.

Unique sensory differences in aquatic species have long been documented. Joshberger et al. [500] noted that in 1,678 Stefano Lorenzini [501] was the first to describe a network of organs in the torpedo ray that became known as the Ampullae of Lorenzini (AoL). Its purpose was unknown for 300 years until Murray [502] measured AoL's electrical properties in elasmobranch fish — sharks, rays and skates. Later work [101, 503–508] confirmed and greatly added to this knowledge. Researchers now know that AoL is likely the primary mechanism that allows elasmobranch fish to detect and map a potential prey's physiology via the very weak changes in electric fields given off by prey's muscle contractions.

Individual ampullae are skin pores that open to the aquatic environment with a jelly-filled canal leading to an alveolus containing a series of electrosensing cells. Within the alveolus, the electrosensitive cells of the ampullae communicate with neurons and this integration of signals from multiple ampullae is what allows elasmobranch fish to detect electric field changes as small as 5 nV/cm [503, 506, 509, 510]. The AoL jelly has been reported as a semiconductor with temperature-dependence conductivity and thermoelectric behavior [500, 509, 510], as well as a simple ionic conductor with the same electrical properties as the surrounding seawater [503, 506]. Josberger et al. [500] attempted to clarify what AoL's role is in electrosensing by measuring AoL's proton conductivity. They found that room-temperature proton conductivity of AoL jelly is very high at 2 ± 1 mS/cm — only 40-fold lower than some current state-of-the-art manmade proton-conducting polymers. That makes AoL the highest conductive biological material reported thus far. They suggested that the polyglycans contained in the AoL jelly may contribute to its high proton conductivity.

Other aquatic magneto-sensory mechanisms more in harmony with terrestrial animals include the presence of ferromagnetic particles in magnetite — tiny naturally produced magnets that align with the Earth's magnetic field, allowing for species' direction and orientation. Magnetite appears to transmit necessary information through a connection with the central nervous system [340, 497, 511]. A magnetite-based system is plausible for cetaceans [512, 513] as magnetite has been found in the meninges dura mater surrounding the brains of whales and dolphins [514, 515]. There is also evidence that local variations/anomalies in the geomagnetic field in certain underwater topographies may play a role in live cetacean strandings [516, 517] which indicates a magnetic compass based on magnetite. And free-ranging cetaceans have shown evidence of magnetoreception-based navigation, e.g., Fin whale migration routes have been correlated with low geomagnetic intensity [513].

Recently, Granger et al. [518] found correlations in data between 31 years of gray whale (*Eschrichtius robustus*) strandings and sunspot activity, especially with RF 'noise' in the 2,800 MHz range. The 11-year sunspot cycle strongly correlates with the intense releases of high-energy particles known as solar storms which can temporarily modify the geomagnetic field, and in turn may modify orientation in magnetoreceptive species. Solar storms also cause an increase in natural broadband RF 'noise'. They examined changes in both geomagnetic fields and RF 'noise' and found RF to be a determinant. Further, they hypothesized that increased strandings during high solar activity is more likely due to radical pair mechanisms which are more reactive with RFR than magnetite, which appears more reactive to ELF-EMF. Two previous studies also found correlations with cetacean strandings and solar activities [519, 520]. Both mechanisms may come into play under different circumstances or act in synergy.

Kremers et al. [512] investigated the spontaneous magnetoreception response in six captive free-swimming bottlenose dolphins (*Tursiops truncates*) to introduced magnetized and demagnetized devices used as controls. They found a shorter latency in dolphins that approached the device containing a strong magnetized neodymium block compared to a control demagnetized block identical in form and density and therefore indistinguishable with echolocation. They concluded that dolphins can discriminate on the basis of magnetic properties — a prerequisite for magnetoreception-based navigation. Stafne and Manger [521] also observed that captive bottlenose dolphins in the northern hemisphere swim predominantly in a counter-clockwise direction while dolphins in the southern hemisphere swim predominantly in clockwise direction. No speculation was offered for this behavior.

How salmon navigate vast distances — from their hatching grounds in freshwater river bottoms to lakes during juvenile growth, then the open ocean during maturity, and with a final return to their neonatal birthing grounds to spawn and die (for most anadromous salmonids) — has fascinated researchers for decades. Research indicates they may use several magneto-senses to accomplish this, including inherited mechanisms [522], imprinting [499, 522], a magnetic compass [499, 522, 523], and biomagnetic materials. Salmon have been found to have crystal chains of magnetite [524]. One recent study found that strong magnetic pulses were capable of disrupting orientation in salmon models [525], indicating a magnetite-based mechanism. In salmon, the migration process is complicated by the fact that the ability to sense geomagnetic fields can be altered by changes in salinity between fresh and salt water, thus pointing to multi-sensory mechanisms [499].

Speculation that salmon use the geomagnetic field in some capacity for their iconic migration goes back decades [526]. Quinn [527] found evidence that sockeye salmon (*Oncorhynchus nerka*) frey use both a celestial and magnetic compass when migrating from river hatching to lakes. Putman et al. [499], who have written extensively on this subject, focused on how salmon navigate to specific oceanic feeding areas — a challenge since juvenile salmon reach feeding habitats thousands of kilometers from natal locations. The researchers experimentally found that juvenile Chinook salmon (*Oncorhynchus tshawytscha*) responded to magnetic fields similar to latitudes of their extreme ocean range by orienting in directions that would lead toward their marine feeding grounds. They further found that fish use the combination of magnetic intensity and inclination angle to assess their geographic location and concluded that the magnetic map of salmon appears to be inherited since the fish had no prior migratory experience. These results, paired with findings in sea turtles (see below), indicate that magnetic maps are widespread in aquatic species and likely explain the extraordinary navigational abilities seen in long-distance underwater migrants [499].

It is less likely that light-sensing radical pair cryptochromes play much of a role in aquatic species though some hypothesize the possibility [528]. Krylov et al. [33], however, noted that there are no anatomical structures or neurophysiological mechanisms presently known for radical pair receptors in the brains of fish and that since light decreases with water depth and fish are capable of orienting in complete darkness using the geomagnetic field, their opinion was that it is too early to say fish have magnetoreception mechanisms based on free radicals, light-dependent or otherwise.

Fish, lobsters, crabs: ELF-EMF

For several reasons having to do with differences in conductivity in water vs. air (see above), RFR is of far less concern in aquatic environments at present than is ELF. With the ever-increasing number of underwater cables used for everything from transcontinental data/communications to power supplies for islands, marine platforms, underwater observatories, off-shore drilling, wind facilities, tidal and wave turbines among others, many new sources of both AC and DC electric current are being created in sea and freshwater environments alike. According to Ardelean and Minnebo writing in 2015 [529], almost 4,971 mi (8,000 km) of high voltage direct current (HVDC) cables were present on the seabed worldwide, 70% of which were in European waters, and this is only expected to grow dramatically as new sources of renewable energy are built to replace fossil fuels globally.

Curiosity about potential adverse effects from cable-generated ELF-EMF on all phases of fish life has also grown, especially in benthic and demersal species that spend significant time near cables in deeper bottom environments for egg laying, larvae growth, and development for most, if not all, of their adult lives.

Fey et al. [494, 495] and Öhman et al. [530] noted that there are two types of anthropogenic exposures created by cables: high voltage direct current (HVDC) that emits static magnetic fields, and three-phase alternating current (AC power transmission) that emit time-varying electromagnetic fields. The density of electric current near underwater cables on the sea floor can vary significantly depending on the type of cable and whether they are positioned on the sea bottom or buried [36, 530]. Noticeable magnetic field changes can occur within meters but generally not more than several meters from the cable. However, Hutchinson et al. [531], in a robust field study and extensive review, found surprisingly stronger and more complex exposures than anticipated (see below).

Since fish are highly sensitive to static magnetic fields (MF), it is important to delineate static fields from anthropogenic alternating current EMF in aquatic studies. In freshwater species under laboratory conditions, Fey et al. [494] found similar results to those of salmon studies (noted above) in northern pike (*Esox lucius*) exposed to a static magnetic field from DC cables (10 mT) during the embryonic phase and in the first six days of post-hatching. No statistically significant MF effect was seen on hatching success, larvae mortality, larvae size at hatching, and growth rate during the first six days of life. However, significant MF effects were seen on hatching time (one day earlier in a magnetic field than in control), yolk-sac size was smaller, and yolk-sac absorption rate was faster. They interpreted the faster yolk-sac absorption in a magnetic field as an indication of increased metabolic rate but added that even if some negative consequences were expected as a result, that the actual risk for increased northern pike larvae mortality seemed negligible. Though higher than 10 mT magnetic field values are hazardous for fish larvae, they added such values do not occur in the natural environment even along underwater cables.

But in follow-up work of longer duration the same general research group reached a different conclusion. Fey et al. [495] studied effects on eggs and larvae of rainbow trout (*Oncorhynchus mykiss*) exposed to a static magnetic field (MF) of 10 mT and a 50 Hz EMF of 1 mT for 36 days (i.e., from eyed egg stage to approximately 26 days post hatching). They found that while neither the static MF nor the 50-Hz EMF had significant effects on embryonic/larval mortality, hatching time, larval growth, or the time of larvae swim-up from the bottom, both fields did however enhance the yolk-sac absorption rates. While they said this was not directly related to a MF effect, it was shown that larvae with absorbed yolk-sacs by the time of swim-up were less efficient in taking advantage of available food at first feeding and gained less weight. They concluded that these exposures could negatively affect the yolk-sac absorption rate thereby hampering fish in important feeding activities needed for fast weight gain and increased survival. In an additional study, Fey et al. [532] observed that rainbow trout reared in a laboratory for 37 days and exposed to a static MF (10 mT) or a 50-Hz EMF (1 mT) showed defects in otolith of the inner ear which is responsible for hearing and balance in fish. The authors concluded that underwater construction and/or cables that emit a MF of 10 mT or higher can affect living organisms within a few meters distance, especially species like trout in settled life stages on the sediment bottom during early development.

Zebrafish (*Danio rerio*) are often used in EMF research in toxicology and developmental biology investigating effects on humans because the genomes are so similar. Li et al. [533] studied ELF-MF on the development of fertilized zebrafish embryos divided into seven groups. Embryos of experimental groups were continuously exposed to 50-Hz sinusoidal MF with intensities of 30, 100, 200, 400, or 800 μT for 96 h. The sham group was identical but without ELF-MF exposure. Results showed that ELF-MF caused delayed hatching and decreased heart rate at early developmental stages but no significant differences were seen in embryo mortality or abnormality. Acridine orange staining assays showed notable signs of apoptosis in the ventral fin and spinal column and transcription of apoptosis-related genes (caspase-3, caspase-9) was significantly up-regulated in ELF-MF-exposed embryos. They concluded that ELF-EMF demonstrated detrimental effects on zebrafish embryonic development, including on hatching, decreased heart rate, and induced apoptosis, although such effects were not a mortal threat. The lower range exposures of this study are found in some aquatic environments.

Sedigh et al. [534] investigated effects on zebrafish exposed to static magnetic fields. Exposures of 1-week acute and 3-week subacute exposures to different static magnetic fields at 2.5, 5, and 7.5 mT were measured on stress indices (cortisol and glucose), sex steroid hormones (17β-estradiol and 17-α hydroxy progesterone) and fecundity. They found a significant change in cortisol, glucose, 17β-estradiol (E_2) and 17-α hydroxy progesterone (17-OHP) levels with increased intensity and duration of exposure and concluded that static magnetic fields at higher intensities showed harmful effects on the reproductive biology of zebrafish during both acute and subacute exposures.

Recent laboratory research by Hunt et al. [535] used the transparent glass catfish (*Kryptopterus vitreolus*) found in slow moving waters in Southeast Asia as a model to investigate magnetoreception. The study used Y-maze chambers, animal tracking software and artificial intelligence techniques to quantify effects of magnetic fields on the swimming direction of catfish. They placed a permanent Neodymium Rare Earth Magnet (11.5 × 3.18 × 2.2 cm) with a horizontal magnetic flux of 577 mT at the magnet's surface at 10 cm from the end of one of the Y-maze arms and found that catfish consistently swam away from magnetic fields over 20 μT. The catfish also showed adaptability to changing magnetic field direction and location. The magnetic avoidance was not influenced by school behavior. Sham exposures produced no avoidance. Such exposures might be found near some underwater cables.

To further elucidate findings of species reactions near underwater cables and fill in knowledge gaps since the 2011 Tricas and Gill review [36], Hutchinson et al. [531] conducted both field and laboratory modeling studies of both AC and DC fields on the American lobster (*Homarus americanus*) and the little skate (*Leucoraja erinacea*). They noted that in previous studies, while behavioral responses had been seen, findings were unable to determine if significant biological effects (e.g., population changes) occurred. The American lobster was modeled because it is a magnetosensitive species [536] and concern existed that EMF from cables might restrict movements and/or migration. Lobsters may migrate up to 50 mi (80 km) one way from deep waters to shallow breeding grounds. The little skate was used as a model for the most electro-sensitive taxa of the elasmobranchs, which may be attracted by/to the EMF of cables, particularly for benthic species, thereby altering their foraging or movement behavior. Both models were therefore thought indicative of potential EMF impacts. In this robust field study, the researchers found that the American lobster exhibited a statistically significant but subtle change in behavioral activity when exposed to the EMF of the HVDC cable (operated at a constant power of 330 MW at 1,175 Amps). The little skate exhibited a strong behavioral response to EMF from a cable powered for 62.4% of the study with the most frequently transmitted electrical current at 16 Amps (at 0 MW, 37.5% of time), 345 Amps (100 MW, 28.6%) and 1,175 Amps (330 MW, 15.2%). They concluded that for both species, the behavioral changes have biological relevance regarding how they will move around and are distributed in a cable-EMF zone, but they noted that the EMF did not constitute a barrier to movements across the cable for either species.

Of interest in this study were the actual field readings near cables. Unexpected significant AC magnetic and electric fields did not match computer models and were observed to be associated with both of the DC power cables studied. The maximum observed AC values along the cable axis were 0.15 μT and 0.7 mV/m for the magnetic and electric fields respectively for one cable, and 0.04 μT and 0.4 mV/m respectively, for the other cable. Also, the cross section of the EMF peaks exhibited by the DC subsea power cables were broader than anticipated at both studied. The DC and AC magnetic fields reached background levels on either side of the cable on a scale of c.a.5 and 10 m from the peak observed value respectively, whereas the AC electric fields reached background on a scale of 100 m (328 ft) from the peak value. Peak observed values occurred almost directly above the cable axis location; there was an offset of 3.3 ft (<1 m) where the cable was twisted. The researchers noted that this observation of AC fields, with broad areas of EMF distortion being associated with DC cables, increased the complexity of interpreting the studies of EMF's biological effects from DC cables. The AC electric fields associated with the AC sea2shore cable (1–2.5 mV/m) were higher than the unanticipated AC electric fields produced by the DC cables (0.4–0.7 mV/m). The magnetic field produced by the AC sea2shore cable (range of 0.05–0.3 μT) was ~10 times lower than modeled values commissioned by the grid operator, indicating that the three-conductor twisted design achieves significant self-cancellation. This entire aspect of the study indicates the need for accurate field assessment, not just computer modeling, and well-designed systems since anomalies occur.

Nyqvist et al. [498] in a thorough review, focused on marine mammals and the use of underwater electromagnetic surveys that map petroleum deposits in seabeds via strong induced EMFs in varied directional applications. They found that EMFs created during such active surveying were within the detectable ranges of marine animals and the fields can potentially affect behavior in electro-perceptive species, but they noted that effects should be limited to within a few kilometers as the electric and magnetic fields created attenuate rapidly. They added that in migrating marine animals, exposures are of short duration and most are close to naturally occurring levels but cautioned that lack of studies is a concern, especially for the most sensitive elasmobranchs at highest risk for disturbance to electric fields. They also noted that with induced magnetic fields, animals using magnetic cues for migration or local orientation during certain time-windows for migration, orientation, or breeding, could be most affected by this surveying technology.

Taorimina et al. [537] studied both static and time-varying magnetic fields on the behavior of juvenile European lobsters (*Homarus gammarus*). Using two different behavioral assays, day-light conditions to stimulate sheltering behavior and exposures to an artificial magnetic field gradient (maximum intensity of 200 μT), they found that juvenile lobsters did not exhibit any behavioral changes compared to non-exposed lobsters in the ambient magnetic field. No differences were noted on the lobsters' ability to find shelter or modified their exploratory behavior after one week of exposure to anthropogenic magnetic fields (225 ± 5 μT) which remained similar to behavior in controls. They concluded that neither static nor time-varying anthropogenic magnetic fields at those intensities significantly impacted the behavior of juvenile European lobsters in daylight conditions, but they noted that evidence exists showing magnetosensitivity changes during different life stages in lobster species, and that since their modeling was on juveniles, their study was therefore an incomplete picture requiring further study.

Scott et al. [538] focused on ELF-EMF effects on commercially important edible/brown crab species (*Cancer pagurus*) and what they found was startling. In laboratory tanks, they simulated EMF (with Helmholtz coils, 2.8 mT evenly distributed, assessments during 24 h periods) that would be emitted from sub-sea power cables now commonly used at offshore renewable energy facilities. They measured stress related parameters ((L-lactate, D-glucose, haemocyanin and respiration rate) along with behavioral and response parameters (antennal flicking, activity level, attraction/avoidance, shelter preference and time spent resting/roaming). They found that although there was no EMF effect on haemocyanin concentrations, respiration rate, activity level or antennal flicking rate, there were significant changes in haemolymph L-lactate and D-glucose natural circadian rhythms, indicating alterations in hormones. Crabs also showed an unusually high attraction to EMF-exposed shelter areas (69%) compared to control shelter areas (9%) and significantly reduced their time roaming by 21%, with adverse implications for food foraging, mating, and overall health. They noted that EMF clearly altered behavior. Crabs spent less time roaming around the tank and more time in a shelter in direct contact with the EMF source, indicating natural roaming/food-or-mate-seeking behavior had been overridden by attraction to EMF. In fact, crabs consistently chose an EMF-exposed shelter over a non-exposed one and were always drawn to the EMF. The results appear to predict that in benthic areas surrounding EMF-emitting cables, there will be an increase in the abundance of *Cancer pagurus* present. They noted that such potential crab aggregation around benthic cables and the subsequent physiological changes in L-lactate and D-glucose levels caused by EMF exposure, is a concern regarding feeding rates, mating, and especially egg incubation directly in increased EMF environments. They concluded that long term investigations are needed regarding chronic EMF exposure, especially on egg development, hatching success and larval fitness, and added that EMF emitted in marine environments from renewable energy devices must be considered as part of the study of cumulative impacts during the planning stages.

Clearly ELF-EMF can affect myriad aquatic species at intensity levels found in proximity to underwater cables at environmental intensities.

Fish: RF-EMF

As mentioned, RFR is of minimal environmental concern for fish since aquatic environments, while highly conductive mediums, also highly attenuate EMF at higher frequencies. This may change in the near future as new technologies now exist that may surpass these obstacles [98], thereby introducing for the first time novel new RFR exposures underwater. Longer wave wireless ELF with expanded ranges are used in anthropogenic sonar (sound navigation ranging), primarily for military applications. These travel easily through water and are known to adversely affect cetaceans and other species that rely on their natural sonar for communication, migration, reproduction and food finding. But sound waves are not considered “EMF” in the strict sense of the term; since the focus of this paper is EMF, sound waves are tangential here. But acoustic damage, especially to cetaceans from military and commercial applications, is well documented and ELF cables used for underwater military submarine communications can have significant EMF exposures near cables. Just because this paper does not address impacts from sound waves in detail does not mean they are without serious effects.

There are, however, three recent studies of RFR on zebrafish included here because it is plausible that such exposures could exist near shallow aquatic environments under some circumstances. Nirwane et al. [539] studied 900-MHz GSM RFR effects on zebrafish (*D. rerio*) neurobehavioral changes and brain oxidative stress as a model for human exposures to cell phones. Exposures were applied daily for 1 h, 14 days, with SAR 1.34 W/Kg. They found 900-MHz GSM radiation significantly decreased socialization and increased anxiety as demonstrated by significant increased time spent in bottom areas, freezing behaviors, and duration and decreased distance travelled, as well as decreased average velocity and number of entries to the upper half of the tank. Exposed zebrafish spent less time in the novel arm of a Y-Maze indicating significant impaired learning compared to the control group. Exposure also decreased superoxide dismutase (SOD) and catalase (CAT) activities while increased levels of reduced glutathione (GSH) and lipid peroxidation (LPO) were encountered indicating compromised antioxidant defense. Post-exposure treatment with melatonin in the water, however, significantly reversed the induced neurobehavioral and oxidative changes.

Piccinettia et al. [540] investigated *in vivo* effects on embryonic development in zebrafish at 100 MHz thermal and nonthermal intensities via a multidisciplinary protocol. Results found 100 MHz RFR affected embryonic development from 24 to 72 h post fertilization in all the analyzed pathways. Most notably at 48 h post fertilization, reduced growth, increased transcription of oxidative stress genes, onset of apoptotic/autophagic processes and a modification in cholesterol metabolism were seen. EMF affected stress by triggering detoxification mechanisms. At 72 h post fertilization, fish partially recovered and reached hatching time comparable to controls. The researchers concluded that EMF-RFR unequivocally showed *in vivo* effects at non-thermal levels.

Dasgupta et al. [541] used embryonic zebrafish models at 3.5 GHz SAR ≈ 8.27 W/kg and exposed developing zebrafish from 6 to 48 h post fertilization, then measured morphological and behavioral endpoints at 120 h post fertilization. Results found no significant impacts on mortality, morphology or photomotor response but noted a modest inhibition of startle response suggesting some levels of sensorimotor disruptions. They concluded that exposures at low GHz levels are likely benign but nevertheless entailed subtle sensorimotor effects. Such effects can affect fish survival in various ways, including inhibited response time to predators, among others. This study was done with an eye toward potential human bioeffects at frequencies used in 4 and 5G technology. It was also conducted at intensities higher than the focus of this paper.

If new technology overcomes the conductivity/attenuation limitations of aquatic environments and introduces more RFR to aquatic species, studies like those cited above may soon have more environmental relevance, even at higher intensities than explored here.

Turtles

Oceanic sea turtle migration joins that of other renowned long-distance migratory species like salmon and over-land monarch butterfly treks, spanning thousands of kilometers and traversing multiple complex environments throughout their life cycles. Sea turtles have long been known to use geomagnetic fields for orientation [542, 543]. Freshwater species (e.g., *Chelydra serpentina*) have also been shown to have a magnetic sense capable of artificial disruption [92] as do terrestrial box turtles (*Terrapene carolina;* [544]).

Sea turtles demonstrate natal homing behavior — the ability to return over great distances to their exact birth location to reproduce [89] and because of anthropogenic disruptions of nesting grounds along beaches, this reproductive homing drive imperils them today. The underlying mechanism is still imperfectly understood but involves 'imprinting' of the intensity and inclination angle of the geomagnetic field at the birth location [545]. The information is then later used in maturity to return to their place of origin.

Sea turtles are by far the most studied models for turtle magnetoreception, especially by the Lohmann Laboratory at the University of North Carolina, U.S. [323, 546–558].

Irwin and Lohmann [559] discussed the advantages and disadvantages of various research approaches used to investigate magnetic orientation behavior in turtles. These include the use of large magnetic coil systems in laboratory settings to generate relatively uniform fields over large areas [560] which allow the magnetic field to be artificially altered and carefully controlled to determine changes in behavioral orientation. This approach, however, is unsuited for manipulating exposures around animals in natural environments or for studying localized body magnetoreceptors, which in turtles are still a mystery. Another approach is to attach a small magnet or electromagnetic coil to an animal to disrupt magnetic orientation behavior — a far easier approach in hatchlings than in juvenile or mature free-swimming species. They note that if the imposed field from an attached magnet or coil is strong enough to interfere with the Earth's field, behavioral orientation changes [116, 544, 561] and the performance of a conditioned response [367, 562] can be observed. This latter approach has been used in field studies for the purpose of blocking access to normal magnetic information [544, 561, 563–565] and to localize magnetoreceptors by disrupting the field around a specific terrapin body part [562]. This technique's disadvantage, however, is that fields rapidly change with distance from the source, making it difficult to quantify the fields that the animal actually experiences.

Most sea turtle studies have involved large magnetic coil systems but Irwin and Lohmann [559] attached small magnets greater in strength than the Earth's fields to two groups of loggerhead sea turtle hatchlings (*Caretta caretta* L.) under laboratory conditions in which turtles are known to orient magnetically [473, 546, 548–550]. They found that magnetic orientation behavior in hatchling turtles can be disrupted via small magnets attached to the carapace which then create exposures over the entire body. They concluded that such an approach can be used to finally determine local magnetoreceptors by varying the location of the magnet and using smaller, weaker magnets that alter the field only around specific anatomical target sites.

In loggerhead sea turtles, there is evidence of an inclination compass [473, 550] that is functionlly similar to the bird magnetic compass reported in European Robins [566, 567]. Lohmann and Lohmann [550] investigated an inclination compass in sea turtles and found it was a possible mechanism for determining latitude. Also investigated were detection of magnetic intensity [551]; natural regional magnetic fields used as navigational markers for sea turtles [557]; and sea turtle hatchlings' mapping abilities [545]. Sea turtles are also known to have magnetite in their heads [104, 568]. Studies with young sea turtles have shown that a significant portion of their navigational abilities involve magnetoreception following hatching [569] — imprinting with the Earth's magnetic field being one of several cues hatchlings use as they first migrate offshore [546, 554]. The magnetic fields that are unique to different areas at sea eventually serve as navigational markers to guide swimming direction to important migratory routes. As juveniles mature, they form topographical magnetic maps where they live that direct them to specific regions. But it has remained largely unknown if mature turtles, specifically nesting females, use such mechanisms in open-sea homing as this magneto-sense may change over time.

Field studies are notoriously difficult with large species at sea but Papi et al. [564] studied mature green turtles (*Chelonia mydas*) during their post-nesting migration over 1,243 mi (2,000 km) from their nesting grounds on Ascension Island in the middle of the Atlantic Ocean back to their Brazilian feeding grounds. They were investigating whether mature female turtles use an inclination compass and geomagnetic fields for direction, or by inference (once that sense is disturbed) by some other means as yet determined. Papi et al. [564] attached very strong DC magnets — significantly stronger than the Earth's fields — to disturb and overcome natural magnetoreception, and thereby determine if they could still navigate back to Ascension Island. Controls had nonmagnetic brass bars attached and some had transmitters glued to their heads. All had tracking devices that communicated with satellites, thus creating strong multi-frequency static and pulsed RFR exposures. Seven turtles were each fitted with six powerful static magnets that produced variable artificial fields surrounding the whole turtle, making reliance on a geomagnetic map impossible. The study's travel courses were very similar to those of eight turtles without magnets that had been tracked via satellite over the same period in the previous year. No differences between the magnetically exposed test turtles and untreated turtles were found regarding navigational performance and general course direction. They concluded that magnetic cues were not essential to turtles on the return trip and speculated that perhaps other factors such as smell or wave current direction may come into play.

Luschi et al. [563], like Papi et al. [564], also investigated the role of magnetoreception and homing in mature sea turtles but used a different design and found very different results. In a large field study in the Mozambique Channel, 20 mature pre-nesting green turtles were also equipped with both strong magnets and satellite tracking devices. The turtles were gathered at their nesting beach on Mayotte Island before egg-laying and transported to four open-sea sites 62–75 mi (100–120 km, respectively) away. There were five releases of four turtles each with three different treatments: turtles magnetically 'disturbed' only during transportation with magnets removed before release; those treated only during the homing trip with magnets attached just prior to release; and controls with nonmagnetic brass discs attached to their heads. Treated turtles had very strong moveable magnets attached to their heads to induce varying magnetic fields around them either at the nesting beach at the start of the relocation journey or on the boat just prior to release for the homing trip. All groups had satellite transmitters attached to their carapaces, thereby creating in the opinion of the authors of this paper, an additional exposure that was not considered as a variable. The researchers also included ocean currents in their assessments, estimated by using oceanographic remote sensing measurements. All but one turtle eventually returned to Mayotte to complete delayed egg-laying. But treated turtles, whether treated during transportation or homing, took significantly longer to reach the destination vs. controls — a surprising finding. Most homing routes showed very long circuitous curved and looping patterns before reaching their target. Control paths were direct. Both treated turtle groups were clearly impaired by the MF exposure, indicating significant recovery time needed between exposure and correcting positional behavior. The researchers hypothesized the existence of a navigational role for geomagnetic information being gathered by those turtles in the passive transportation group, as well as the possibility that magnetic disturbance during transportation may have persisted for some time after the removal of the magnets in that group, thus rendering the two treated groups functionally equivalent during their homing journeys. They also noted that exposures may have physically altered magnetite particles, thus creating a longer lasting effect but they said that since long-lasting after-effects of magnet application have not been described, this theory could neither be inferred nor dismissed.

Lohmann [323] reviewed both of the above studies and added that in addition to the two causal hypotheses of Luschi et al. [563] regarding their unexpected findings of turtle circuitous migration routes, another explanation would include the positioning of the satellite transmitters in the Papi et al. [564] study on turtle heads vs. on the carapace of the Luschi models. He added that since satellite transmitters also produce magnetic fields capable of disrupting magnetoreception, and since the Papi group also attached satellite transmitters on the heads of several control turtles, that re-analyzing the Papi study using only turtles with satellite transmitters placed on the carapace like the Luschi study could show evidence consistent with the hypothesis that adult turtles exploit magnetic cues in navigation. He concluded that sea turtles, like all other animals studied to date, likely exploit multiple cues for navigation since even with artificial magnetic disturbance causing impaired performance, the magnets in either study did not prevent turtles from eventually reaching their target beaches. This implies that turtles can also rely on other sources of information [570, 571] such as celestial compasses, wave direction [572], or olfactory cues like other species — a significant finding.

The sum total of the studies mentioned above is that sea turtle species are highly sensitive to Earth's fields and are capable of adapting to subtle anthropogenic disruption.

Turtles: RF-EMF

Turtles may also be senstitive to RFR, especially during incubation while on land, and/or initial hatchling stages if they are exposed to anthopogenic RF-EMF that could distort the imprinting memory they use in later life to locate their birthsite beaches again. For example, if a radar or communications base station is installed on or near the beach of a nesting site, could that affect the initial "imprinting" process? Perhaps augment imprinting and make return easier? Or conversely overwhelm the subtle imprinting process at the start and make return impossible? If the latter is valid, such technology could lead to extinction of sensitive species since it interrupts the reproduction process. In the very least, in sensitive species, disorientation might result as discussed above.

To characterize the underlying compass mechanisms in turtles, Landler et al. [92] studied freshwater juvenile snapping turtles' (*Chelydra serpentine*) ability for spontaneous magnetic alignment to the Earth's geomagnetic fields. Using exposure to low-level RFR near the Larmor frequency (1.2 MHz) that is related to free radical pair formation, turtles were first introduced to the testing environment without the presence of RFR ("RF off, RF off") and they were found to consistently align toward magnetic north. But when subsequent magnetic testing conditions were initially free of RFR, then included an introduced signal ("RF off, RF on"), they became disoriented. Thus, introduction of a RFR field could affect the turtles' alignment response to the natural magnetic field. The RFR field used was only 30–52 nT (1.43 MHz). In the following reverse scenario, when the turtles were initially introduced to the testing environment with RFR present but then removed ("RF on, RF off"), they became disoriented when tested *without* RFR. And with RFR on in both cases ("RF on, RF on"), they aligned in the opposite direction toward magnetic south. Clearly test turtles were affected by the exposures. The researchers concluded that the sensitivity of the spontaneous magnetic alignment response of the turtles to RFR was consistent with a radical pair mechanism (see "Mechanisms" above). In addition, they concluded that the effect of RFR appeared to result from a change in the pattern of magnetic input, rather than elimination of magnetic input altogether. Their findings indicated that turtles, when first exposed to a novel environment, form a lasting association between the pattern of magnetic input and their surroundings, and that they may form a larger internal GPS-like mapping ability when they meet any new magnetic reference framework based on natural magnetic cues, from multiple sites and localities.

They also showed that RFR at or near the Larmor frequency (1.2–1.43 MHz) had the ability to disrupt snapping turtle natural orientation, establish its own novel orientation, and completely reverse a natural orientation, leading back to the complex questions asked above regarding imprinting and possible reproductive disruption. Although the Landler et al. study [92] was conducted in a freshwater, non-homing species, snapping turtles are long-lived with a low reproduction success rate. Even small disruptions to this species from anthropogenic sources could have an outsized population effect over time. If this freshwater species is any indication of potential RFR effects, researchers need to further investigate RFR in long-distance migrating turtle species that imprint on land. We simply do not know the full range of possible effects across frequencies with which turtle species come in contact at vulnerable points throughout development and lifetimes.

Nematodes and smaller biota

There are reports of sensitivity to EMF in lesser taxa as well. EMF is known to affect numerous other species including: nematodes (Earth and aquatic worms), mollusks (snails), amoeba (single-celled organisms), molds, algae, protozoans, yeast, fungi, bacteria, and viruses (to a limited extent) — with ramifications for creation of antibiotic resistant bacteria strains. Below are some representative examples of observed effects.

Nematodes

Common soil-based nematode species like *C. elegans* serve as a useful whole-organism model for genetic and multicellular organism investigations. They are routinely used as a research model to investigate key biological processes including aging, neural system functioning, and muscle degeneration, to name a few. This species' genetic and phenotypic traits are extremely well documented and they can thus be used as important proxies for quantitative analyses [573]. Nematodes have a short lifespan, are hermaphrodites, and demonstrate effects quickly. As lab models they are used primarily for information that can be applied to humans but we can also glean important information and extrapolate to environmental exposures under certain circumstances. Healthy soil worm populations are critical to soil health upon which we all depend.

Hung et al. [574] investigated static magnetic field (SMF) effects on life span and premature aging in *C. elegans*. Nematodes were grown in SMFs varying from 0 to 200 mT. They found that SMF's accelerated development and reduced lifespan in wild-type nematodes. They also found increases in heat shock proteins that were selective and dose dependent.

Vidal-Gadea et al. [66] investigated magnetic orientation in *C. elegans* to identify magnetosensory neurons and found that they orient to the Earth's geomagnetic field during vertical burrowing migrations. Well-fed worms migrated up, while starved worms migrated down. Populations isolated from around the world were found to migrate at angles to the magnetic vector that would vertically translate to their native soil, with northern- and southern-hemisphere worms displaying opposite migratory preferences in conjunction with natural geomagnetic fields. They also found that magnetic orientation and vertical migrations required the TAX-4 cyclic nucleotide-gated ion channel in the AFD sensory neuron pair while calcium imaging showed that these neurons respond to magnetic fields even without synaptic input. They hypothesized that *C. elegans* may have adapted magnetic orientation to simplify their vertical burrowing migration by reducing the orientation task from three dimensions to one.

C. elegans have also demonstrated sensitivity to electric fields via electrotaxis (also known as galvanotaxis) which is the directed motion of living cells or organisms guided by an electric field or current and often seen in wound healing. Sukul and Croll [575] found that nematodes exposed to an electrical current (0.02–0.04 mA, potential differences 2–6 V) demonstrated a directional sensorily-mediated orientation toward the current at first, but at 2 mm from the electrode, individual worms increased reversing behaviors which then remained uniform as they moved in a constant direction parallel to the exposure. A few which did not reverse direction died (presumably from electrocution) at 6 V or 0.4 mA. They concluded that adult *C. elegans* move directionally at selected combinations of voltage and potential differences and that electrophoresis could be eliminated.

Gabel et al. [576] also investigated electric field effects on directionality on *C. elegans* with an eye toward better understanding how the nervous system transforms sensory inputs into motor outputs. They used time-varying electric fields modulated at 100 Hz across an agar surface with a defined direction and amplitude up to 25 V/cm. They found that the nematodes deliberately crawl toward the negative pole in an electric field at specific angles to the direction of the electric field in persistent forward movements with the preferred angle proportional to field strength. They also found that the nematodes orient in response to time-varying electric fields by using sudden turns and reversals (normal reorientation maneuvers). They also found that certain mutations or laser ablation that disrupt the structure and function of amphid sensory neurons also disrupted their electrosensory behavior and that specific neurons are sensitive to the direction and strength of electric fields via intracellular calcium dynamics among the amphid sensory neurons. This study showed that electrosensory behavior is crucial to how the *C. elegans* nervous system navigates and can be disrupted at some intensities found in the environment.

Maniere et al. [573] also found *C.elegans* was sensitive to electric fields and that when submitted to a moderate electric field, worms move steadily along straight trajectories. They hypothesized that imposing electric fields in research settings was an inexpensive method to measure worms' crawling velocities and a method to get them to self-sort quickly by taking advantage of their electrotactic skills.

An early RFR study of *C elegans* by Daniells et al. [577] found this species to be a useful model for investigating stress-responses. In the majority of investigations, they used 750 MHz with a nominal power of 27 dBm; controls were shielded and all temperatures were strictly controlled. Stress responses were measured in terms of beta-galactosidase (reporter) induction above control levels. Response to continuous microwave radiation showed significant differences from 25 degrees C in controls at 2 and 16 h, but not at 4 or 8 h. Using a 5 × 5 multiwell plate array exposed for 2 h, the 25 microwaved samples showed highly significant responses compared with a similar control array. Experiments in which the frequency and/or power settings were varied suggested a greater response at 21 than at 27 dBm, both at 750 and 300 MHz indicating a nonlinear effect, although extremely variable responses were observed at 24 dBm and 750 MHz. Lower power levels tended to induce greater responses — the opposite of simple heating effects. They concluded that microwave radiation causes measurable stress to transgenic nematodes via increased levels of protein damage within cells at nonthermal levels.

Tkalec et al. [578] found oxidative and genotoxic effects in earthworms (*Eisenia fetida*) exposed *in vivo* to RFR at 900 MHz, at 10, 23, 41 and 120 V m(-1) for 2 h using a Gigahertz Transversal Electromagnetic (GTEM) cell. All exposures induced significant effects with modulation increasing such effects. Their results also indicated antioxidant stress response induction with enhanced catalase and glutathione reductase activity, indicating lipid and protein oxidative damage. Antioxidant responses and damage to lipids, proteins and DNA differed depending on EMF level, modulation, and exposure duration.

Aquatic and semi-aquatic worm species also show sensitivity to EMF. Jakubowska et al. [579] investigated behavioral and bioenergetic effects of EMF at 50 Hz, 1 mT fields (comparable to exposures near underwater cables) in polychaete ragworms (*Hediste diversicolor)* that live and burrow in the sand/mud of beaches and estuaries in intertidal areas of the North Atlantic. While they found no attraction or avoidance behavior to EMF, burrowing activity was enhanced with EMF exposure, indicating a stimulatory effect. Food consumption and respiration rates were unaffected but ammonia excretion rate was significantly reduced in EMF-exposed animals compared to control conditions at only geomagnetic fields. The mechanisms remained unclear. The authors said this was the first study to demonstrate effects of environmentally realistic EMF values on the behavior and physiology of marine invertebrates.

Van Huizen et al. [67] investigated effects of weak magnetic fields (WMF) on stem-cells and regeneration in an *in vivo* model using free-swimming flatworms (*Planaria* ssp*)* that are capable of regenerating all tissues including the central nervous system and brain. This regeneration ability is due to the fact that about 25% of all their cells are adult stem cells (ASC). Injury is followed by a systemic proliferative ASC response that initially peaks at ~ 4 h, followed by ASC migration to the wound site over the first 72 h when a second mitotic peak occurs. Like salamander regeneration (see "Amphibians" above) this activity produces a blastema — a group of ASC cell growth that forms the core of new tissues. Full regeneration of damaged planaria tissues or organs occurs through new tissue growth and apototic remodeling/scaling of old tissues within 2–3 weeks. Following amputation above and below the pharynx (feeding tube), they exposed amputation sites to 200 μT WMF. At three days post-amputation, they found that 200 μT exposure produced significantly reduced blastema sizes compared to both untreated and earth-normal 45 μT field strength controls, indicating a WMF interference effect to regeneration. They also found that the 200 μT exposure was required early and had to be maintained throughout blastema formation to affect growth, and that shorter, single-day exposures failed to affect blastema size. In addition, they found weak magnetic fields produced field strength–dependent effects. These included significant reductions of blastema size observed from 100–400 μT, but conversely, a significant increase in outgrowth occurred at 500 μT. They hypothesized that WMF effects were caused by altered reactive oxygen species (ROS) levels, which peak at the wound site around 1-h post-amputation and are required for planarian blastema formation. This study shows that weak anthropogenic magnetic fields can affect stem cell proliferation and subsequent differentiation in a regenerative species, and that field strength can increase or decrease new tissue formation *in vivo*. This is a significant finding for regenerating species of all kinds, and may affect non-regenerating species as well. Sea lamprey eels (*Petromyzon marinus*), a fish species, are also known to regenerate even after multiple amputations [580].

Mollusks, amoeba, molds, algae, protozoans

Mollusks (marine versions are called chitons) are long known to manufacture magnetite in their teeth and to use fields weaker than the geomagnetic field for kinetic movement and direction [52, 117, 340, 524]. Lowenstam [118] first discovered that magnetite was the major mineral in the teeth of marine chitons, thought to give teeth their natural hardness. But Ratner [62] discovered chitons use magnetite as a magnetic compass when he found a number of chiton species have radulae (tongues) that are covered by ferro-magnetic (magnetite) denticles. The radulae of *Acompapleura granulata* and *Chiton squamosis* were also found to be ferro-magnetic but the shells were not. Live specimens of a chiton (*Chaetopleura apiculata*) that also have ferro-magnetic radulae were found to rotate more and move farther in a magnetic field weaker than in the Earth's stronger geomagnetic field, indicating a nonlinear directionality. Ratner concluded that chitons are responsive to magnetic fields and demonstrate kinetic movements within them.

Some snails are sensitive to EMFs. Nittby et al. [581] observed analygesic effects in land snails (*Helix pomatia*) caused by GSM-1900 RFRs when snails lost sensitivity to pain on a hot plate test after nonthernal exposure to RFR.

Smaller organisms have also long shown effects from EMF. Goodman et al. [582] found delays in mitotic cell division in slime mold (*Physarum polycephalum*) with ELF-EMF exposures. Friend et al. [583] found perpendicular and parallel elongation of the giant amoeba Chaos chaos (*Chaos carolinensis*) in alternating electric fields over a wide frequency range (1 Hz–10 MHz) with characteristic changes as a function of frequency. Marron et al. [584] found effects on ATP and oxygen levels in another species of slime mold (*P. polycephalum*) after exposures to 60 Hz sinusoidal electric and magnetic fields. Luchien et al. [585] found a stimulating effect on the productivity of the algal biomass (*Chlorella sorokiniana*) for a magnetic field of 50 Hz but an inhibitory effect at 15 Hz in these microalgae.

Protozoans, thought to be more related to animals than microbes, also show sensitivity to EMF. Protozoans, as single-celled eukaryotes, are generally larger than bacteria which are classified as prokaryotes. The two organisms are structurally different: bacterial cells lack a nucleus while protozoa contain organelles such as mitochondria. Bacteria generally absorb nutrients through their cell walls while protozoa feed on bacteria, tissue, and organic matter and can be both infectious and parasitic. These protozoa include human parasites that cause diseases such as amoebic dysentery, malaria, giardiasis, leishmaniasis, trichomoniaisis, toxoplasmosis and others. Animal species are also affected by protozoans which can severely weaken and shorten their lifespans.

Rodriguez-de la Fuente et al. [586] tested ELF-EMF (60 Hz, 2.0 mT for 72 h) on two infectious protozoans, *Trichomonas vaginalis* and *Giardia lamblia*, and found growth alterations in both species which they attributed to alterations in cell cycle progression and cellular stress. Cammaerts et al. [587], used RFR (GSM 900-MHz at 2 W vs. control) on protozoans (*Paramecium caudatum*) and found individuals moved more slowly and sinuously than usual and that their physiology was affected. Paramecia became broader, pulse vesicles had difficulty expelling content to the outside of their cells, cilia moved less efficiently, and trichocysts became more visible — all effects that indicate poor functioning or cell membrane damage. They hypothesized that the first impact of RFR could be to cell membranes.

Clearly there are multiple effects at all levels documented in lower taxa from multi-frequency exposures that are now found in the environment.

Yeast and fungi

Yeast is often used in lab models, especially since 1996 when a complete genomic sequence of *Saccharomyces cerevisiae* was created. In fact it is now considered a "premier model" [588] for eukaryotic cell biology as well as having helped establish whole new fields of inquiry such as "functional genomics" and "systems biology" which focus on the interactions of individual genes and proteins to reveal specific properties of living cells and whole organisms.

EMF research is rich with studies using yeast models too numerous to fully analyze here. However we include a small sample of recent EMF research with potential significance to environmental exposures.

Lin et al. [589] investigated glucose uptake and transcriptional gene response to ELF-EMF (50 Hz) and RFR (2.0 GHz) on several strains of budding yeast (*S. cerevisiae*). Results determined that ELF-EMF and RFR exposure can upregulate the expression of genes involved in glucose transportation and the tricarboxylic acid (TCA) cycle, but not glycolysis pathways, thus showing that such exposures can affect energy metabolism which is closely related with cellular response to environmental stress. Glucose metabolism is fundamental to all living cells' need for energy, with related significance to many disease states including most cancers.

In a magnetic field study by Mercado-Saenz et al. [590], premature aging and cellular instability were found in yeast (*S. cerevisiae*) exposed to low frequency, low intensity sinusoidal magnetic fields (SMF continuous exposure at 2.45 mT, 50 Hz) and pulsed magnetic fields (PMF 1.5 mT, 25 Hz, 8 h/day). Chronological aging was evaluated during 40 days and cellular stability was evaluated by a spontaneous mutation count and the index of respiratory competence (IRC). They found exposure to PMF produced accelerated aging while SMF did not, and decreased mitochondrial mutation during aging was also seen with PMF. No alterations in respiratory competence were observed for either SMF or PMF exposures. They concluded that exposure to PMF accelerated chronological aging and altered the spontaneous frequency of mitochondrial mutation during the aging process, whereas the SMF used had no effect, thus showing abnormal effects on cell activity from pulsed exposures.

Because yeast cells are known to be sensitive to magnetic fields, some industrial and therapeutic applications to human health have been investigated. These investigations serve to illuminate what we know about yeast and fungal reactions to EMF in general, as well as specific uses. For industrial applications, Wang et al. [591] investigated low level static magnetic fields (SMF) on mold (*Aspergillus versicolor*) growth which can have high impacts on metal corrosion in environmental conditions conducive to mold growth. This is especially problematic in fine electronic circuit boards produced today. Using a

10 mT static magnetic field (SMF) perpendicular to the surface of printed circuit boards, they found the magnetic field inhibited mold growth and surface corrosion which were slowed down, unlike control boards without applied magnetic fields where mold formed a spore-centered corrosion pit that then led to macroscopic regional uniform corrosion. This demonstrated changes in cell/spore growth at a low intensity exposure that can be found in the environment.

Also with an eye toward commercial possibilities, Sun et al. [592] found that a polysaccharide of *Irpex lacteus* (a white-rot fungus found widely in the environment which breaks down organic materials but also is commercially used to treat nephritis in humans) was sensitive to low-intensity ELF-EMF as demonstrated by increased biomass and polysaccharide content, as well as induced malformed twists on the sample cell surfaces. Polysaccharides are carbohydrates with a large number of sugar molecules used as energy sources in living cells. They identified varying changes in multiple differentially expressed genes after exposure to alternating current EMF (50 Hz, 3.5 mT, 3 h per day, for 4 days). They found initial sharp increases in growth rates in exposed samples that were then marked by significant declines in EMF's influence over time, although there were also important lasting effects. Global gene expression alterations from EMF indicated pleiotropic effects (capable of affecting multiple proteins or catalyzing multiple reactions) were related to transcription, cell proliferation, cell wall and membrane components, amino acid biosynthesis and metabolism. Polysaccharide biosynthesis and metabolism were also significantly enriched in the EMF-exposed samples. They concluded that EMF significantly increased amino acid contents and was therefore deemed a suitable method for increasing fermentation of microorganisms, presumably for commercial use. However, the significance of this study to environmental exposures relates to the multiple ways that ELF alternating current common to electric power generation changed yeast gene expression. There is at least one clinical case of a different strain of *I. lacteus* taking on a rare infectious and dangerous quality in an immunocompromised human [593]. The question is: can now-ubiquitous ELF-EMF contribute to potentially emerging new forms of yeast contagion?

The same question arises with *Candida albicans* and other pathogenic yeasts that have rapidly developed resistance to antifungal medications. *C. albicans* can live harmlessly in human microflora, but certain lifestyle circumstances or immunosuppression can turn it into an opportunistic pathogen. It can also infect some non-human animals. While chronic mucocutaneous candidiasis can infect the skin, nails, and oral and genital mucosae, under high host immunodeficiency *C. albicans* can enter the bloodstream and induce systemic infections with mortality between 30 and 80% [594]. There has been increasing resistance of *C. albicans* to traditional antifungal agents, such as fluconazole and amphotericin B [595, 596]. Resistance mechanisms include overproduction of membrane drug efflux transporters and/or changes in gene expression [597].

Two investigations in search of new therapeutic strategies were conducted using EMF. Sztafrowski et al. [594] investigated the use of static magnetic fields (SMF, 0.5 T) on *C. albicans* cultures in the presence of two commonly used antifungal medications. Their aim was to assess whether SMF had any impact on general viability of *C. albicans* hyphal transition and its susceptibility to fluconazole and amphotericin B. They found reduction of *C. albicans* hyphal length in EMF-exposed samples. They also found a statistically significant effect on *C albicans* viability when SMF was combined with amphotericin B. They hypothesized that this synergistic effect may be due to the plasma membrane binding effects of amphotericin B and that SMF could influence domain orientation in the plasma membrane. They concluded, with caution, that the use of a SMF in antifungal therapy could be a new supporting option for treating candidas infections.

Novickij et al. [598] also focused on therapeutic possibilities given the multi-drug resistance and side effects to antifungal therapies. Their aim was to optimize the electroporation-mediated induction of apoptosis using pulses of varied duration (separately and in combination with formic acid treatment) and to identify yeast apoptotic phenotypes. They focused on nonthermal nanosecond pulsed electric fields (PEF 3 kV, 100 ns – 1 ms squarewave; and 250, 500, 750 ns duration 30 kV/cm PEF, 50 pulses, 1 kHz) as a therapeutic alternative and/or to enhance effects in combination with conventional treatments. In three yeast models, *S. cerevisiae* (as control) and drug resistant *Candida lusitaniae* and *Candida guilliermondii*, they found that nanosecond PEF induced apoptosis in all three strains. Combining PEF with a weak formic acid solution improved induced apotosis and inactivation efficacy in the majority of the yeast population. Yeast cells showed DNA breaks and other changes. They concluded that PEF could be a useful new non-toxic protocol to treat some fungal diseases and minimize tissue damage.

Choe et al. [599] studied ion transportation and stress response on a yeast strain (K667) to ELF-EMF (60 Hz, 0.1 mT, sinusoidal or square waves), specifically investigating internal ionic homeostasis via the cell membrane involving metal ions and cation transports (cations are ionic species of both atoms and molecules with a positive charge). They found significantly enhanced intracellular cation concentrations as ELF-EMF exposure time increased, as well as other changes. This study has implications for soil health as yeast can be an integral aspect of how healthy organic soil matter is formed. They concluded that EMF and yeast could also play a role in the bioremediation processes in metal-polluted environments.

Lian et al. [600] studied effects of ELF-EMF (50 Hz, 0–7.0 mT) and RFR (2.0 GHz, 20 V/m, temperature at 30 °C, average SAR single cell/0.12 W/kg) on two budding yeast strains (NT64C and SB34) and prion generation/propagation. They found under both EMF exposures that *de novo* generation and propagation of yeast prions (URE3) were elevated in both yeast strains. The prion elevation increased over time and effects were dose-dependent. The transcription and expression levels of heat shock proteins and chaperones were not statistically significantly elevated after exposure but levels of reactive oxygen species (ROS), as well as superoxide dismutase (SOD) and catalase (CAT) activities were significantly elevated after short-term, but not long-term exposure. This work demonstrated for the first time that EMF exposure could elevate the *de novo* generation and propagation of yeast prions, supporting the researcher's hypothesis that ROS may play a role in the effects of EMF on protein misfolding. ROS levels also mediate other broad effects of EMF on cell function. They concluded that effects of EMF exposure on ROS levels and protein folding may initiate a cascade of effects negatively impacting many biological processes.

The effects of EMF on protein folding cannot be overstated. Proteins must fold into proper three-dimensional conformations to carry out their specific functions — intact proteins are critical to the existence of all life. Misfolding not only impairs function but leads to disease. Folding inside of cells does not happen spontaneously but rather depends on molecular helpers called chaperones. Protein misfolding has been implicated in Alzheimer's, Parkinson's, and Huntington's diseases, among others. The devastating Creutzfeldt–Jakob disease is caused by prion misfolding in the brain, which causes abnormal signaling in neurons that eventually leads to paralysis and death. Wildlife can also suffer from prion diseases such as chronic wasting in deer, elk, and other cervids, and cattle can suffer from so-called "mad-cow" disease. The two studies from above [599, 600] have implications for how such diseases are spread through soil with possible links to environmental EMFs.

It is clear from the above that ELF-EMF and RF-EMF, using multiple signaling characteristics, are biologically active in both temporary and permanent ways in yeast/fungi species with wide environmental implications across numerous taxa.

Bacteria

Strains of bacteria are known to be magnetotactic and use geomagnetic fields for direction. Blakemore [63] was the first to suggest in 1973 that bacteria in North American saltwater marsh muds use magnetite as a sensor when he discovered not only that bacteria were highly attracted to an external magnet but they also had magnetite crystals that caused them to align with the lines of the Earth's magnetic fields. This was also discovered to be geolocation specific to the North Pole in northern samples and South Pole-seeking in southern species [52, 63, 511]. The bacteria showed "mud-up" and "mud-down" behavior along magnetic field gradients when mud was disturbed, indicating a magnetic compass. Since that early work, a whole new field called electromicrobiology has developed with discoveries that include some electro-active bacteria being responsible for magnetite formation, with others creating their own electric "wires" in mud flats with implications for new technologies [601].

Among the more troubling EMF effects are bacterial alterations with pressing implications for antibiotic resistance. Since the 1940s [602], nonthermal effects were documented in bacterial, viral, and tissue cultures with applied low-repetition 20-MHz pulses. Most studies spanning the 1940s though the 1980s focused on EMF's ability to kill microbes and fungi in human food sources at high intensity, consequently most research was focused on thermal intensities. That work still continues today as microwaves have been shown to be an efficient means for killing microbes [50]. But microbes also react to much lower nonlethal intensities and recent work finds effects from both ELF and RFR.

The common bacteria *Escherichia coli*, which can live harmlessly in the gut of humans and many other animal species, can also turn virulent and kill through food-borne illnesses. *E. coli* comes in many strains, is well studied, and now considered the most genetically and physiologically characterized bacterium. *E. coli* encounter varied and numerous environmental stressors during growth, survival, and infection, including heat, cold, changes in Ph levels, availability of food/water supplies, and EMF. Along with other bacteria, they respond by activating groups of genes and heat shock proteins (see "Mechanisms" above) which can eventually lead to stress tolerance for survival purposes. But induced stress tolerance can also lead to increased virulence, as well as enhanced tolerance to other stressors that confer cross-protection [603].

Salmen and colleagues [604, 605] published papers of EMF effects on bacterial strains documenting the growing investigation of microbes related to antibiotic resistance with many findings stressing responses to EMF [606–610]. Cellini et al. [611] investigated *E. coli*'s adaptability to environmental stress induced by ELF exposures to 50-Hz magnetic fields at low intensities (0.1, 0.5, 1.0 mT) vs. sham controls. They found exposed samples and controls displayed similar total and culturable counts, but increased cell viability was observed in exposed samples re-incubated for 24 h outside of the test solenoid compared to controls. Exposure to 50 Hz EMF (20–120 min) also produced a significant change in *E. coli* morphotype with a presence of coccoid cells aggregated in clusters after re-incubation of 24 h outside of the magnetic field-solenoid. Atypically lengthened bacterial forms were also noted, indicating probable alteration during cell division. Some differences in RNA-AFLP analysis were also seen for all intensities evaluated. They concluded that exposure to 50-Hz ELF-EMF is a bacterial stressor as evidenced by its immediate response in modifying morphology (from bacillary to coccoid) and inducing phenotypical and transcriptional changes. Despite this stressor effect, it was also seen that exposed samples significantly increased viability, suggesting the presence of VBNC cells. They concluded that further studies were needed to better understand ELF-EMF in bacterial cell organization. They did not extrapolate to the obvious — that *E. coli* was changed in an abnormal way but nevertheless strengthened in viability — a recipe for antibiotic resistance.

Crabtree et al. [612], in a small human study, investigated the biomic relationship of human bacteria exposed to both static magnetic fields (SMF) and RFR. Using laboratory culture strains and isolates of skin bacteria collected from the hand, cheek, and chin areas of four volunteers who had different (self-reported) cell phone use histories, they found varied growth patterns of *E. coli*, *Pseudomonas aeruginosa*, and *Staphylococcus epidermidis* under static magnetic fields on different bacterial species. Isolates of skin microbiota showed inconsistent growth among the test subjects, likely due to their differing cell phone usage histories (classified as heavy, medium and light) and other variables. The growth of *Staphylococci* was increased under RFR in certain individuals while in others growth was suppressed. This was complicated by the different body areas tested, some with higher chronic exposures such as the hands, as well as other variables when one test subject used an antibacterial face wash. Volunteers in the heavy use category showed less bacterial growth on the hands, possibly due to microbe habituation. Overall, and despite the small sample, they concluded RFR can disrupt the balance in skin microbiota, making it more vulnerable to infection by specific opportunistic and/or other foreign pathogens. They noted that both SMF and RF-EMFs have significant but variable effects on the growth of common human bacteria; that bacterial growth was either unaffected, increased, or suppressed depending on the species of bacteria; and that bacterial responses seemed to be determined by historic exposure to RF-EMF and life style. This study, even with inherent limitations, indicates changes in microbes with EMFs and may prove a novel way to study bacteria with significance for real-life exposures to humans and animals alike.

Salmen et al. [605] also found highly variable results from RFR (900 and 1,800 MHz) effects on DNA, growth rate, and antibiotic susceptibility in *Staphylococcus aureus*, *Staphylococcus epidermidis*, and *P. aeruginosa*. Using an active cell phone handset, they exposed bacteria to 900 and 1,800 MHz for 2 h, then injected samples into a new medium where growth rate and antibiotic susceptibility were evaluated. Regarding DNA, they found no differences in *S. aureus* and *S. epidermidis* when exposed to 900 and 1,800 MHz vs. controls, but *P. aeruginosa* showed changes in DNA band patterns following such exposures. Regarding growth rates, with the exception of a significant decrease after 12 h exposure to 900 MHz, no significant effects on growth of *S. aureus* and *S. epidermidis* were seen. But the growth of *P. aeruginosa* was significantly reduced following exposure for 10 and 12 h to 900 MHz, while no significant reduction in growth followed exposure to 1,800 MHz. Regarding antibiotic susceptibility, in the drugs studied (i.e., amoxicillin 30 mg, azithromycin 15 mg, chloramphenicol 10 mg, and ciprofloxacin 5 mg), with the exception of *S. aureus* treated with amoxicillin (30 mg), EMF-exposure had no significant effect on bacterial sensitivity to antibiotics. This study shows variability among bacterial species not only to different frequencies common in the environment today but also to changes in sensitivity to some antibiotics but not others. There may have been design problems with this study, however.

Several studies investigated WiFi signals on bacterial strains. Taheri et al. [610] assessed exposure to 900-MHz GSM mobile phone radiation and 2.4-GHz RFR from common WiFi routers to see if cultures of *Listeria monocytogenes* and *E. coli* resulted in altered susceptibility to 10 different antibiotics. They found narrow windows in which microbes became more resistant: For L. *monocytogenes* no significant changes in antibacterial activity between exposed and nonexposed samples — except for Tetracycline (Doxycycline) — were noted. For *E. coli*, however, there was a significant change in antimicrobial activities suggesting RFR exposures can influence antibiotic susceptibility of *E. coli* more than in *Listeria*. For window and pronounced effects, they found *L. monocytogenes* exhibited different responses to each antibiotic. For Doxycycline, the window occurred after 6 h exposure to WiFi and mobile phone-RFR. After 9 h of exposure to WiFi for Ciprofloxacin and Sulfonamide (Tremethoprin/sulfamethoxazole), bacteria tended to become more resistant. By contrast, the pattern for Levofloxacin and Penicillin (Cefotaxime/Deftriaxone) showed increased sensitivity. For *E.coli*, the pattern of the response to WiFi and mobile phone RFR was the same: maximum antibiotic resistance was seen between 6 and 9 h of exposure but after 12 h, a stress response lead to a return to preexposure conditions indicating an adaptive reaction. Taheri et al. [609] found similar nonlinear window effects and differences in growth rates in *Klebsiella pneumonia*, while Mortazavi et al. [613] found similar window effects in *E coli*. In addition, they saw significant increased growth rates after radiation exposures in both Gram-negative *E. coli* and Gram-positive *L. monocytogenes*. They concluded that such window effects can be determined by intensity and dose rate; that exposure to RFR within a narrow window can make microorganisms resistant to antibiotics; and that this adaptive phenomenon is a human health threat. The same can be inferred for many non-human species.

Said-Salman et al. [614] evaluated non-thermal effects of WiFi at 2.4 GHz for 24 and 48 h (using a WiFi router as the source) on the pathogenic bacterial strains *E. coli* 0157H7, *S. aureus, and S. epidermis* for antibiotic resistance, motility, metabolic activity and biofilm formation. Results found that WiFi exposure altered motility and antibiotic susceptibility of *E. coli* but there was no effect on *S. aureus and S. epidermis*. However, exposed cells (vs. unexposed controls) showed an increased metabolic activity and biofilm formation ability in *E. coli*, *S. aureus and S. epidermis*. They concluded that WiFi exposure acted as a bacterial stressor by increasing antibiotic resistance and motility of *E. coli*, as well as enhancing biofilm formation in all strains studied. They indicated the findings may have implications for the management of serious bacterial infections.

Movahedi et al. [615] also investigated antibiotic resistance, using short-term exposure to RFR from a mobile phone simulator (900 MHz, 24 h) on *P. aeruginosa* and *S. aureus* against 11 antibiotics. They found significant changes in structural properties and resistance to the numerous antibiotics studied. *P. aeruginosa* was resistant to all antibiotics after 24 h of exposure vs. non-exposed controls while *S. aureus* bacteria were resistant to about 50%. They also found structural changes in all exposed samples and increased cell wall permeability.

In a field study near cell towers, Sharma et al. [616] looked at changes in microbial diversity and antibiotic resistance patterns in soil samples taken near four different base stations with control samples taken >300 m away. *Stenotrophomonas maltophilia, Chryseobacterium gleum,* and *Kocuria rosea* were isolated and identified in soil samples collected near the exposed zones. They found greater antibiotic resistance in microbes from soil near base stations compared to controls, with a statistically significant difference in the pattern of antibiotic resistance found with nalidixic acid and cefixime when used as antimicrobial agents. They concluded that cell tower radiation can significantly alter the vital systems in microbes and make them multi-drug resistant.

Researchers have also investigated ELF-EMF effects on bacterial growth and antibiotic sensitivity. Segatore et al. [608] investigated 2 mT, 50 Hz exposures on *E. coli* ATCC 25922 and *P. aeruginosa* ATCC 27853 and found EMF significantly influenced the growth rate of both strains, notably at 4, 6, and 8 h of incubation. The number of cells was significantly decreased in exposed bacteria vs. controls. And at 24 h incubation, the percentage of cells increased (*P. aeruginosa* ~ 42%; *E. coli* ~ 5%) in treated groups vs. controls which suggested to the researchers a progressive adaptive response. However, they saw no remarkable change in antibiotic sensitivity. Potenza at al. [617] also found effects at high-intensity static magnetic fields at 300 mT on growth and gene expression in *E.coli* but that would be a high environmental exposure.

Viruses

There is a paucity of research on viral species and EMF, likely due to the fact that viruses lack ferromagnetic materials, are difficult to study, and don't make good general lab models other than to investigate their direct impact on specific *in vivo* end points. Virology research thrives in its own specialized niche and has not been used for basic modeling like so many other living life forms as noted throughout this paper. There is long-standing debate on whether viruses are even alive.

However, one wide-ranging discussion by Zaporozhan and Ponomarenko [618] hypothesized a possible complex mechanistic link between influenza pandemics, natural sun spot cycles, and non-thermal effects of weak magnetic fields via cryptochromes/radical pairs, gene expression pathways, and stress-induced host immunological alterations favorable to influenza epidemics. Noting that most — though not all — major influenza epidemics occurred in time intervals starting 2–3 years before and ending 2–3 years after maximum solar activity, they hypothesized that solar cycles are able to both regulate and entrain processes of biological microevolution in viral species (among others), as well as influence human biorhythms in synergistic ways that could lead to influenza epidemics. Although others have also noted links between influenza pandemics and sunspot activity — possibly based on changes in migratory bird patterns as viral vectors [619–621]— and some have linked sun spots with other adverse human health events, these effects remain of interest but are still hypothetical. UV radiation, which is not covered in this paper, is known to suppress cell-mediated immunity and is therefore capable of adversely affecting the course of a viral infection in some mammal species. Ambient EMF in lower frequency ranges may also be reducing immune viability across species which can theoretically foster opportunistic virulence. Far more EMF research needs to be conducted on viruses; one fruitful approach might be synergistic investigations in virus-infected plant species.

The previous studies of microbes show a pattern of sensitivity in microorganisms to EMF with associations that encompass a wide range of critical changes, including consistent stress responses, alterations in growth and viability, cell membrane alterations, and clear patterns of how easily antibiotic resistance forms in microbial life to now ubiquitous EMF levels.

Plants (see Part 2, Supplement 4, for a table of flora studies: ELF, RFR)

Plants have evolved in highly sensitive ways to natural and manmade EMF in all phases of germination, growth and maturation [31]. Magnetoreception, which is well documented in animals such as birds, has also been described in plants [622] and plant species can respond to subtle changes in EMF in the environment, including in whole plant communities [623]. They may even 'communicate' and gather various kinds of 'information' via electrical signals in neuron-like cells in root tips and elsewhere [624]. Some hypothesize [625] that a form of vibrational and acoustic sensitivity around 220 Hz may play a role in plant life, although not everyone agrees [626].

Almost all vegetation is subject to complex multi-frequency fields due to their soil-based root systems and high water content, plus above-ground ambient RFR exposures makes plants uniquely susceptible to effects near transmission towers [623, 627]. Many EMF studies have found both growth stimulation as well as dieback. The presence of numerous RFR-emitters in the German and Swiss Alps is thought to have played a role in the deforestation there [628]. The 'browning' of treetops is often observed near cell towers, especially when water is near tree root bases [25]. Treetops, with their high moisture content and often thick vegetative canopy, are known RFR waveguides. In fact, military applications utilize this capability in treetops for communication signal propagation in remote areas and for guidance of low-flying weapons systems [629].

How flora interacts with EMF is still a mystery but a clear pattern has emerged in researching the database for this paper: static ELF-EMF has largely been found beneficial to plant and seed growth [630] while RFR is detrimental. Plants clearly have magnetoreception in their stationary condition. The normal ground state of magnetic fields for plants is the relatively constant natural geomagnetic field that averages between 25 and 65 μT depending on location and seasonal variations [631]. Atmospheric changes, such as thunderstorms and lightning, can cause intermittent changes in ambient magnetic fields. These activities are also generally associated with rainwater critical to virtually all plant life. Plants can detect these changes and prepare for growth using the upcoming rainfall. Trees are seen extending their branches skyward long before rain actually occurs and such changes match alterations in tree polarities [632].

There are many studies showing an increase in the growth rate in plants, such as studies of seed germination exposed to alternating magnetic fields. Plants also respond similarly to high intensity static magnetic fields. This may mean that the physiological mechanism in plants that causes magnetic field-induced growth is finely tuned to a certain intensity of magnetic flux. Any variation in intensity or shape of the ambient magnetic field could activate or hinder this growth mechanism.

Lightning, for instance, generates fast and intense electromagnetic pulses (EMP). EMP has consistently been shown to cause biological effects [633] with just one pulse. Plants may have mechanisms so sensitive that they can detect the energy of EMP from kilometers away. The pulse causes a transient change in the environmental magnetic field that may be detected by one or more of the mechanisms mentioned in the "Mechanisms" section above, as well as discussed below. EMP has been closely investigated for military applications for its ability at high intensities to disable electronics. While much of the military-supported research finds no biological effects from EMP exposure, non-military supported research does show effects. This parallels the same findings in industry vs. non-industry research patterns [165, 634].

There is a long history on the study of effects of EMF exposure on plant growth, notably, the work of the Indian scientist Sir Jagadish Bose (1858–1937) who proposed the electric nature of plant responses to environmental stimuli and studied effects of microwaves on plant tissues and membrane potentials [635]. Interestingly, Bose investigated the effects of millimeter waves [636] now applicable to 5G technology. Bose, arguably, was a pioneer of wireless communication.

Another early pioneer in EMF effects on plants was Harold Saxon Burr (1889–1973) at Yale University who investigated the electric potential of trees in two tree species (a maple and an elm) located on one property and another maple tree for comparison growing 40 miles (64 km) away. Measurements of numerous parameters were taken using embedded electrodes that recorded hourly from 1953 to 1961 [637]. Simultaneous records of temperature, humidity, barometric pressure, sunlight, moon cycles, sunspot activity, weather conditions, atmospheric-potential gradients, earth-potential gradients, and cosmic rays were correlated with tree potentials. Burr also installed equipment that measured the potential between electrodes in the Earth (about 10 miles apart) and the potential gradient of the air, and found that the air and Earth potentials fluctuated exactly with the phase of the tree potentials although the trees were not always synchronous. Burr ultimately found that the electrical environment correlated closely with tree potentials in a kind of entrainment to diurnal, lunar and annual cycles. Meteorological parameters did not correlate in any immediate way other than when passing thunderstorms elicited anomalous behavior in the trees in direct parallel to measurements with the Earth electrodes. This follows the theory noted above that plants can sense EMP and take immediate information from it.

There are no other long-term field studies as detailed as Burr's of magnetic field effects on a plant species. However, another field study of RFR in Latvia [638] measured effects directly on trees near the Skrunda Radio Location Station, an early warning radar system that operated from 1971 to 1998. The system operated in the 156–162 MHz frequency range transmitting from four pulsed two-way antennas that had operated continuously for over 20 years by the time of the study. In permanent plots in pine forest stands, at varying distances from the radar station and in control areas, tree growth changes were measured and analyzed using retrospective tree ring data. They found a statistically significant negative correlation between the relative additional increment in tree growth and the intensity of the electric field with the radial growth of pine trees diminished in all plots exposed to RFR. The decreased growth began after 1970, which coincided with the initial operation of the station and was subsequently observed throughout the period of study. The effects of many other environmental and anthropogenic factors were also evaluated but no significant effects on tree growth were correlated. This may have been the first detailed field study of plants and RFR.

Many studies of EMF and plants are today conducted in laboratories and have often focused on growth promotion to create higher yields of food-producing plants. Effects of static EMF, pulsed EMF, ELF-EMF, and RF-EMF have been reported. There are, in fact, over 200 studies on plants and EMF alone — too numerous to review here. See Part 2, Supplement 4, for a Table of studies on plant seedlings and development based on the types of EMF's tested.

As noted in Supplement 4 and in Halgamuge [627], frequently static and ELF-magnetic fields generally improve plant growth whereas RFR retards it. This is the opposite of results from animal and animal-cell culture experiments in which ELF-MF usually produces the same effects as RFR. It is interesting to note that Hajnorouzi et al. [639] and Radhakrishma et al. [640] proposed that MF decreases environmental stress in plants whereas Vian et al. [641, 642] considered RFR as a systemic stressor. A major morphological difference between animal and plant cells is that plant cells have a cell wall that is an active physiological organelle which regulates growth and cell division and controls cellular communications. The cell wall contains a considerable amount of water [643]. Is it possible that absorption of RFR by cell-wall water causes a microthermal effect that adversely affects plant cell functions and even causes cell death, whereas thermal effects are not likely to occur with ELF-EMF exposure.

Some plant roots have been found sensitive to both ELF and RFR. Belyavskaya [644] found a strong cytochemical reaction in pea root cells after exposure to low level magnetic fields. Kumar et al. [645] found cyto- and genotoxicity in root meristems of *Allium cepa* with 900-MHz and 1,800-MHz RFR. Chandel et al. [646] studied cytotoxic and genotoxic activity on DNA integrity in root meristems of *A. cepa* using 2,100-MHz RFR and found exposure caused DNA damage with a significant decrease in HDNA accompanied by an increase in TDNA while TM and OTM did not change significantly compared to controls. Biological effects were dependent on the duration of exposure with maximum changes seen at 4 h.

In a series of studies, Stefi et al. [647–649] investigated the effects of long term RFR exposure from the base units of common cordless DECT phone systems (pulsed transmission mode 1,882 MHz, 24 h/day, 7 d/week) on various plant species (*Arabidopsis thaliana, Pinus halepensis, Gossypium hirsutum* respectively) and found structural and biochemical alterations. Compared to controls in Faraday cages, exposed plant biomass was greatly reduced and leaf structure was only half as thick. Leaves were thinner and possessed greatly reduced chloroplasts which contributed to overall reduced vitality. Root systems were also adversely affected. They concluded that RFR is a stressor and noxious to plant life. A study of similar design [650] did not find the same effects on maize (*Zea mays*) which they attributed to that plant's structural differences although chloroplasts were severely affected (see also Kumar et al. [651]).

Jayasanka and Asaeda [652] published a lengthy review that focused on microwave effects in plants. Studies indicate effects depend on the plant family and growth stage involved; and exposure duration, frequency, and power density, among other factors. They concluded that even for short exposure periods (<15 min to a few hours), nonthermal effects were seen that can persist for long periods even if initial exposures were very short. In addition, they noted that since base stations operate 24 h/day, neither short exposures nor recovery periods are possible in natural habitats as plants are continuously exposed throughout their life cycles. They said that variations in the power density and frequency of microwaves exert complex influences on plants, and that clearly diverse plant species respond differently to such factors. They concluded it is necessary to rethink the exposure guidelines that currently do not take nonthermal effects into consideration.

There are numerous reports of adverse RFR effects on mature flora. Waldman-Salsam et al. [653] reported leaf damage in trees near mobile phone towers/masts. In a detailed long-term field monitoring study from 2006 to 2015 in two German cities, they found unusual and unexplainable tree damage on the sides of trees facing the towers and correlated it to RFR measurements vs. control areas without exposures. They found that tree-side differences in measured values of power flux density corresponded to tree-side differences in damage. Controls, which consisted of 30 selected trees in low radiation areas without visual contact to any phone mast and power flux density under 50 $\mu W/m^2$, showed no damage. They concluded that nonthermal RFR from mobile phone towers is harmful to trees and that damage that affects one side eventually spreads to the whole tree.

Vian et al. [642] published a review of plant interactions with high frequency RFR between 300 MHz and 3 GHz and noted that reports at the cellular, molecular, and whole plant scale included: numerous modified metabolic activities (reactive oxygen species metabolism, α- and β-amylase, Krebs cycle, pentose phosphate pathway, chlorophyll content, and terpene emission among others); altered gene expression (calmodulin, calcium-dependent protein kinase, and proteinase inhibitor); and reduced growth (stem elongation and dry weight) after nonthermal RFR exposure. They said changes occur in directly exposed tissues as well as systemically in distant tissues and proposed that high-frequency RFR be considered a genuine environmental factor highly capable of evoking changes in plant metabolism.

Halgamuge [627] also published a review that found weak non-thermal RFR affects living plants. The author analyzed data from 45 peer-reviewed studies of 29 different plant species from 1996 to 2016 that described 169 experimental observations of physiological and morphological changes. The review concluded that the data substantiated that RFR showed physiological and/or morphological effects (89.9%, $p<0.001$). The results also demonstrated that maize, roselle, pea, fenugreek, duckweeds, tomato, onions and mungbean plants are highly sensitive to RFR and that plants appear more responsive to certain frequencies between 800 and 1,500 MHz ($p<0.0001$); 1,500 and 2,400 MHz (p 0.0001); and 3,500 and 8,000 MHz ($p=0.0161$). Halgamuge [627] concluded that the literature shows significant trends of RFR influence on plants.

There is particular concern for impacts to flora and 5G since millions of small antennas mounted on utility poles, transmitting in MMW and other broadband frequencies, already are — or will soon be — in very close proximity to vegetation, creating both near- and -far field exposures. As noted in Halgamuge [627], the following are some studies investigating GHz frequencies already in use or planned for 5G that found significant effects on plants: Tanner and Romero-Sierra [654] on accelerated growth of Mimosa plant (10 GHz, 190 mW/cm^2, 5–10 min); Scialabba and Tamburello [655] on reduced hypocotyls growth rate in radish (*Raphanus sativus*) (10.5 GHz, 8 mW or 12.658 GHz, 14 mW for 96 h); Tafforeau et al. [656] induced meristem (actively dividing group of cells) production in *Linum usitatissimum* (105 GHz for 2 h at 0.1 mW/cm^2); and Ragha et al. [657] (9.6 GHz, 30 min) found germination depended on exposure parameters on *Vigna radiata*, *Vigna aconitifolia*, *Cicer arietinum* and *Triticum aestivum* plants. This is an area in immediate need of further investigation given the results from the previous studies.

A thorough review of RFR effects to trees and other plants was published by Czerwinski et al. [622] who reported that ecological effects on whole plant communities could occur at a very low exposure level of 0.01–10 $\mu W/cm^2$ — certainly comparable to limits examined in this paper. They focused on frequencies between 0.7 and 1.8 GHz and included multiple complex indicators for plant types, biometrics, and environmental factors. It was the first comprehensive paper that extended beyond using narrower research methods. They noted that although the literature on the effects of RFR on plants is extensive, not a single field study had assessed the biological response at the level of a whole plant community, biome, or ecosystem, but rather focused mostly on short-term laboratory studies conducted on single species. They said, "…This dissonance is particularly striking in view of the fact that alterations in a plant community's structure and composition have long been considered to be well founded, sensitive and universal environmental indicators." The paper serves as a predictive model for complex future field studies on larger ecosystems.

Interesting EMF synergistic effects were found with static magnetic fields and bacteria in plants. Seeking non-chemical methods to improve seed germination after prolonged periods of storage when seed viability can deteriorate, Jovičić-Petrović et al. [658] studied the combined effects of bacterial inoculation (*Bacillus amyloliquefaciens* D5 ARV) and static magnetic fields (SMF, 90 mT, 5 and 15 min) on white mustard (*Sinapis alba* L.) seeds. Their results found that biopriming with the plant growth-promoting *B. amyloliquefaciens* increased seed growth by 40.43%. Seed response to SMF alone was dependent on treatment duration. While SMF at 5 min increased the germination percentage, exposure at 15 min lowered seed germination compared with the control. However, the negative effect at the longer exposure was neutralized when combined with the bacterial inoculation. Both germination percentages were significantly higher when SMF was combined with the bacteria (SMF, 5 min, + D5 ARV; and SMF, 15 min + D5 ARV; 44.68 and 53.20%, respectively) compared with control. They concluded that biopriming and SMF treatment gave better results than bacterial inoculation alone. The highest germination percentage — 53.20% of germinated seeds — was seen with the bacterium and 15 min exposure to 90 mT, demonstrating a synergistic effect. They concluded that such techniques can be used for old seed revitalization and improved germination.

Even aquatic plants have been found sensitive to artificial electric fields. Klink et al. [659] assessed electric field exposures on growth rates and the content of trace metals of *Elodea canadensis*. Plants were exposed in a laboratory to an electric field of 54 kV/m for seven days. Plant length and Fe, Mn, Ni, Pb, and Zn were measured. Results showed the applied electric fields slightly enhanced root growth. They also found changes in mineral absorption; Mn and Ni were significantly lower while Pb and Zn were significantly higher in exposed plants. Fe content did not differ between control and exposed plants. They concluded that electric fields had potential use for phytoremediation in trace metal contaminated waters. This study also has implications for long term aquatic plant health in general.

Also working with electric fields, Kral et al. [660] found fascinating regeneration in plant root tips in *Arabidopsis* at varying electric field exposures and time durations with the weaker exposures producing the most growth. They found that imposed electric fields can perturb apical root regeneration and that varying the position of the cut and the time interval between excision and stimulation made a difference. They also found that a brief pulse of an electric field parallel to the root could increase by up to two-fold the probability of its regeneration, perturb the local distribution of the hormone auxin, and alter cell division regulation with the orientation of the root towards the anode or the cathode playing a role.

While mechanisms are still unclear regarding how EMFs affect plants, oxidative effects appear to play a significant role. Oxidative changes have been reported in many studies in plants after exposure to EMF [578, 639, 661–671]. EMF-related stress has been proposed by Vian et al. [641, 642], Roux et al. [672, 673], and Radhakrishma et al. [640]. Other mechanisms affecting plants such as ferromagnetism, radical-pairs, calcium ions and cryptochromes have also been proposed [674, 675].

It is apparent that plant growth and physiology — with their root systems anchored in the ground while their 'heads' manifest in the air — are affected by exposure to EMF in complex synergistic ways and that they are susceptible to multi-frequency exposures throughout their life spans.

Conclusion

Effects from both natural and man-made EMF over a wide range of frequencies, intensities, wave forms, and signaling characteristics have been observed in all species of animals and plants investigated. The database is now voluminous with *in vitro, in vivo,* and field studies from which to extrapolate. The majority of studies have found biological effects at both high and low-intensity man-made exposures, many with implications for wildlife health and viability. It is clear that ambient environmental levels are biologically active in all non-human species which can have unique physiological mechanisms that require natural geomagnetic information for their life's most important activities. Sensitive magnetoreception allows living organisms, including plants, to detect small variations in environmental EMF and react immediately as well as over the long term, but it can also make some organisms exquisitely vulnerable to man-made fields. Anthropogenic EMF may be contributing more than we currently realize to species' diminishment and extinction. Exposures continue to escalate without understanding EMF as a potential causative and/or co-factorial agent. It is time to recognize ambient EMF as a potential novel stressor to other species, design technology to reduce exposures to as low as reasonably achievable, keep systems wired as much as possible to reduce ambient RFR, and create laws accordingly — a subject explored more thoroughly in Part 3.

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Part 2: supplements

Supplement 1: Genetic Effects of RFR Exposure
Supplement 2: Genetic Effects at Low Intensity Static/ ELF EMF Exposure
Supplement 3: Biological Effects in Animals and Plants Exposed to Low Intensity RFR
Supplement 4: Effects of EMF on plant growth

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Part 2. Supplement 1.
Genetic Effects at Low Level RFR Exposure

RFR studies	Power density/SAR (<0.1 W/Kg)	Effects observed
Aitken et al. (2005)	Mice to 900-MHz RFR for 7 days at 12 h/day; SAR 0.09 W/kg	Mitochondrial genome damage in epididymal spermatozoa.
Akdag et al. (2016)	Male Wistar-Albino rats to 2400 MHz RFR from a Wi-Fi signal generator for a year; SAR 0.000141 (min)-0.007127 (max) W/kg	DNA damage in testes.
Alkis et al. (2019a)	Rats exposed to 900 MHz (brain SAR 0.0845 W/kg), 1800 MHz (0.04563 W/kg), and 2100 MHz (0.03957 W/kg) RFR 2 h/day for 6 months	Increased DNA strand breaks and oxidative DNA damage in brain.
Alkis et al. (2019b)	Rats exposed to 900 MHz, 1800 MHz, and 2100 MHz RFR 2 h/day for 6 months; maximum SAR over the rat 0.017 W/kg	DNA strand beaks and oxidative DNA damage in testicular tissue.
Atasoy et al. (2013)	Male Wister rats exposed to 2437 MHz (Wi-Fi) RFR; 24 h/day for 20 weeks; maximum SAR 0.091 W/kg	Oxidative DNA damage in blood and testes.
Beaubois et al. (2007)	Leaves of tomato plant exposed to 900-MHz RFR for 10 min at 0.0066 mW/cm^2	Increased expression of leucine-zipper transcription factor (bZIP) gene.
Belyaev et al. (2005)	Lymphocytes from human subjects exposed to GSM 915 MHz RFR for 2 h ; SAR 0.037 W/kg;	Increased condensation of chromatin.
Belyaev et al. (2009)	Human lymphocytes exposed to UMTS cell phone signal (1947.4 MHz, 5 MHz band	Chromatin affected and inhibition of DNA double-strand break.

	width) for 1 h; SAR 0.04 W/kg	
Bourdineaud et al. (2017)	Eisenia fetida earthworms exposed to 900 MHz for 2 h; SAR 0.00013-0.00933 W/kg	DNA genotoxic effect and HSP70 gene expressions up regulated.
Campisi et al. (2010)	Rat neocortical astroglial to CW 900 MHz RFR for 5, 10, or 20 min; incident power density 0.0265 mW/cm^2	Significant increases in DNA fragmentation.
Chaturvedi et al. (2011)	Male mice exposed to 2450 MHz RFR, 2 h/day for 30 days; SAR 0.03561 W/kg	Increased DNA strand breaks in brain cells.
Deshmukh et al. (2013)	Male Fischer rats exposed to 900 MHz (0.0005953 W/kg), 1800 MHz (0.0005835 W/kg), and 2450 MHz (0.0006672 W/kg) RFR for 2 h/day, 5 days/week for 30 days.	Increased DNA strand breaks in brain tissues.
Deshmukh et al. (2015)	Male Fischer rats exposed to 900 MHz (0.0005953 W/kg), 1800 MHz (0.0005835 W/kg), and 2450 MHz (0.0006672 W/kg) RFR for 2 h/day, 5 days/week for 180 days.	Increased DNA strand breaks in brain tissues.
Deshmukh et al. (2016)	Male Fischer rats exposed to 900 MHz (0.0005953 W/kg), 1800 MHz (0.0005835 W/kg), and 2450 MHz (0.0006672 W/kg) RFR for 2 h/day, 5 days/week for 90 days.	Increased DNA strand breaks in brain tissues.
Eker et al. (2018)	Female Wistar albino rats exposed to 1800-MHz RFR for 2 h/day	Caspase-3 and p38MAPK gene expressions increased in eye tissues.

	for 8 weeks; SAR 0.06 W/kg	
Furtado-Filho et al. (2014)	Rats of different ages (0-30 days) exposed to 950 MHz RFR for 0.5 h/day for 51 days (21 days of gestation and 6-30 days old): SAR pregnant rat 0.01-0.03 W/kg; neonate 0.88 W/kg, 6-day old 0.51 W/kg, 15-day old 0.18 W/kg, 30-day old 0.06 W/kg.	Decreased DNA strand breaks in liver of 15-day old and increased breaks in 30-day old rats..
Gulati et al. (2016)	Blood and buccal cells of people lived close (<400 meters) to a cell tower; 1800 MHz, Maximum power density (at 150 meters) 0.00122 mW/cm^2, some subjects lived in the area for more than 9 yrs	Increased DNA strand breaks in lymphocytes and micronucleus in buccal cells.
Gürler (2014)	Wistar rats exposed to 2450 MHz RFR 1 h/day for 30 consecutive days; power density 0.0036 mW/cm^2	Increased oxidative DNA damage in brain and blood.
Hanci et al. (2013)	Pregnant rats exposed 1 h/day on days 13-21 of pregnancy to 900-MHz RFR at power density 0.0265 mW/cm^2.	Testicular tissue of 21-day old offspring showed increased DNA oxidative damage.
He et al. (2016)	Mouse bone marrow stromal cells exposed to 900 MHz RFR 3 h/day for 5 days; SAR 4.1 x 10^{-4} W/kg (peak), 2.5 x 10_{-4} W/kg (average)	Increased expression of PARP-1 mRNA
Hekmat et al. (2013)	Calf thymus exposed to 940 MHz RFR for	Altered DNA structure at 0 and 2 h after exposure.

	45 min; SAR 0.04 W/kg	
Keleş and Süt (2021)	Pregnant rats exposed to 900-MH RFR at 0.0265 mW/cm2; 1 h/day from E13.5 until birth; thoracis spine of offspring examined.	Down regulation of H3K27me3 gene, am epigenetic modification to the DNA packaging protein Histone H3 in motor nerons.
Kesari and Behari (2009)	Male Wistar rats exposed to 50 GHz RFR for 2 h/day for 45 days; SAR 0.0008 W/kg	Increased in brain tissue DNA strand.
Kumar R. et al. (2021)	Male Wistar rats exposed to 900, 100, 2450 MHz RFR at SARs of 5.84×10^{-4} W/kg, 5.94×10^{-4} W/kg and 6.4×10^{-4} W/kg respectively for 2 h per day for 1-month, 3-month and 6-month	Microwave exposure with increasing frequency and exposure duration brings significant ($p < 0.05$) epigenetic modulations which alters gene expression in the rat hippocampus. Global DNA methylation was decreased and histone methylation was increased.
Kumar S. et al. (2010)	Male Wistar rats exposed to 10-GHz RFR for 2 h a day for 45 days, SAR 0.014 W/kg	Increased micronucleus in blood cells.
Kumar S. et al. (2013)	Male Wistar rats exposed to 10 GHz RFR for 2 h a day for 45 days; SAR 0.014 W/kg	Increased micronucleus in blood cells and DNA strand breaks in spermatozoa.
Marinelli et al. (2004)	Acute T-lymphoblastoid leukemia cells exposed to 900 MHz RFR for 2-48 h, SAR 0.0035 W/kg	Increased DNA damage and activation of genes involved in pro-survival signaling.
Markova et al. (2005)	Human lymphocytes exposed to 905 and 915 MHz GSM signals for 1 h; SAR 0.037 W/kg	Affected chromatin conformation and 53BP1/gamma-H2AX foci
Markova et al. (2010)	Human diploid VH-10 fibroblasts and human	Inhibited tumor suppressor TP53 binding protein 1 (53BP1) foci

	adipose-tissue derived mesenchymal stem cells exposed to GSM (905 MHz or 915 MHz) or UMTS (1947.4 MHz, middle channel) RFR for 1, 2, or 3 hr; SAR 0.037-0.039 W/kg	that are typically formed at the sites of DNA double strand break location.
Megha et al. (2015a)	Fischer rats exposed to 900 and 1800 MHz RFR for 30 days (2 h/day, 5 days/week), SAR 0.00059 and 0.00058 W/kg	Reduced levels of neurotransmitters dopamine, norepinephrine, epinephrine, and serotonin, and downregulation of mRNA of tyrosine hydroxylase and tryptophan hydroxylase (synthesizing enzymes for the transmitters) in the hippocampus.
Megha et al. (2015b)	Fischer rats exposed to 900, 1800, and 2450 MHz RFR for 60 days (2 h/day, 5 days/week); SAR 0.00059, 0.00058, and 0.00066 W/kg	Increased DNA damage in the hippocampus
Nittby et al. (2008)	Fischer 344 rats exposed to 1800 MHz GSM RFR for 6 h; SAR whole body average 0.013 W/kg, head 0.03 W/kg	Expression in cortex and hippocampus of genes connected with membrane functions.
Odaci et al. (2016)	Pregnant Sprague - Dawley rats exposed to 900 MHz RFR 1 h each day during days 13 - 21 of pregnancy; whole body average SAR 0.024 W/kg	Testis and epididymis of offspring showed higher DNA oxidation.
Pandey et al. (2017)	Swiss albino mice exposed to 900-MHz RFR for 4 or 8 h per day for 35 days; SAR 0.0054-0.0516 W/kg	DNA strand breaks in germ cells.
Pesnya and Romanovsky (2013)	Onion (Allium cepa) exposed to GSM 900-MHz RFR from a cell	Increased the mitotic index, the frequency of mitotic and chromosome abnormalities, and

	phone for 1 h/day or 9 h/day for 3 days; incident power density 0.0005 mW/cm^2	the micronucleus frequency in an exposure-duration manner.
Phillips et al. (1998)	Human Molt-4 T-lymphoblastoid cells exposed to pulsed signals at cellular telephone frequencies of 813.5625 MHz (iDEN signal) and 836.55 MHz (TDMA signal) for 2or 21 h. SAR 0.0024 and 0.024 W/Kg for iDEN and 0.0026 and 0.026 W/kg for TDMA)	Changes in DNA strand breaks
Qin et al. (2018)	Male mice exposed to 1800-MHz RFR 2 h/day for 32 days, SAR 0.0553 W/kg	Inhibition of testosterone synthesis might be mediated through CaMKI/RORα signaling pathway.
Rammal et al. (2014)	Tomato exposed to a 1250-MHz RFR for 10 days at 0.0095 mW/cm^2	Increased expression of two wound-plant genes.
Roux et al. (2006)	Tomato plants exposed to a 900-MHz RFR for 2-10 min at 0.0066 mW/cm^2	Induction of stress gene expression.
Roux et al. (2008)	Tomato plants exposed to a 900-MHz RFR for 10 min at 0.0066 mW/cm^2	Induction of stress gene expression.
Sarimov et al. (2004)	Human lymphocytes exposed to GSM 895-915 MHz signals for 30 min; SAR 0.0054 W/kg	Condensation of chromatin was observed.
Shahin et al. (2013)	Female mice (Mus musculus) exposed to continuous-wave 2.45 GHz RFR 2 h/day for 45v days; SAR 0.023 W/kg	Increased DNA strand breaks in the brain.

Sun Y. et al. (2017)	Human HL-60 cells exposed to 900 Hz RFR 5 h/day for 5 days; peak and average 0.00041 and 0.00025 W/kg, respectively.	Increased oxidative DNA damage and decreased mitochondrial gene expression.
Tkalec et al. (2013)	Earthworm (Eisenia fetida) exposed to comtinupus-wave and AM-modulated 900-MHz RFR for 2 - 4 h; SAR 0.00013, 0.00035, 0.0011, and 0.00933 W/kg	Increased DNA strand breaks.
Tsybulin et al. (2013)	Japanese Quail embryos exposed in ovo to GSM 900 MHz signal from a cell phone intermittently (48 sec ON/12 sec OFF) during initial 38 h of brooding or for 158 h (120 h before brooding plus initial 38 h of brooding): SAR 0.000003 W/kg	The lower duration of exposure decreased DNA strand breaks, whereas higher duration resulted in a significant increase in DNA damage.
Vian et al. (2006)	Tomato plants exposed to a 900-MHz RFR for 10 min at 0.0066 mW/cm^2	Induction of mRNA encoding the stress-related bZIP transcription factor.
Yakymenko et al. (2018)	Quail embryos exposed to GSM 1800 GHz signal from a smart phone (48 s ON/12 s OFF) for5 days before and 14 days during incubation, power density 0.00032 mW/cm^2	Increased DNA strand breaks and oxidative DNA damage.
Zong et al. (2015)	Mice exposed to 900 MHz RFR 4 h/day for 7 days; SAR 0.05 W/kg	Attenuated bleomycin-induced DNA breaks and repair,

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Table 1

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Part 2. Supplement 2.
Genetic Effects at Low Intensity Static/ELF EMF Exposure

Static and ELF EMF Studies	magnetic flux density	Effects observed
Agliassa et al. (2018)	Arabidopsis thaliana (thale cress) exposed to 0.00004 mT static magnetic field for 38 days after sowing	Changes in gene expression in leaf and floral meristem.
Baek et al. (2019)	Mouse embryonic stem cells exposed to hypomagnetic field (<0.005 mT) up to 12 days	Induced abnormal DNA methylation.
Bagheri Hosseinabadi et al. (2020)	Blood samples from thermal power plant workers; mean levels of exposure to ELF magnetic and electric fields were 0.0165 mT (±6.46) and 22.5 V/m (±5.38), respectively.	DNA strand breaks .in lymphocytes.
Baraúna et al. (2015)	Chromobacterium violaceum bacteria cultures exposed to ELF-EMF for 7 h at 0.00066 mT	Five differentially expressed proteins detected including the DNA-binding stress protein.
Belyaev et al. (2005)	Human lymphocytes exposed to 50 Hz magnetic field at 0.015 mT (peak) for 2 h (measurements made at 24 and 48 h after exposure).	Induced chromatin conformation changes.
Dominici et al. (2011)	Lymphocytes from welders (average magnetic field exposure from personal dosimeters 0.00781 mT (general environmental level 0.00003 mT)	Higher micronucleus frequency correlated with EMF exposure levels; decreased in sister chromatid exchange frequency.

Heredia-Rojas et al. (2010)	Human non-small cell lung cancer cells (INER-37) and mouse lymphoma cells (RMA E7) (transfected with a plasmid with hsp70 expression when exposed to magnetic field and contains the reporter for the luciferases gene) exposed to a 60-Hz magnetic field at 0.008 and 0.00008 mT for 20 min.	An increased in luciferase gene expression was observed in INER-37 cells.
Liboff et al. (1984)	Human fibroblasts dring the middle of S phaseexposed to 15 Hz-4 kHz sinusoidal MF	Enhanced DNA synthesis at between 5-25 μT
Sarimov et al. (2011)	Human lymphocytes exposed to 50-Hz magnetic field at 0.005-0.02 mT for 15-180 min	Magnetic field condensed relaxed chromatin and relaxed condensed chromatin.
Villarini et al. (2015)	Blood leukocytes from electric arc welders presumably exposed to 50-Hz EMF (mean 0.0078 mT; range: 0.00003-0.171 mT)	Decreased DNA strand beaks.
Wahab et al. (2007)	Human peripheral blood lymphocytes exposed to 50 Hz sinusoidal (continuous or pulsed) or square (continuous or pulsed) magnetic fields at 0.001 or 1 mT for 72 h.	Increase in the number of sister chromatid exchange/cell
Zendehdel et al. (2019)	Peripheral blood cells of male power line workers in a power plant. The median value of the magnetic	Increased in DNA strand breaks.

	field at the working sites was 0.00085 mT.	

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Part 2. Supplement 3
Biological Effects in Animals and Plants Exposed to Low-Intensity RFR

		SAR (W/kg)	Power density ($\mu W/cm^2$)	Effects reported
Aitken et al. (2005)	Mice exposed to 900 MHz RFR, 12/day. 7 days	0.09		Genotoxic effect in sperm.
Akdag et al. (2016)	Rats exposed to 2400 MHz RFR from a Wi-Fi signal generator for a year	0.000141 (min)- 0.007127 (max)		DNA damage in testes.
Alimohammadi et al. (2018)	pregnant mice exposed to 915 MHz RFR; 8h/day, 10 days.		0.045	Offspring had increased fetal weight, enlarged liver and tail deformation
Alkis et al. (2019a)	Rtas exposed to 900; 1800; and 2100 MHz RFR; 2 h/day. 6 months	Brain SAR: 900 MHz - 0.0845; 1800 MHz- 0.04563; 210 MHz- 0.03957		DNA single strand break and oxidative damages in frontal lobe.
Alkis et al. (2019b)	Rats exposed to 900; 1800; and 2100 MHz RFR; 2 h/day. 6 months	maximum SAR over the rat body 0.017		DNA strand beaks and oxidative DNA damage in testicular tissue.
Atasoy et al. (2013)	Rats exposed to 2437 MHz (Wi-Fi) RFR; 24 h/day for 20 weeks	maximum SAR 0.091		Oxidative DNA damage in blood and testes.

Balmori et al. (2010)	Frog (Rana temporaria) exposed to 88.5 – 1873.6 MHz, cell phone base station emissions; 2 months from egg phase to tadpole		0.859-3.25 (1.5-3.8 V/m)	Retarded development and increased mortality rate.
Balmori et al (2015)	White stocks lived within 200 m of a Phone mast, GSM-900 MHz and DCS-1800 MHz signals		1.48	Affected reproduction rate.
Bartos et al. (2019)	Cockroach exposed to broadband RF noise		429 nT	Light-dependent slowing of circadian rhythm.
Beaubois et al. (2007)	Tomato plant exposed to 900-MHz RFR for 10 min		6.6	Increased expression of leucine-zipper transcription factor (bZIP) gene in leaves.
Bedir et al. (2018)	Rat exposed to 2100 MHz RFR, 6 or 19 h/day, 30 days	0.024		Oxidative stress-mediated renal injury.
Belyaev et al. (1992)	E. coli exposed to 51.62-51.84 and 41.25-41.50 GHz RFR, 5-15 min		1	Suppressed radiation-induced repair of genome conformation state.
Belyaev et al. (2005)	915 MHz GSM signal, 24 & 48 hr	0.037		Genetic changes in human white blood cells
Belyaev et al. (2009)	915 MHz, 1947 MHz; GSM, UMTS signals 24 & 72 hr	0.037		DNA repair mechanism in human white blood cells
Bourdineaud et al. (2017)	Earthworm (Eisenia fetida) exposed to 900 MHz RFR, 2 hr	0.00013-0.009		DNA modification.

Burlaka et al. (2013)	Japanese quail embryos exposed to GSM 900 MHz RFR; 158-360 hr		0.25	Oxidative DNA damage and free radical formation
Capri et al. (2004)	900 MHz, GSM signal, 1 hr/day, 3 days	0.07		Cell proliferation and membrane chemistry
Cammaerts and Johansson (2015)	Brassicaceae lepidium sativum (cress d'alinois) seed exposed to 900 and 1800 MHz RFR, 4, 7, and 10 days		0.007-0.01	Defect in germination.
Cammaerts et al. (2013)	Ants exposed to GSM signal for 180 h		0.1572	Affected food collection and response to pheromones.
Cammaerts et al. (2014)	Ants exposed to GSM signal for 10 min		0.5968	Affected social behavior.
Campisi et al. (2010)	Rat neocortical astroglial cells exposed to 50-Hz modulated 900 Mhz RFR, 5-20 min		26	Free radical production and DNA fragmentation.
Czerwinski et al. (2020)	Plant community exposed to cell phone base station radiation		0.01-0.1	Biological effects observed.
Chaturvedi et al. (2011)	Rat brain cells exposed to 2450 MHz RFR, 2 h/day for 30 days	0.03561		Increased DNA strand breaks.
Comelekoglu et al. (2018)	Rat sciatic nerve exposed to 1800 MHz RFR, 1 hr/day, 4 weeks	0.00421		Changes in electrical activity, increased catalase, and degeneration of myelinated fibers.

De Pomerai et al. (2003)	Protein exposed to 1 GHz RFR, 24 & 48 hr	0.015		Protein damages
Deshmukh et al. (2013)	Rats exposed to 900, 1800, and 2450 MHz RFR ; 30 days	0.0006-0.0007		DNA strand breaks in brain.
Deshmukh et al. (2015)	Rats exposed to 900, 1800, and 2450 MHz RFR; 180 days	0.0006-0.0007		Declined cognitive functions, increased brain HSP70 and DNA strand break.
Deshmukh et al. (2016)	Rats exposed 900, 1800, and 2450 MHz; 90 days	0.0006-0.0007		Declined cognitive functions, increased brain HSP70 and DNA strand break in rats
Dutta et al. (1984)	human neuroblastoma cells exposed to 915 MHz RFR, sinusoidal AM at 16 Hz	0.05		Increase in calcium efflux.
Dutta et al. (1994)	Escherichia coli cultures containing a plasmid with a mammalian gene for enolase were exposed for 30 min to 147 MHz RFR AM at16 or 60 Hz	0.05		Enolase activity in exposed cultures RFR at AM at 16 Hz showed enhanced activity enhanced, and AM at 60 Hz showed reduced activity. (Modulation frequencies. 16 and 60 Hz, caused similar effects.)
Eker et al. (2018)	Rats exposed to 1800 MHz RFR, 2 hr/day for 8 weeks	0.06		Increased caspase-3 and p38MAPK expressions in eye.
Fesenko et al. (1999)	Mice exposed to 8.15 – 18 GHz RFR, 5 hr to 7 days, direction of response depended on exposure duration		1	Changes in immunological functions.

Forgacs et al. (2006)	Mice exposed to 1800 MHz RFR, GSM- 217 Hz pulses, 576 µs pulse width; 2 hr/day, 10 days	0.018		Increase in serum testosterone.
Frątczak et al. (2020)	Ticks exposed to 900 MHz RFR		0.1	Ticks attracted to the RFR, particularly those infected with Rickettsia (spotted fever).
Friedman et al. (2007)	Rat and human cells exposed to 875 MHz RFR, 30 min		5	Activation of signaling pathways.
Furtado-Filho et al. (2014)	Pregnant rats exposed to 950 MHz RFR for 0.5 h/day for 51 days (21 days of gestation and 6-30 days old)	SAR pregnant rat 0.01-0.03 W/kg; neonate 0.88 W/kg, 6-day old 0.51 W/kg, 15-day old 0.18 W/kg, 30-day old 0.06 W/kg		Decreased DNA strand breaks in liver of 15-day old and increased breaks in 30-day old offspring.
Gandhi et al. (2015)	People who lived within 300 m of a mobile-phone base station.		1.15	Increased DNA damage in lymphocytes, more in female than in male subjects.
Garaj-Vrhovac et al. (2011)	Operators of two types of marine radars (3, 9.4, and 5.5 GHz); average time on job 2-16 yrs	0.0005-0.004 (time averaged)		Increased genetic damages in blood lymphocytes

Gremiaux et al. (2016)	Rose exposed to 900 MHz RFR, 3x 39min every 48 h at 2 stages of development	0.00072		Delayed and reduced growth.
Gulati et al. (2016)	People lived close (<400 meters) to a cell tower; 1800 MHz, , some subjects lived in the area for more than 9 yrs		Maximum power density (at 150 meters) 1.22	Increased DNA strand breaks in lymphocytes and micronucleus in buccal cells.
Gulati et al. (2020)	DNA damage in human lymphocytes	Cells exposed to UMTS signals at different frequency channels used by 3 G mobile phone (1923, 1947.47, and 1977 MHz) for 1 or 3 h; SAR 0.04 W/kg		DNA damage found only in cells exposed to 1977-MHz field.
Gupta et al. (2018)	Rtas exposed to 2450 MHz RFR; 1h/day 28 days	0.0616		Cognitive deficit, loss of mitochondrial functions, activation of apoptotic factors in hippocampus; affected cholinergic system.
Gurler et al. (2014)	Rats exposed to 2.45 GHz RFR, 1 h/day, 30 days		3.59	Increased DNA damage in brain.

Halgamuge et al. (2015)	Growth parameters of soybean seedlings	GSM 217 Hz-modulated (4.8×10^{-7}, 4.9×10^{-5}, and 0.0026 W/kg) SAR or CW (0.00039 and 0.02 W/kg) 900-MHz RFR for 2 h		Modulated and CW fields produced different patterns of growth effects. There was an amplitude effect and extremely low-level modulated field (4.8×10^{-7} W/kg) affected all parameters.
Hanci et al. (2013)	Pregnant rats exposed 1 h/day on days 13-21 of pregnancy to 900-MHz RFR		26.5	Testicular tissue of 21-day old offspring showed increased DNA oxidative damage.
Hanci et al. (2018)	Rats exposed to 900 MHz RFR, 1 h/day to postnatal day 60.	0.0067		Changes in morphology and increase in oxidative stress marker in testis.
Hassig et al. (2014)	Cows exposed to 916.5 MHz signal similar to GSM base station, 30 days 16 h 43 min per day		38.2	Changes in redox enzymes (SOD. CAT, GSH-px
He et al. (2016)	Mouse bone marrow stromal cells exposed to 900 MHz RFR 3 h/day for 5 days	2.5×10^{-4}		Increased expression of PARP-1 mRNA
Hekmat et al. (2013)	Calf thymus exposed to 940 MHz RFR, 45 min	0.04		Conformational changes in DNA.

Ivaschuk et al. (1997)	Nerve growth factor-treated PC12 rat pheochromocytoma cells 836.55 MHz TDMA signal, 20 min	0.026		Transcript levels for c-jun altered.
Ji et al. (2016)	Mouse bone-marrow stromal cells exposed to 900 MHz RFR, 4 hr/day for 5 days		120	Faster kinetics of DNA-strand break repair.
Keleş et al. (2019)	Rats exposed tp 900 MHz RFR; 1h/day, 25days	0.012		Higher number of pyramidal and granule neurons in hippocampus.
Kesari and Behari (2009)	Rats exposed to 50 GHz RFR; 2hr/day, 45 days	0.0008		Double strand DNA breaks observed in brain cells
Kesari and Behari (2010)	Rats exposed to 50 GHz RFR; 2 hr/day, 45 days	0.0008		Changes in oxidative processes and apoptosis in reproductive system.
Kesari et al. (2010)	Rats exposed to 2450 MHz RFR at 50-Hz modulation, 2 hr/day, 35 days	0.11		DNA double strand breaks in brain cells
Kumar et al. (2010a)	Rats exposed to 10 GHz RFR, 2h/day 45 days	0.014		Cellular changes and increase in reactive oxygen species in testes
Kumar et al. (2010b)	Rats exposed to 10 GHz RFR, 2 h/day, 45 days; or 50 GHz, 2h/day, 45 days	0.014 (10 GHz) 0.0008 (50 GHz)		Genetic damages in blood cells.

Kumar et al. (2013)	Rats exposed to 10 GHz RFR for 2 h a day for 45 days	0.014		Increased micronucleus in blood cells and DNA strand breaks in spermatozoa.
Kumar et al. (2015)	maize seedlings exposed to 1899 MHz RFR, 0.5-4 h		33.2	Retarded growth and decreased chlorophyll content.
Kumar et al. (2021)	Epigenetic modulation in the hippocampus of Wistar rats	Rats exposed to 900 MHz, 1800 MHz, and 2450 MHz RFR at a specific absorption rate (SAR) of 5.84×10^{-4} W/kg, 5.94×10^{-4} W/kg and 6.4×10^{-4} W/kg respectively for 2 h per day for 1-month, 3-month and 6-month periods.		Significant epigenetic modulations were observed in the hippocampus, larger changes with increasing frequency and exposure duration.
Kwee et al. (2001)	Transformed human epithelial amnion cells exposed to 960 MHz GSM signal, 20 min	0.0021		Increased Hsp-70 stress protein.
Landler et al. (2015)	Juvenile snapping turtle (c. serpentina) exposed to 1.43 MHz RFR, 20 min		20-52 nT	Disrupted magnetic orientation.

Lazaro et al. (2016)	50, 100, 200, 400 m from ten mobile telecommunication antennas		0.0000265 - 0.106	Distance-dependent effects on abundance and composition of wild insect pollinators
Lerchl et al. (2008)	383 MHz (TETRA), 900 and 1800 MHz (GSM) 24 hr/day, 60 days	0.08		Metabolic changes in hamster.
López-Martín et al. (2009)	Pulse-modulated GSM and unmodulated signals; 2 hr	0.03-0.26		c-Fos expression in brain of picotoxin-induced seizure-prone rats
Magras and Xenos (1997)	Mice in 'antenna park'-TV and FM-radio, exposure over several generations		0.168	Decrease in reproductive functions.
Marinelli et al. (2004)	Human leukemia cell exposed to 900 MHz CW RFR 2 - 48 hr	0.0035		Cell's self-defense responses triggered by DNA damage.
Makova et al. (2005)	human white blood cells exposed to 915 and 905 MHz GSM signal, 1 hr	0.037		Altered chromatin conformation.
Markova et al. (2010)	in human diploid VH-10 fibroblasts and human adipose-tissue derived mesenchymal stem cells exposed to GSM (905 MHz or 915 MHz) or UMTS (1947.4 MHz, middle channel) RFR for 1, 2, or 3 hr;	0.037-0.039		Inhibited tumor suppressor TP53 binding protein 1 (53BP1) foci that are typically formed at the sites of DNA double strand break location.

Megha et al. (2015a)	Rats exposed to 900 and 1800 MHz RFR for 30 days (2 h/day, 5 days/week)	0.00059 and 0.00058		Reduced levels of neurotransmitters dopamine, norepinephrine, epinephrine, and serotonin, and downregulation of mRNA of tyrosine hydroxylase and tryptophan hydroxylase (synthesizing enzymes for the transmitters) in the hippocampus.
Megha et al. (2015b)	Rats exposed to 900, 1800, and 2450 MHz RFR for 60 days (2 h/day, 5 days/week)	0.00059, 0.00058, and 0.00066		Increased DNA damage in the hippocampus.
Monselise et al. (2011)	Etiolated duckweed exposed to AM 1.287 MHz signal form transmitting antenna		0.859 (1,8-7.8 V/m)	Increased alanine accumulation in cells.
Navakatikian and Tomashevskaya (1994)	Rats exposed to 2450 MHz CW and 3000 MHz pulse-modulated 2 μs pulses at 400 Hz, Single (0.5-12 hr) or repeated (15-60 days, 7-12 hr/day)	0.0027		Behavioral and endocrine changes, and decreases in blood concentrations of testosterone and insulin. CW-no effect
Nittby et al. (2007)	Rats exposed to 900 MHz GSM signal, 2 hr/wk, 55wk	0.0006		Reduced memory functions.
Nittby et al. (2008)	Rats exposed to 915 MHz GSM signal, 6 hr	0.013 (whole body average); 0.03 (head)		Altered gene expression in cortex and hippocampus.

Novoselova et al. (1999)	Mice exposed to RFR from 8.15 -18 GHz, 1 sec sweep time-16 ms reverse, 5 hr		1	Changes in Functions of the immune system.
Novoselova et al. (2004)	Mice exposed to RFR from 8.15 -18 GHz, 1 sec sweep time-16 ms reverse, 1.5 hr/day, 30 days		1	Decreased tumor growth rate and enhanced survival.
Novoselova et al. (2017)	Mice exposed to 8.15 -18 GHz RFR, 1 Hz swinging frequency, 1 hr		1	Enhanced plasma cytokine.
Odaci et al. (2016)	Pregnant Sprague - Dawley rats exposed to 900 MHz RFR 1 h each day during days 13 - 21 of pregnancy	0.024		Testis and epididymis of offspring showed higher DNA oxidation.
Özsobacı et al. (2020)	Human kidney embryonic cells (HEK293) exposed to 3450 MHz RFR, 1 h		1.06	Changed oxidative enzyme activity and increased apoptosis.
Panagopoulos and Margaritis. (2010a)	Flies exposed to GSM 900 and 1800 MHz RFR, 6 min/day, 5 days		10	‘Window’ effect of GSM radiation on reproductive capacity and cell death.
Panagopoulos and Margaritis. (2010b)	Flies exposed to GSM 900 and 1800 MHz RFR, 1- 21 min/day, 5 days		10	Reproductive capacity of the fly decreased linearly with increased duration of exposure.
Panagopoulos et al. (2010)	Flies exposed GSM 900 and 1800 MHz RFR, 6 min/day, 5 days		1-10	Affected reproductive capacity and induced cell death.
Pandey et al. (2017)	Mice exposed to 900-MHz RFR for	0.0054-0.0516		DNA strand breaks in germ cells.

	4 or 8 h per day for 35 days			
Pavicic et al. (2008)	Chinese hamster V79 cells exposed to 864 and 935 MHz CW RFR, 1-3 hrs	0.08		Cell growth affected.
Perov et al. (2019)	Rats exposed to 171 MHz CW RFR, 6h/day, 15 days	0.006		Stimulation of adrenal gland activity.
Persson et al. (1997)	Rats exposed to 915 MHz RFR -CW and pulse-modulated (217-Hz, 0.57 ms; 50-Hz, 6.6 ms) 2-960 min.	0.0004		Increase in permeability of the blood-brain barrier. CW more potent.
Pesnya and Romanovsky (2013)	Onion exposed to GSM 900-MHz RFR from a cell phone for 1 h/day or 9 h/day for 3 days.		0.5	Increased mitotic index, frequency of mitotic and chromosome abnormalities, and micronucleus frequency.
Phillips et al. (1998)	Human leukemia cells exposed to 813.5625 MHz (iDEN); 836.55 MHz (TDMA) signals, 2 hr and 21 hr	0.0024		DNA damage observed.
Piccinetti et al. (2018)	Zebrafish exposed to 100 MHz RFR, 24-72 h post-fertilization	0.08		Retarded embroyonic development.
Postaci et al. (2018)	Rats exposed to 2600 MHz RFR, 1 h/day, 30 days	0.011		Cellular damages and oxidative damages in liver.

Pyrpasopoulou et al. (2004)	Rats exposed to 9.4 GHz GSM (50 Hz pulses, 20 µs pulse length) signal, 1-7 days postcoitum	0.0005		Exposure during early gestation affected kidney development.
Qin et al. (2018)	Mice exposed to 1800-MHz RFR, 2 h/day for 32 days	0.0553		Inhibition of testosterone synthesis.
Rafati et al. (2015)	Frog gastroenemius muscle exposed to cell phone jammers; 1 m away, 3x 10 min periods	For different jammers:0.01-0.05		Latency of contraction of prolonged.
Ranmal et al. (2014)	Tomato exposed to 1250-MHz RFR for 10 days.		9.5	Increased expression of two wound-plant genes.
Roux et al. (2006)	Tomatoes exposed to 900-MHz RFR for 2-10 min		6.6	Induction of stress gene expression in tomato.
Roux et al. (2008a)	Tomatoes exposed to 900 MHz RFR		6.6	Changes in Gene expression and energy metabolism.
Roux et al. (2008b)	Tomato plants exposed to 900 MHz RFR (>30 min)		6.6	Changes in energy metabolism in leave of tomato plant.
Salford et al. (2003)	Rats exposed to 915 MHz GSM, 2 hr	0.02		Nerve cell damage in brain.
Sarimov et al. (2004)	Human lymphocytes exposed to 895-915 MHz GSM signal, 30 min	0.0054		Chromatin affected similar to stress response.

Schwarz et al. (2008)	Human fibroblasts exposed to 1950 MHz UMTS signal, 24 hr	0.05		Changes in genes.
Shahin et al. (2013)	Mice exposed to 2450 MHz RFR, 2 h/day for 45 days	0.023		Increased DNA strand breaks in the brain.
Singh et al. (2012)	Hung beans exposed to 900 MHz RFR, 0.5-2 h		8.54	Reduced root length and number of roots per hypocotyls.
Sirav and Seyhan (2011)	Rats exposed to CW 900 MHz or 1800 MHz for 20 min	CW 900 MHz (0.00426 W/kg) or 1800 MHz (0.00146 W/kg)		Increased blood-brain barrier permeability in male rats, no significant effect on female rats.
Sirav and Seyhan (2016)	Rats exposed to pulsed-modulated (217 Hz, 517 µs width) 900 MHz or 1800 MHz 6 RFR for 20 min	0.02		In male rats, both frequencies increased blood-brain barrier permeability, 1800 MHz is more effective than 900 MHz; in female rats, only 900 MHz filed caused an effect.
Somosz et al. (1991)	Rat embryo 3T3 cells exposed to 2450-MHz 16-Hz square modulated RFR	0.024		Increased the ruffling activity of the cells, and caused ultrastructural alteration in the cytoplasm. CW was less effective.
Soran et al. (2014)	Plants exposed to GSM and WLAN signals		10 (GSM) 7 (WLAN)	Enhanced release of terpene from aromatic plants; essential oil contents in leaves enhanced by GSM radiation but reduced by WLAN radiation in some plants.

Stagg et al. (1997)	Glioma cells exposed to 836.55 MHz TDMA signal, duty cycle 33%, 24 hr	0.0059		Glioma cells showed significant increases in thymidine incorporation, which may be an indication of an increase in cell division.
Stankiewicz et al. (2006)	Human white blood cells exposed to 900 MHz GSM signal, 217 Hz pulses-.577 ms width, 15 min	0.024		Immune activities of human white blood cells affected.
Sun Y. et al. (2017)	Human HL-60 cells exposed to 900 Hz RFR, 5 h/day for 5 days	peak and average SAR 4.1×10^{-4} and 2.5×10^{-4} W/kg		Increased oxidative DNA damage and decreased mitochondrial gene expression.
Szymanski et al. (2020)	Human cells exposed to Pulse-modulated 900 MHz RFR, two 15-min exposure	0.024		Human blood mononucleus cells demonstrated high immunological activity of monocytes and T-cell response to concanavalin A.
Tkalec et al. (2013)	Earthorm exposed to continuous-wave and AM-modulated 900- MHz RFR for 2 - 4 h	0.00013, 0.00035, 0.0011, and 0.00933		Increased DNA strand breaks.
Tsybulin et al. (2012)	Japanese Quail embryos exposed to GSM 900 MHz signal during first 38 h or 14 days of fertilization		0.2	Enhanced development and survival in Japanese Quail embryos probably via a free radical-induced mechanism.
Tsybulin et al. (2013)	Japanese Quail embryos exposed to GSM 900 MHz signal, 48 sec on/12 sec off; 38 or 158 h	0.003		Decreased DNA strand break at 38 h and increased in 158h exposure in cells.

Vargová et al. (2017)	Ticks exposed to 900 MHz RFR		0.07	Ticks showed greater movement activity, with jerking movement of whole body or first pair of legs.
Vargová et al. (2018)	Ticks exposed to 900 MHz and 5000 MHz RFR		0.105	In a tube with half shielded for RFR, ticks exposed to 900 MHz concentrated on exposed side, and escaped to shielded side when exposed to 5000 MHz
Velizarov et al. (1999)	Human epithelial amnion cells exposed to 960 MHz GSM signal, 217 Hz square-pulse, duty cycle 12%, 30 min	0.000021		Decreased proliferation
Veyret et al. (1991)	Exposure to 9.4 GHz 1 μs pulses at 1000 pps, also with or without sinusoidal AM between 14 and 41 MHz, response only with AM modulation, direction of response depended on AM frequency	0.015		Changes in functions of the mouse immune system.
Vian et al. (2006)	Tomato plants exposed to 900 MHz RFR		6.6	Stress gene expression in plant.

Vilić et al. (2017)	Oxidative effects and DNA damage in honey bee (Apis mellifera) larvae		Honey bee larvae were exposed to 900-MHz at unmodulated field at 27 $\mu W/cm^2$ and modulated (80% AM 1 kHz sinusoidal) field at 140 $\mu W/cm^2$, for 2 hr.	Oxidative effect with exposure to unmodulated field. DNA damage increased after exposure to modulated field.
Waldmann-Salsam et al. (2016)	Mobile phone mast, long-term exposure		>0.005	Damages to trees
Wolke et al. (1996)	Heart muscle cells of guinea pig exposed to 900, 1300, 1800 MHz, square-wave modulated at 217 Hz; Also 900 MHz with CW, 16 Hz, 50 Hz and 30 KHz modulations	0.001		Changed calcium concentration in heart muscle cells.
Yakymenko et al. (2018)	Quail embryos exposed to GSM 1800 GHz signal from a smart phone (48 s ON/12 s OFF) for5 days before and 14 days during incubation		0.32	Increased DNA strand breaks and oxidative DNA damage.

Yurekli et al. (2006)	945 MHz GSM, 217 Hz pulse-modulation 7 hr/day, 8 days	0.0113		Free radical chemistry.
Zong et al. (2015)	Mice exposed to 900 MHz RFR, 4 h/day for 7 days	0.05		Attenuated bleomycin-induced DNA breaks and repair.

Author Note: *Many of the biological studies are acute, mostly one-time, exposure experiments, whereas exposure to ambient environmental man-made EMF is chronic. Acute and chronic exposures will likely end up with different consequences. Living organisms can compensate for the effect at the beginning of exposure and growth promotion in plants could be a result of over-compensation. After prolonged exposure, a breakdown of the system could occur, leading to detrimental effects. This sequence of response is basically how a living organism responds to stressors. The timeline of response depends on the physiology of an organism and also the intensity of exposure*

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Supplement 4. Effects of EMF on plant growth

	Experimental conditions	**Results**
STATIC MAGNETIC FIELD		
Abdani Nasiri et al.(2018)	medicinal sage;15-30 mT, 5 min	enhanced growth
Baghel et al. (2016)	soybean; 200 mT, 1h,	increased growth
Bahadir et al. (2018)	sweet pea ; 125 mT, 24-72 h	promoted germination
Bhardwaj et al. (2012)	cucumber; 100-250 mT, 1-3 h	increased germination rate, length of seedling and dry weight
Ćirković et al. (2017)	wheat ; 340 mT, 16 h	increased growth rate
Florez et al. (2007)	maize;125 and 250 mT, 1 min to 10 days	increased growth rate
Jovičić-Petrović et al. (2021)	White mustard seed, 90 mT, 5 or 15 min	suppressed germination, but synergistic with a plant growth-promoting bacterial strain Bacillus amyloliquefaciens D5 ARV
Kataria et al. (2020)	soybean; 200 mT, 1 h	stimulated germination and promoted growth
Kim et al. (2016)	agricultural plants ; 130-250 mT, 4 days	increased stem and root lengths
Patel et al. (2017)	maize; 200 mT, 1 h	enhanced germination
Payez et al. (2013)	wheat; 30 mT, 4 days	promoted growth
Razmioo andAlinian (2017)	Cumin seed; 150, 250 500 mT or 1T for min	improved germination, growth and oil and essential contents
Shabrangy et al. (2021)	barley seeds, 7 mT, 1,3, or 6 h	Improved seed germination rate, root and shoot lengths, and biomass weight
Vashisth and Joshi (2017)	maize; 50-250 mT, 1-4 h	enhanced seed growth
Vashisth and Nagarajan (2008)	chickpea; 0-250 mT, 1-4 h	increased speed of germination, seedling length and dry weight
Xu et al. (2013)	rock cress, removal of the local geomagnetic field (~45 µT)	suppressed growth
PULSED MAGNETIC FIELD		

Bhardwaj et al. (2016)	green pea; 100 mT, 1 h, 6-min on/off	enhanced germination and growth
Bilalis et al. (2012)	corn; 3 Hz; 12.5 nT, 1 x 10^{-6} wave duration, 0-15 min	promoted plant growth and yield
Efthimiadou et al. (2014)	tomato; 3 Hz, 12.5 mT, 1 x 10^{-6} s duration, 0-15 min	enhanced plant growth
Radhakrishnan et al. (2012a)	soybean; 1 Hz, 1.5 µT, 5 h/day for 20 days	improved plant growth
Radhakrishnan et al. (2012b)	soybean; 10 Hz, 1.5 µT, 5 h/day for 20 days	improved plant growth
ELF MAGNET FIELD		
De Souza et al. (2008)	lettuce; 60-Hz, 120-160 mT, 1-5 min	enhanced growth and final yield
Fischer et al. (2004)	sunflower and wheat; 16.67 Hz; 20 µT, 12 days	increased fresh and dry weights and growth rate
Huang and Wang (2008)	Mung bean; 10-60 Hz modulated, 12 h, 6.38-16.20 µT	20 and 60 Hz, enhanced growth; 30, 40 and 50 Hz inhibited growth
Leelapriya et al. (2003)	cotton;10 Hz, 0.1 mT, 5 h/day for 20 days	enhanced germination
Naz et al. (2012)	okra; 50 Hz, 99 mT, 3 and 11 min	increased germination
Novitskii et al. (2014)	radish; 50 Hz, 500 µT,5 days	stimulated lipid formation
Shine et al. (2011)	soybean; 50 Hz, 0-300 mT, 30-90 min	improved germination parameters and biomass
Yano et al. (2004)	radish; 60 Hz, 50 µT plus a parallel 48-µT static magnetic field, 10-15 days	decreased CO_2 uptake , fresh and dry weights and leaf area
RFR		
Cammaerts and Johansson (2015)	Garden cress; 900 and 1800 MHz, 0.007-0.01 µW/cm^2, 10 days	decreased germination
Grémiaux et al. (2016)	rose, 900 MHz, 0.00072 W/kg, 3 hr once or 3 times, every 48 hr	delayed and reduced growth
Halgamuge et al. (2015)	Soybean seedling. 900 MHz GSM pulsed or CW, 0.45 mW/cm^2, 2 h	GSM radiation reduced outgrowth of epicotyls; CW exposure reduced outgrowth of roots and hypocotyls.
Kumar et al. (2015)	maize;1800 MHz, 0.5-4 h, 33.2 µW/cm^2	retarded growth and reduced chlorophyll content

Mildažienė et al. (2019)	sunflower seed; 5.28 MHz, 5, 10, 15 min 0.74 mT	changes in phytohormone balance, development and leaf protein expression
Payez et al. (2013)	wheat; 10 KHz, 4 days, 25 mW/cm^2	reduced water intake, increased speed of growth, reduced seeding vigor index I
Senavirathna et al. (2014)	Parrot feather (Myriophyllum aquaticum), 2000 MHz, 0.142 mW/cm^2, 1 h	Reduction in growth
Singh et al. (2012)	Mung bean; 900 MHz, 8.54 $\mu W/cm^2$, 0.5-2 h	reduced root length and number of roots per hypocotyls
Tkalec et al. (2009)	Onion; 400 and 900 MHz, 2h, 446 $\mu W/cm^2$	induced mitotic aberrations due to impairment of the mitotic spindle

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SANTA FE NEW MEXICAN

Report says wireless radiation may harm wildlife

- By Scott Wyland swyland@sfnewmexican.com
- Feb 5, 2022 Updated Feb 7, 2022

Timeline for wireless radiation oversight

1980s to 1996: The Environmental Protection Agency measures levels of wireless radiation in the U.S. and is tasked with developing safety limits. The agency issues findings in a 1984 report on biological effects and a 1986 report on environmental exposure levels.

1995: The EPA meets with the Federal Communications Commission and presents its plan to develop safety limits for the potentially harmful electromagnetic fields that wireless technologies produce.

1996: The EPA's research on EMFs is defunded. The agency

2 of 3

A cell tower off I-25 on Jan. 31.
Luis Sánchez Saturno/The New Mexican

Health researchers raised concerns in the 1990s about the possible harmful effects of wireless radiation from cellphones and towers, closes is project measuring EMF levels in U.S. cities.The FCC adopts wireless radiation rules and safety limits proposed by industry-connected groups.

1999: The Food and Drug Administration asks the National Toxicology Program to study cellphone radiation because of the lack of safety data on the health effects from long-term exposure.

2008: The National Research Council issues a report called "The Identification of Research Needs Relating to Potential Biological or Adverse Health Effects of Wireless Communications Devices." Congress holds a hearing on the health effects of cellphone use.

2009: The U.S. Senate holds hearings on the health effects of cellphones' wireless radiation.

2012: A Government Accountability Office report recommends cellphone test procedures be reassessed to ensure they reflect real world use and are based on the latest science.

2013: The FCC opens an official inquiry asking if wireless radiation limits should be updated.Thousands of pages of scientific evidence are submitted

and their warnings met pushback from telecommunications companies on the verge of growing a mega-industry.

Industry-backed researchers assured federal agencies health concerns — especially those centered on the possibility of low-level microwaves causing cancer — lacked conclusive evidence.

Regulators accepted their assessments, and the alarm bells went silent.

Now a trio of researchers have compiled a report saying the widespread installation of cell towers and antennas is generating electromagnetic fields — EMFs for short — that could be physiologically harmful.

The report focuses on potential impacts on wildlife, trees, plants and insects, such as bees, because there are no regulations protecting them from EMFs emanating from wireless antennas. Wildlife protections are becoming more vital as this radiation — known more specifically as radiofrequency EMFs — escalates through 5G technologies, the researchers warn.

"There needs to be regulatory standards to address EMFs affecting wildlife," said Albert Manville, a retired U.S. Fish and Wildlife Service biologist and one of the paper's authors.

Manville also is an adjunct science professor at Johns Hopkins University.

to the FCC for its inquiry.

2019: The FCC issues a decision not to update the 1996 standards.

2020: The Environmental Health Trust files a petition against the FCC arguing the 2019 decision was not based on an adequate review of the data submitted.

2021: The U.S Court of Appeals in Washington, D.C., rules the FCC must review its 1996 guidelines and justify why they shouldn't be updated.

Source: Environmental Health Trust

He said he provided the Federal Communications Commission with some research on how the electromagnetic pollution can hurt wildlife and the steps that could be taken to lessen the impacts.

But the FCC has been unresponsive, Manville said, arguing the agency tends to accommodate the industry it's supposed to regulate.

"That's unfortunate, but that's just the way it is," he said.

The FCC did not respond to questions about whether it would consider making efforts to reduce animals' EMF exposure.

The three authors drew from 1,200 peer-reviewed studies to compile a three-part, 210-page report titled "Effects of non-ionizing electromagnetic fields on flora and fauna." It was published in the journal *Reviews on Environmental Health*.

Science journalist Blake Levitt, lead author of the report, said they dug up overlooked studies that contained compelling research on how living organisms react to low-level EMFs. Their compilation invalidates any claims that the EMFs don't cause biological effects, she said.

"We just blew the whole thing out of the water and took it to the ecosystem level, which is really where it needed to go," Levitt said. "Nobody had done that before. We need a whole lot more scrutiny put to the low-intensity stuff."

Ambient EMFs have risen exponentially in the past quarter-century, as cellphones were widely adopted, to become a ubiquitous and continuous environmental pollutant, even in remote areas, the report said, adding studies indicate EMFs can affect animals' orientation, migration, food finding, reproduction, nest building, territorial defense, vitality, longevity and survival.

EMFs' toxic effects on an animal's cells, DNA and chromosomes have been observed in laboratory specimens — and thus would apply to wildlife, according to the report.

Many types of wildlife are exposed to EMFs from wireless sources, such as deer, seals, whales, birds, bats, insects, amphibians and reptiles, the report said. Many species have been found more sensitive to EMFs than humans in some ways.

The report recommends new laws that include the redesign of wireless devices and infrastructure to reduce the rising ambient levels.

It comes several months after a federal court in Washington, D.C., ordered the FCC to review its guidelines for wireless radiation and justify why it should retain them, as the standards haven't been updated since 1996. This radiation should not be confused with radioactivity, the court noted, adding microwaves used in transmitting signals are low enough to not heat tissues in what are known as "thermal effects."

But medical studies suggest the lower-level radiation could cause cancer, reproductive problems, impaired learning and motor skills, disrupted sleep and decreased memory.

These studies and others were submitted to the FCC after it opened a notice of inquiry in 2013 under the administration of former President Barack Obama to probe the adequacy of the 1996 guidelines, which were geared toward avoiding thermal effects, the court said.

In 2019, the Trump administration's FCC deemed the inquiry unnecessary, saying the 1996 rules were sufficient and required no revision.

Two judges called that FCC action "arbitrary and capricious," saying the FCC made the decision out of hand, ignoring all the science presented and offering no reasonable, fact-based argument to back it up.

Santa Fe New Mexican, Report says wireless radiation may harm wildlife by Scott Wyland 2/07/2022

The agency also failed to look at the technological developments in the past 25 years and how they've changed the degree of exposure, the judges wrote. And they said it refused to examine possible health effects from EMFs that fall below the threshold set in 1996.

"When an agency in the commission's position is confronted with evidence that its current regulations are inadequate or the factual premises underlying its prior judgment have eroded, it must offer more to justify its decision to retain its regulations than mere conclusory statements," the judges wrote.

"Rather, the agency must provide 'assurance that [it] considered the relevant factors,' " they added.

The FCC's reluctance to ensure wireless transmissions are safe for human health extends to wildlife, even as 5G technology gains momentum, said Theodora Scarato, executive director of the Environmental Health Trust, a nonprofit think tank that led the petition against the FCC.

Scarato said her group is promoting the wildlife report to fill a crucial gap in wireless oversight.

She plans to submit the report to the FCC as it conducts its new review of wireless radiation, with the hope the report will go on the record and be considered when crafting future rules.

Regulators need to determine how much EMFs must be curbed to safeguard flora and fauna, she said.

"What is a limit for a person is going to be different" than for animals, Scarato said.

The study notes EMFs can disrupt the Earth's natural magnetic fields that birds, cats, fish and other animals use to navigate and orient themselves.

Towers keep the EMFs away from people on the ground but leave birds vulnerable because they fly near the transmitters and even perch on them, Scarato said.

"Air needs to be designated as habitat," she said. "And EMFs need to be regulated like other pollutants."

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The transmissions can disorient bees, causing them to become lost, not return to their hives and die, Manville said.

The bees are already threatened by pesticides and climate change, he said. “It’s death by a thousand cuts.”

If they have a mass die-off, it could be disastrous for growers that depend on them to pollinate crops, he added.

Manville said as a federal biologist, he pushed to get the Interior Department to establish an environmental review that covered how new sources of wireless radiation would affect wildlife. Interior officials were receptive in 2014, but his proposal stalled at the Commerce Department, which was in charge of internet technology, he said. Then later, the Trump administration scrapped it.

Scarato said this “landmark paper” could be the catalyst for creating wildlife guidelines.

“The challenge before us is there isn’t an environmental agency who’s even looking at the science at this time,” she said. The study’s authors “make the case for regulations that we need.”

Scott Wyland
Reporter

Wildlife Review Scientific References

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From: Melissa Smith
To: Public Comment; City Council
Subject: please treat all residences equally in the Wireless Ordinance
Date: Tuesday, May 10, 2022 5:01:22 PM

Dear Los Altos City Council,

In the Wireless Ordinance, please consider including fire safety precautions that include 1000 ft setbacks for all residences (whether in a residential "zone" or not (e.g, CD/R3 Commercial Downtown/Multiple Family should fall in the same tier as other residences)), schools, daycares, parks, hospitals, religious facilities, and fire and sheriff stations so that people have enough time to evacuate due to a fire.

Please also include annual radiofrequency (RF) testing of cell facilities by an independent certified RF engineer to ensure compliance with all FCC standards for RF emissions.

Thank you,
Melissa Smith