Review Paper

Biological Effects of Radiofrequency Electromagnetic Fields above 100 MHz on Fauna and Flora: Workshop Report

Blanka Pophof,[1] Bernd Henschenmacher,[1] Daniel R. Kattnig,[2] Jens Kuhne,[1]
Alain Vian,[3] and Gunde Ziegelberger[1]

Abstract—**This report summarizes the effects of anthropogenic radiofrequency electromagnetic fields with frequencies above 100 MHz on flora and fauna presented at an international workshop held on 5–7 November 2019 in Munich, Germany. Anthropogenic radiofrequency electromagnetic fields at these frequencies are commonplace; e.g., originating from transmitters used for terrestrial radio and TV broadcasting, mobile communication, wireless internet networks, and radar technologies. The effects of these radiofrequency fields on flora, fauna, and ecosystems are not well studied. For high frequencies exceeding 100 MHz, the only scientifically established action mechanism in organisms is the conversion of electromagnetic into thermal energy. In accordance with that, no proven scientific evidence of adverse effects in animals or plants under realistic environmental conditions has yet been identified from exposure to low-level anthropogenic radiofrequency fields in this frequency range. Because appropriate field studies are scarce, further studies on plants and animals are recommended.**

Health Phys. 124(1):31–38; 2023

Key words: electromagnetic fields; environmental impact; health effects; radiofrequency

INTRODUCTION

For many decades, the environment has been exposed to manmade radiofrequency electromagnetic fields (RF-EMFs) at frequencies exceeding 100 MHz, which mainly originate from VHF and UHF radio and TV-towers, military and civil radiocommunication services, and radar devices. In many countries, the implementation and expansion of mobile communication infrastructure, including the introduction of the new 5G mobile wireless communication technology, and the increase of digitally transmitting devices as well as radar-sensing technologies into almost all areas of everyday life has led and is still leading to changing exposure conditions of the environment to RF-EMFs.

Based on recognized scientific evidence, the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP 2020) set out to protect against scientifically substantiated adverse health effects of RF-EMFs. However, these guidelines are established for the protection of humans. While it is generally assumed that animals, plants, and ecosystems are protected if humans are protected (ICNIRP 2000), different actual exposure conditions and interaction mechanisms could give rise to specific effects on flora and fauna. Flying animals may, for example, approach the close vicinity of transmitters, resulting in exposures at intensity levels exceeding the accepted limits. Furthermore, due to resonance effects and smaller body dimensions, the power absorption efficiency in the GHz range is higher for small animals like insects compared to humans.

In view of the above intricacies, the scientific knowledge of the effects of RF-EMFs on the environment, flora, and fauna is limited. The last comprehensive summary was provided by ICNIRP over 20 y ago (ICNIRP 2000). In order to summarize the current state of knowledge and to identify research needs, the German Federal Office for Radiation Protection (BfS) organized the international workshop "Environmental effects of electric, magnetic and electromagnetic fields: flora and fauna" in Munich, 5 – 7 November 2019. This report deals with the current knowledge of bioeffects of RF-EMFs with frequencies above 100 MHz, as presented during this meeting. This cutoff frequency has been chosen because weak RF-EMFs with frequencies below 100 MHz are known to potentially interfere with the

---

[1] Competence Centre for Electromagnetic Fields, Department Effects and Risks of Ionizing and Non-Ionizing Radiation, Federal Office for Radiation Protection, 85764 Oberschleißheim, Germany; [2] Department of Physics and Living Systems Institute, University of Exeter, Stocker Road, Exeter, EX4 4QD, United Kingdom; [3] Univ Angers, Institut Agro, INRAE, IRHS, SFR QUASAV, F-49000 Angers, France.

The authors declare no conflicts of interest.

For correspondence contact: Blanka Pophof, Competence Centre for Electromagnetic Fields, Department of Effects and Risks of Ionizing and Non-Ionizing Radiation, Federal Office for Radiation Protection, Ingolstädter Landstraße 1, 85764 Oberschleißheim, Germany, or email at bpophof@bfs.de.

(*Manuscript accepted* 3 *August* 2022)

0017-9078/22/0

DOI: 10.1097/HP.0000000000001625

perception of the geomagnetic field by the Radical Pair Mechanism (but not by other pathways, e.g., magnetite or induction). This mechanism and related effects are discussed in an accompanying contribution (Pophof et al. 2022) focusing on static fields and electromagnetic fields with frequencies below 100 MHz. Here, we concentrate on results presented at the workshop, documented by publications of the speakers (see acknowledgements) and references in their presentations and abstracts. The titles and abstracts of all presentations are accessible online (BfS 2020). Additionally, peer-reviewed publications co-authored by the presenters and/or directly related to the topics presented at the workshop, published between the workshop (November 2019) and the end of 2021, were considered. The literature search was based on the database EMF-Portal, which systematically summarizes scientific research data on the effects of EMFs and covers most of the relevant databases (e.g., Medline/Pubmed and IEEE Explore).

Key questions to be answered at the workshop were:

- What are the effects of RF-EMFs on animals, plants, and ecosystems?
- Are there any adverse effects of anthropogenic RF-EMFs on animals, plants, and ecosystems?
- What are the most significant research gaps?
- How can such gaps in the research be closed?

RESULTS

Anthropogenic RF-EMFs

High-power radiofrequency transmitters are used for providing terrestrial radio and TV broadcast services. Only a small number of transmitters are necessary to cover large areas. In contrast, public mobile communications require a dense network of fixed transmitters with significantly smaller transmitting power at each site. Both types of transmitters emit RF-EMFs into the surrounding environment, which are commonly characterized in terms of their power density and/or electric field strengths.

Detailed knowledge about EMF exposure is necessary to assess possible RF-EMF-related effects on animals and plants. Physical phenomena, such as absorption, reflection, and diffraction, influence the propagation of RF-EMFs. Therefore, the field distribution nearby an antenna does not only depend on the complex antenna characteristics but also on the surrounding topography and the presence of objects. Hence, both, RF-source and RF-propagation path features can introduce significant temporal and spatial field heterogeneity, which necessitates precise measurement or modeling to correctly assess field distributions and properties. The distance to the source alone is a poor proxy for exposure; measurements and calculations are a prerequisite for a valid exposure assessment.

In most cases, a biological response will not be directly elicited by the ambient RF-EMF outside of the body (body/tissue external exposure metric) but by the RF-EMF coupled to or induced in the exposed object (body/tissue-internal exposure metrics). Depending on the (putative) biophysical mechanism, either the absorbed RF power (or energy) per unit mass or the body/tissue-internal electric or magnetic field is of interest for assessing the effect of RF-EMF exposure on a biological system.

In contrast to frequencies below 100 MHz, where there is strong evidence that induced electric fields and tissue internal magnetic fields can also give rise to specific biological effects (as discussed at the workshop; BfS 2020, Pophof et al. 2022), at higher frequencies, only a power (or energy)-dependent biophysical mechanism, namely conversion into thermal energy, is substantiated by current scientific evidence.

The widely accepted exposure metric for this biological mechanism is the specific absorption rate (SAR) expressed in W kg^{-1}. The magnitude and distribution of the SAR strongly depend on the frequency, polarization, field strength, and field distribution of the external RF-EMF as well as on the electric properties (conductivity and permittivity) and structure of the exposed object. Complex numerical simulations using anatomically resolved specimen models, as well as far-field or near-field EMF source models appropriate for the investigated exposure situation, are required for a valid exposure assessment.

Compared to international guidelines, typical ambient RF-EMF levels are quite low at places where humans are typically present, but some animals may easily approach the exclusion zones surrounding the transmitters.

The current and earlier mobile telecommunication networks mainly operate at frequencies between 100 MHz and 6 GHz. However, due to increased numbers of users and demand for bandwidth, it is expected that future networks will also use carrier frequencies up to 300 GHz (Colombi et al. 2015). Due to the resonance phenomenon, at higher frequencies and smaller wavelengths, the energy absorption in small animals, e.g., insects, will increase disproportionately.

Specifically, the absorption of RF-EMFs by insects was recently studied using numerical simulations (Thielens et al. 2018) based on the finite-difference time-domain (FDTD) algorithm. The approach relied on measurements of dielectric parameters and the development of accurate 3D models with high spatial resolution; i.e., small model features relative to the studied wavelengths. X-ray microtomography was used to obtain models for a set of insect simulations (Thielens et al. 2018) with sufficient spatial resolution for FDTD in the frequency range of interest.

The far-field exposure to RF-EMFs in the 0.6 to 120 GHz frequency band was investigated using these models and corresponding dielectric parameters obtained from a literature survey. The absorbed power in insects depended on insect size, morphology, and EMF frequency. In the 0.6-6 GHz frequency range, RF-EMF absorption efficiency increased with frequency for all studied insect species. Normalized to an incident field strength of 1 V m^{-1}, the RF-EMF absorption was either constant or increased slightly with frequency in the 6–120 GHz range (Thielens et al. 2018).

In honeybees, a relatively small shift of 10% of the environmental incident power density from frequencies below 3 GHz to higher frequencies led to a relative increase in absorbed power by a factor larger than three. Such a shift in frequencies is expected in future networks, which implies that exposure to RF-EMFs will significantly increase for insects in future telecommunication networks (Thielens et al. 2020).

The energy absorption due to far-field RF exposure in the yellow fever mosquito *Aedes aegypti* was examined between 2 and 240 GHz. For a given incident power, the absorption increased with increasing frequency between 2 and 90 GHz with a peak between 90 and 240 GHz. The authors conclude that higher absorption of RF power by future technologies can result in dielectric heating and potentially influence the biology of this mosquito (De Borre et al. 2021).

Biological effects

Most studies on possible long-term effects of RF-EMF exposure have been performed in laboratories on well-established animal models, without consideration of the wildlife and ecosystems. A review (Cucurachi et al. 2013) focused on ecologically relevant endpoints, like growth, development, and fertility in five groups of organisms (birds, insects, other vertebrates, other organisms, and plants). In the majority of the identified studies, possible ecologically relevant effects were observed. However, the lack of a dose-response relationship and standardization and the low number of field studies presently limit the possibility to draw conclusions on the ecosystem level.

Thermal effects. Tissue heating as a result of the absorption of RF-EMF electromagnetic energy is a well proven effect and the basis for exposure limit recommendations (ICNIRP 2020b). Absorption of RF-EMFs above certain levels may lead to elevation of body temperature in exposed animals, as demonstrated in primates (de Lorge et al. 1984; D'Andrea et al. 2003a and b) and laboratory rodents. At low ambient temperatures, the absorbed power may help to save energy otherwise invested in heat production, and the actual metabolic rate of the animal is reduced (Gordon 1987). At higher ambient temperatures, within and above the thermoneutral zone, the animals cannot compensate by reducing their basal energy turnover any more, resulting in exposure-induced body temperature increase and consequently heat stress. To maintain thermal homeostasis, the thermoregulatory system uses multiple autonomic and behavioral strategies to either reduce heat production or increase heat loss (e.g., via peripheral vasodilation and sweating) when exposed to high temperatures (Gordon 2017).

Behavioral thermoregulatory responses, such as seeking a cooler environment, are indeed the most frequently used thermo-effectors to minimize thermal stress. Like humans, mice and rats are able to maintain a relatively stable core temperature over a wide range of ambient temperatures. While humans are better adapted to establish a stable core temperature during heat stress (e.g., by sweating and a more efficient regulation of blood flow), small rodents are less sensitive to high levels of RF-EMF exposure, as their larger surface area per body mass allows for a more rapid dissipation of heat by convection, conduction, and radiation (Gordon and Ferguson 1984; Gordon 2017). Consequently, one finds an allometric (i.e., not isometric) relationship between the efficacy of RF-EMFs to induce hyperthermia and the specific absorption rate (SAR), which is inversely proportional to body size and weight. As an example, in a mouse (m = 30 g), significant body temperature increases are detected at SARs of 10–30 W kg^{-1}, while similar responses in rhesus monkeys (m = 4 kg) are already observed at SARs below 1 W kg^{-1} (Gordon and Ferguson 1984).

This strong dependency of threshold SAR on body mass might have contributed to the results of a large study on chronic cell phone RF-EMF exposure on mice and rats, which was published by the National Toxicology Program (NTP 2018a and b). The NTP concluded that under their experimental conditions (all exposure levels were above recommended limits for whole body exposure), there was clear evidence of a carcinogenic activity of GSM and CDMA-modulated RF-EMFs in male rats. This conclusion, which has been challenged by other EMF-scientists and organizations (ICNIRP 2020a; US FDA 2020), was based on a correlation between RF-EMF exposure strength and incidences of malignant schwannoma in the heart of male rats. In contrast to male rats, NTP rated the quality of evidence as "equivocal" for female rats and male and female mice, because it was unclear whether cancers were associated with exposure in these animals with lower body mass.

Extrapolating from preceding pilot studies on up to 9 mo-old male rats (Wyde et al. 2018) and accounting for the fact that the exposure was switched off twice during the day for technical reasons, there is evidence that the exposure pattern-induced temperature fluctuations in adult male rats exceeded the normal physiological range (Kuhne et al. 2020). This suggests that chronic thermoregulatory stress might have caused a chronic excessive load on the heart in the aging male rats, as both hyper- and hypothermia can significantly affect heart rate and blood pressure in rats (Lin et al. 1994). If so, this could explain the finding of a significantly elevated incidence of cardiomyopathy in exposed male rats and may also have contributed to the increased incidence of malignant schwannoma in the heart (Kuhne et al. 2020).

Surprisingly, exposed male rats lived longer due to an exposure-related reduced severity of chronic progressive nephropathy and its corresponding side effects. As the animals were held in a cool laboratory, the potential mechanism of substituting metabolism by RF-EMF absorption might have led to a reduced food intake, which could explain the observed reduced severity of the chronic progressive nephropathies. It was shown in the past that restriction of caloric intake is an efficient measure to prevent the disease (Hard and Khan 2004; Deerberg et al. 1990). However, high exposures are necessary to absorb a specific power that is comparable to the metabolic rate of animals (a prerequisite for both a drastic impact of thermal energy on metabolism and/or whole-body temperature elevations), which animals do not typically experience outside of the laboratory.

Invertebrates. There are only a few relevant field studies focusing on insects. One carefully designed field experimental study (Vijver et al. 2014) on the impact of the exposure to GSM base station signals (900 MHz) was performed on different endpoints of the reproductive capacity. Four insect species (the predatory bug *Orius laevigatus*, the springtail *Folsomia candida*, the parasitic wasp *Asobara japonica,* and the fruit fly *Drosophila melanogaster*) were exposed or sham-exposed (shielded by a Faraday cage) for 48 h at a distance of 16 m to 151 m from a GSM 900 MHz base station. The measured power density for the exposed groups varied from 0.1 to 4.3 mW m^{-2} and did not correlate significantly with distance, but the changes over time were similar between locations. The reproductive capacity of the exposed insect species was monitored for three weeks after initial exposure in the laboratory and was found to be unaffected by the short-term RF-EMF exposure.

The vast majority of flowering plants, including many important crops, rely on pollination by animals. For this reason, it is important to assess whether anthropogenic EMFs represent an additional and growing threat to pollinators. The EU EKLIPSE project (www.eklipse-mechanism.eu) organized a foresight activity identifying the state of scientific research and gaps in knowledge concerning the emerging issue of anthropogenic EMF impact on wildlife. The evidence assessment protocols of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES, www.ipbes.net) were used to assess the level of risk to pollinators from anthropogenic EMFs and to highlight uncertainties and knowledge gaps. A literature study was performed to gather a representative but not exhaustive set of relevant peer-reviewed papers published from 2000 onward, coincident with the onset of the proliferation of mobile technologies. Studies were scored according to their scientific and technical quality, and key messages were extracted. The EKLIPSE report documented the sparseness of high-quality scientific literature and the scarcity of data regarding anthropogenic EMF impacts on wildlife (Malkemper et al. 2018).

Overall, the lack of high-quality scientific studies means that knowledge of the risk to pollinators from anthropogenic EMF is either inconclusive, unresolved, or established only partially (Vanbergen et al. 2019). Few experimental studies concerning the effects of RF-EMFs on honeybees were performed (Kimmel et al. 2007; Favre 2011; Odemer and Odemer 2019), but these studies lack proper dosimetry, controls, and exposure assessments. Exposure by commercial DECT or mobile phones is far from realistic and does not provide evidence that anthropogenic RF-EMFs affect insect behavior in ecosystems under natural conditions. It is worth mentioning that radar at 900 MHz has been used for many years in research for tracking flight pathways of bees, and even long-term radar exposure did not appear to induce adverse effects (Woodgate et al. 2016).

A well-designed field study on potential effects of mobile telecommunication base stations on wild pollinator communities was carried out on two Aegean islands (Lazaro et al. 2016). The field strengths of RF-EMFs were measured at four distances between 50 and 400 m in the vicinity of 10 base stations located in comparable, homogeneously flower-rich landscapes. The frequency of the RF-EMFs ranged from 800 MHz to 2.6 GHz. The electric field strengths did not differ significantly between the islands or with distance to the base station and ranged from 0.01 V m^{-1} to 0.63 V m^{-1}. The abundance of key wild pollinator groups (wild bees, hoverflies, bee flies, remaining flies, beetles, butterflies, and wasps) was recorded at all measurement points using traps. Additionally, the species richness of wild bees and hoverflies was estimated. On both islands, beetle, wasp, and hoverfly abundance decreased with increasing field strengths, whereas the abundance of underground-nesting wild bees and bee flies increased. The species richness of hoverflies tended to decrease with field strength solely on one island. The species richness of wild bees was not significantly related to RF-EMFs. The correlative approach of the study does not allow controlling for other confounding variables that could have affected the abundance. If causal, the negative impact on the abundance of some species and the altered species composition of wild pollinator communities in natural habitats might be of ecological relevance.

Scientific evidence that anthropogenic RF-EMFs might impact the abundance or diversity of pollinators is limited to the single study described above (Lazaro et al. 2016). Consequently, whether anthropogenic RF-EMFs pose a significant threat to insect pollinators and the benefits they provide to ecosystems and humanity remains to be established (Vanbergen et al. 2019); given the overall decline of insect diversity and abundance, hence further investigations are urgently needed.

Vertebrates. There are few observational studies on the effects on RF-EMFs of mobile communications on bird populations. From 26 ecologically relevant studies on birds, 70% found an effect (Cucurachi et al. 2013). Only five studies were performed in the field. The focus of the laboratory studies was on the development of chicken embryos; the most frequent endpoints were growth, development, and fertility. Overall, while the results were heterogeneous, the authors of the review study concluded that mobile phone radiation, in particular 900 MHz GSM, could be a factor effecting bird ecology (Cucurachi et al. 2013).

In a field study, the abundance of house sparrows (*Passer domesticus*) was estimated in the city of Valladolid, Spain, from 2002 to 2006 (Balmori and Hallberg 2007). Sparrow abundance correlated negatively with field strength (1 MHz - 3 GHz range, maximal field strength 4 V m^{-1}), i.e., more sparrows were observed at locations with lower field strength. A similar correlation was found between sparrow densities and electric field strengths at 900/1,800 MHz in Belgium (Everaert and Bauwens 2007). These findings report correlations that do not necessarily imply a causal relationship between mobile phone radiation and bird abundance because covarying factors cannot be excluded. These findings cannot be explained by the disruption of magnetoreception of birds by weak broadband radiofrequency magnetic fields, as this effect is prominent in the low MHz region (Engels et al. 2014) but not expected at the frequencies typical for mobile communication. Specifically, frequencies above 100 MHz do not interfere with the radical-pair mechanism likely underlying magnetic orientation of night migratory birds (Hiscock et al. 2017).

Two studies tested the effect of radar signals in the 1–4 GHz range on bats and found a significant reduction in their activity at field strengths above 2 V m^{-1}. The bats appeared to avoid areas with RF-EMFs in the GHz range. The avoidance did not correlate with insect abundance (Nicholls and Racey 2007, 2009). There is no known interaction with the magnetic sense at this frequency; instead it is hypothesized that the animals hear (microwave hearing; Lin and Wang 2007) or thermally perceive the radar pulses close to the transmitter.

Public reports and case studies have reported adverse effects on farm animals, but controlled scientific investigations are scarce. In one study (Hässig et al. 2012), a 10 times higher risk for calves to be born with strong nuclear cataracts in the eye was observed after a mobile phone base station had been erected in the vicinity of a farm. Common causes, such as infection or poisoning, could be excluded. However, the coincidence in time is not sufficient proof of a causal relationship. Other reasons, e.g., a genetic predisposition, were discussed, but the exact cause of the increased incidence of cataracts remained unknown.

The prevalence and etiology of nuclear cataract in veal calves was assessed in another investigation (Hässig et al. 2009) using a histological approach to study the lens, along with measurements of glutathione peroxidase, catalase, and superoxide dismutase activity as indicators of oxidative stress in the aqueous humor of each eye. Nuclear cataracts of variable severity were found in 32% of the calves. This is still within the normal prevalence in Switzerland, which is relatively high. However, the prevalence of nuclear cataract and the parameters of oxidative stress were significantly increased at locations with higher field strength in comparison to locations with lower field strength. The role of confounders and other environmental agents was not assessed. A more controlled, although not blinded, study was performed on dairy cows (Hässig et al. 2014). Here, the activities of glutathione peroxidase, catalase, and superoxide dismutase were measured in blood samples taken before and after a 14-d exposure to 900 MHz electric fields (range 3.4-29 V m^{-1}). The results showed mixed effects on the activity of the three investigated enzymes and marked inter-individual differences. Overall, no clear picture emerged with respect to possible mobile telecommunication radiation-dependent effects on oxidative stress levels in farm animals.

The few field studies on vertebrates show some correlations between RF-EMFs and adverse biological effects, but due to possible confounders, a causal relationship cannot be established. Possible ecological effects should be followed up, especially in flying animals capable of closely approaching transmitters.

Plants. An older field study (Schmutz et al. 1996) investigated the effect of RF-EMFs (2,450 MHz, 0.007–300 W m^{-2}) on young spruce and beech trees, documenting a temperature increase of up to about 4 °C at highest exposure. There were no observable visual symptoms of damage, e.g., reduced crown transparency. The floral concentrations of some nutrients were reduced but remained within the sufficiency range.

Over the past 15 y, several laboratory studies (Vian et al. 2006; Roux et al. 2008) were performed to characterize plant responses to RF-EMFs at 900 MHz. The aim was to establish a formal and unequivocal link between the exposure and changes in plant metabolism. To avoid contribution of external parameters to the experiment, a short time exposure (10 min) in a mode stirred reverberation chamber was used. This approach allowed generating an, on average, spatio-temporally homogeneous and isotropic high frequency electromagnetic field. Immediate responses of tomatoes, i.e., gene expression and ATP synthesis, were investigated. Exposure to a low amplitude (5 V m^{-1}) RF-EMF (900 MHz) caused a rapid increase in the accumulation of several mRNAs, such as calmodulin and other stress-related genes. These accumulations appeared within 15 min, sustained for an hour, and did not show up in the control, non-exposed plants (Vian et al. 2006). The same experimental protocol caused a rapid drop in adenylate energy charge. Treatments with calcium counteracting drugs prevented the molecular responses (Roux et al. 2008). The response was systemic, i.e., it occurred in the whole plant if only part of it was exposed to RF-EMF. The phytohormone abscisic acid was crucial for the distant response in non-exposed tissues (Beaubois et al. 2007). All these effects represented reactions of the plants to an environmental influence but not an injury. There were no changes in the morphology and growth of tomatoes.

To follow plant development for the duration of several weeks, rose plants were used instead of tomatoes. Plant organs exposed to RF-EMF (5 V m^{-1}, 900 MHz) were unaffected in their development. In contrast, the meristems that were exposed led to the production of shorter axes, demonstrating a delayed response (Gremiaux et al. 2016).

RF-EMFs at frequencies of 3.350 MHz, 8.800 MHz, and 900 MHz caused reduced root growth in the common onion (*Allium cepa*), which was accompanied by chromosomal aberrations and genotoxic effects that increased with exposure duration (1–4 h) (Chandel et al. 2019; Kumar et al. 2020).

Long-term exposure (120 d) of the common bean (*Phaseolus vulgaris*) at 915 MHz resulted in a considerable increase of plant height, root length, and dry mass, accompanied by morphological modifications of plant tissue (Surducan et al. 2020).

Kundu et al. (2021a) indicated changes in rice seed germination and gene expression of stress-related genes as well as phytochrome B and C in 12- and 32-d-old seedlings after periodic exposure (1837.5 MHz, 2.75 mW m^{-2}). A single 2.5-h exposure of 12-d-old seedlings also caused changes in gene expression (Kundu et al. 2021a). Upregulation of stress-related genes, e.g., calmodulin and phytochrome B, was also observed after a single exposure of 40-d-old rice plants (Kundu et al. 2021b).

The current scientific knowledge concerning effects of weak RF-EMFs on plant development and the underlying physiological, biochemical, and molecular mechanisms is summarized in Kaur et al. (2021).

Environmental exposures to RF-EMFs have increased in the last two decades, and this trend may continue. The effects of this exposure at plant community level are unknown and difficult to assess in a scientifically appropriate manner. An observational study (Waldmann-Selsam et al. 2016) described damage of tree canopy on the side facing mobile phone base stations. However, due to the selective approach (i.e., not all trees were selected randomly), no scientific conclusion can be drawn on the basis of these observations alone.

Czerwinski et al. (2020) proposed recently new indicators and methods (e.g., altered species composition, altered biomass production, and changed plant canopy structure) to study the effects of EMF exposures on plant communities through a comparison between control and exposed pre-defined areas, for which the plant community, the climatic conditions, and the levels of exposure to EMF are well known.

Laboratory experiments at field strengths of several Vm^{-1} showed responses of plants to RF-EMF, which are comparable to a mild stress but not injurious to the plant. Well-controlled field studies are still lacking. The question is to decipher if the effects observed in the laboratory would still be visible under field conditions where the influence of other environmental factors, including light, temperature extremes, and pollution, may predominate.

CONCLUSION AND RESEARCH RECOMMENDATIONS

The results presented at the workshop did not show any sound scientific evidence of adverse effects of low-level anthropogenic RF-EMFs at frequencies exceeding 100 MHz on animals or plants under realistic environmental conditions. Extrapolations from laboratory animal studies, often performed at higher exposure levels, do not allow conclusions on ecological effects of RF-EMFs at low levels. Field studies of an appropriate quality are scarce in both animals and plants and so far do not show clear evidence supporting adverse effects of RF-EMFs. Some correlations between RF-EMFs and adverse biological effects were observed, but bias and confounding factors cannot be excluded. If the effects of weak RF-EMFs were confirmed independently by high quality studies, a logical next step would be to seek the corresponding biophysical mechanism(s).

In contrast to EMFs with frequencies below 100 MHz, for which there is evidence supporting several potential interaction mechanisms based on both theory and experiment (as discussed at the workshop; BfS 2020, Pophof et al. 2022), only the conversion of electromagnetic into thermal energy has been substantiated as a biophysical mechanism for frequencies exceeding 100 MHz. The efficiency to induce biologically significant temperature effects at a given SAR in animals is inversely dependent on body size and mass. For critical body heating, high exposures are required, which non-flying animals typically do not experience outside of the laboratory. The lack of a potential biophysical mechanism that could convincingly explain effects of low-level RF-EMF exposure complicates the design of future laboratory studies. So far, no clear suggestions for further laboratory research on effects of weak RF-EMFs on wild animals have emerged. In flying species (insects, birds, bats), which can approach typical RF-EMF sources closer than can humans, biological effects should be further investigated in the field.

In plants, the scientific literature (Kaur et al. 2021) and the results of the workshop imply that plants react to weak RF-EMFs under laboratory conditions by modifying various physiological parameters. Although some datasets have been acquired, it is difficult to establish an accurate picture of the molecular and developmental events following RF-EMF exposure. This is attributable to various factors, including the diversity of exposure sources and experimental designs. It could therefore prove fruitful to focus research on a few model species (e.g., tomato, *Arabidopsis*, alfalfa) for which the genomes have been sequenced and well-established experimental methods are available. This should be addressed by two different strategies, mainly at the molecular and biochemical scales (with focus on possible mechanisms) and at the whole plant scale. In a next step, the results of laboratory experiments should be verified by field studies to investigate whether or not effects, if any, extend to plant populations.

Acknowledgments—We thank the invited speakers Margaret Ahmad, John Bolte, Dirk Geschwendtner, Christopher Gordon, Michael Hässig, Amparo Lazaro, Henrik Mouritsen, Daniel Robert, and Michael Winklhofer for their contributions to the workshop, Andrew Gill, Richard Holland, Joseph Kirschvink, Massimo Maffei, Benjamin Paffhausen, Heiko Schmaljohann, Gernot Schmid, Arno Thielens, and Adam Vanbergen for their contributions to the workshop and comments on the manuscript and especially Pascal Malkemper for his help with the preparation of this manuscript, several critical reads and comments.

We dedicate this work to the late Christopher J. Gordon. Chris gave one of his last scientific presentations during the international workshop that is summarized in this paper. Chris was a biologist by training and spent 30 years at the US Environmental Protection Agency as a research physiologist. During his career he investigated the influence of various environmental factors, especially non-ionizing radiation on thermoregulation in animals and humans and authored numerous scientific articles on that topic. We will miss his wit and dedication to research.

REFERENCES

Balmori A, Hallberg O. The urban decline of the house sparrow (*Passer domesticus*): a possible link with electromagnetic radiation. Electromagn Biol Med 26:141–151; 2007.

Beaubois E, Girard S, Lallechere S, Davies E, Paladian F, Bonnet P, Ledoigt G, Vian A. Intercellular communication in plants: evidence for two rapidly transmitted systemic signals generated in response to electromagnetic field stimulation in tomato. Plant. Cell Environ 30:834–844; 2007.

BfS. Internationaler Workshop zum Einfluss elektrischer, magnetischer und elektromagnetischer Felder auf die belebte Umwelt - Vorhaben 3619I02420 [online]. 2020 (in German). Available at ***http://nbn-resolving.de/urn:nbn:de:0221-2020050821802***. Accessed 15 December 2021.

Chandel S, Kaur S, Issa M, Singh HP, Batish DR, Kohli RK. Exposure to mobile phone radiations at 2350 MHz incites cyto- and genotoxic effects in root meristems of *Allium cepa*. J Environ Health Sci Eng 17:97–104; 2019.

Colombi D, Thors B, Tornevik C. Implications of EMF exposure limits on output power levels for 5 G devices above 6 GHz. IEEE Antennas Wirel Propag Lett 14:1247–1249; 2015.

Cucurachi S, Tamis WLM, Vijver MG, Peijnenburg WJGM, Bolte JFB, De Snoo GR. A review of the ecological effects of radiofrequency electromagnetic fields. Env Internat 51:116–140; 2013.

Czerwinski M, Januszkiewicz L, Vian A, Lazaro A. The influence of bioactive mobile telephony radiation at the level of a plant community—possible mechanisms and indicators of the effects. Ecol Indic 108:105683; 2020.

D'Andrea JA, Adair ER, de Lorge JO. Behavioral and cognitive effects of microwave exposure. Bioelectromagnet 6(Suppl): S39–62; 2003a.

D'Andrea JA, Chou CK, Johnston SA, Adair ER. Microwave effects on the nervous system. Bioelectromagnet 6(Suppl):S107–147; 2003b.

De Borre E, Joseph W, Aminzadeh R, Müller P, Boone MN, Josipovic I, Hashemizadeh S, Kuster N, Kühn S, Thielens A. Radio-frequency exposure of the yellow fever mosquito (*A. aegypti*) from 2 to 240 GHz. PLoS Comput Biol 17:e1009460; 2021.

de Lorge JO. Operant behavior and colonic temperature of *Macaca mulatta* exposed to radio frequency fields at and above resonant frequencies. Bioelectromagnet 5:233–246; 1984.

Deerberg F, Rap KG, Kaspareit-Rittinghausen J, Lörcher K. The effect of food restriction by time-scheduled feeding on the development of body-weight, lifespan and incidence of spontaneous tumours and diseases in male Han:SPRD rats. Z Versuchstierkd 33:9–17; 1990.

Engels S, Schneider NL, Lefeldt N, Hein CM, Zapka M, Michalik A, Elbers D, Kittel A, Hore PJ, Mouritsen H. Anthropogenic electromagnetic noise disrupts magnetic compass orientation in a migratory bird. Nature 509:353–356; 2014.

Everaert J, Bauwens D. A possible effect of electromagnetic radiation from mobile phone base stations on the number of breeding house sparrows (*Passer domesticus*). Electromagn Biol Med 26:63–72; 2007.

Favre D. Mobile phone-induced honeybee worker piping. Apidologie 4:270–279; 2011.

FDA Review of published literature between 2008 and 2018 of relevance to radiofrequency radiation and cancer [online]. 2020. Available at ***https://www.fda.gov/media/135043/download***. Accessed 4 July 2022.

Gordon CJ. Reduction in metabolic heat production during exposure to radio- frequency radiation in the rat. J Appl Physiol 62: 1814–1818; 1987.

Gordon CJ. The mouse thermoregulatory system: its impact on translating biomedical data to humans. Physiol Behav 179:55–66; 2017.

Gordon CJ, Ferguson JH. Scaling the physiological effects of exposure to radiofrequency electromagnetic radiation: consequences of body size. Int J Radiat Biol 46:387–397; 1984.

Gremiaux A, Girard S, Guerin V, Lothier J, Baluska F, Davies E, Bonnet P, Vian A. Low-amplitude, high-frequency electromagnetic field exposure causes delayed and reduced growth in *Rosa hybrida*. J Plant Physiol 190:44–53; 2016.

Hard GC, Khan KN. A contemporary overview of chronic progressive nephropathy in the laboratory rat, and its significance for human risk assessment. Toxicol Pathol 32:171–180; 2004.

Hässig M, Jud F, Nägeli H, Kupper J, Spiess B. Prevalence of nuclear cataract in Swiss veal calves and its possible association with mobile telephone antenna base stations. Schweiz Arch Tierheilk 151:471–478; 2009.

Hässig M, Jud F, Spiess B. Increased occurence of nuclear cataract in the calf after erection of a mobile phone base station. Schweiz Arch Tierheilkd 154:82–86; 2012.

Hässig M, Wullschleger M, Naegeli H, Kupper J, Murbach M, Capstick M, Kuster N, Spiess B. Influence of non-ionizing radiation of base stations on the activity of redox proteins in bovines. BMC Vet Res 10:136; 2014.

Hiscock HG, Mouritsen H, Manolopoulos DE, Hore P. Disruption of magnetic compass orientation in migratory birds by radiofrequency electromagnetic fields. Biophys J 113:1475–1484; 2017.

ICNIRP. Effects of electromagnetic fields on the living environment. In: Matthes R, Bernhardt JH, Repacholi MH, eds. Proceedings of the international seminar on effects of electromagnetic fields on the living environment. Munich: International Commission on Non-Ionizing Radiation Protection: pp. 280; 2000.

ICNIRP. Critical evaluation of two radiofrequency electromagnetic field animal carcinogenicity studies published in 2018. Health Phys 118:525–532; 2020a.

ICNIRP. Guidelines for limiting exposure to electromagnetic fields (100 KHz to 300 GHz). Health Phys 118:483–524; 2020b.

Kimmel S, Kuhn J, Harst W, Stever H. Electromagnetic radiation: influences on honeybees (*Apis mellifera*). IIAS - InterSymp Conference, Baden-Baden. Baden-Baden:IIAS; 2007.

Kaur S, Vian A, Chandel S, Singh HP, Batish DR, Kohli RK. Sensitivity of plants to high frequency electromagnetic radiation: cellular mechanisms and morphological changes. Rev Environ Sci Biotechnol 20:55–74; 2021.

Kuhne J, Schmidt JA, Geschwentner D, Pophof B, Ziegelberger G. Thermoregulatory stress as potential mediating factor in the NTP cell phone tumor study. Bioelectromagnet 41:471–479; 2020.

Kumar A, Kaur S, Chandel S, Singh HP, Batish DR, Kohli RK. Comparative cyto- and genotoxicity of 900 MHz and 1800 MHz electromagnetic field radiations in root meristems of *Allium cepa*. Ecotoxicol Environ Saf 188:109786; 2020.

Kundu A, Vangaru S, Bhattacharyya S, Mallick AI, Gupta B. Electromagnetic irradiation evokes physiological and molecular alterations in rice. Bioelectromagnet 42:173–185; 2021a.

Kundu A, Vangaru S, Bhowmick S, Bhattacharyya S, Mallick AI, Gupta B. One-time electromagnetic irradiation modifies stress-sensitive gene expressions in rice plant. Bioelectromagnet 42:649–658; 2021b.

Lazaro A, Chroni A, Tscheulin T, Devalez J, Matsoukas C, Petanidou T. Electromagnetic radiation of mobile telecommunication antennas affects the abundance and composition of wild pollinators. J Insect Conserv 20:315–324; 2016.

Lin JC, Wang Z. Hearing of microwave pulses by humans and animals: effects, mechanism, and thresholds. Health Phys 92: 621–628; 2007

Lin MT, Lin KW, Young MS. Effects of body temperature on cardiovascular functional parameters in rats. J Therm Bio 19: 123–128; 1994.

Malkemper EP, Tscheulin T, Vanbergen AJ, Vian A, Balian E, Goudesbune L. The impacts of artificial electromagnetic radiation on wildlife (flora and fauna). Current knowledge overview: a background document to the web conference. A Report of the EKLIPSE Project [online]. 2018. Available at ***https://www.eklipse-mechanism.eu/emr_conference***. Accessed 10 September 2021.

National Toxicology Program. NTP Technical Report on the toxicology and carcinogenesis studies in Sprague Dawley (HSD: Sprague Dawley® SD®) rats exposed to whole-body radio frequency radiation at a frequency (900 MHz) and modulations (GSM and CDMA) used by cell phones. Technical Report 595 [online]. 2018a. Available at ***https://ntp.niehs.nih.gov/go/tr595***. Accessed 10 September 2021.

National Toxicology Program. NTP Technical Report on the toxicology and carcinogenesis studies in B6C3F1/N mice exposed to whole-body radio frequency radiation at a frequency (1, 900 MHz) and modulations (GSM and CDMA) used by cell phones. Technical Report 596 [online]. 2018b. Available at ***https://ntp.niehs.nih.gov/go/tr596***. Accessed 10 September 2021.

Nicholls B, Racey PA. Bats avoid radar installations: could electromagnetic fields deter bats from colliding with wind turbines? PLoS ONE 2:e297; 2007.

Nicholls B, Racey PA. The aversive effect of electromagnetic radiation on foraging bats: a possible means of discouraging bats from approaching wind turbines. PLoS One 4:e6246; 2009.

Odemer R, Odemer F. Effects of radiofrequency electromagnetic radiation (RF-EMF) on honey bee queen development and mating success. Sci Total Environ 661:553–562; 2019.

Pophof B, Henschenmacher B, Kattnig DR, Kuhne J, Vian A, Ziegelberger G. Biological Effects of Electric, Magnetic, and Electromagnetic Fields from 0 to 100 MHz on Fauna and Flora. Workshop Report. Health Phys 24(1):39–52; 2022.

Roux D, Faure C, Bonnet P, Girard S, Ledoigt G, Davies E, Gendraud M, Paladian F, Vian A. A possible role for extra-cellular ATP in plant responses to high frequency, low amplitude electromagnetic field. Plant Signal Behav 3383–3385; 2008.

Schmutz P, Siegenthaler J, Stäger C, Tarjan D, Bucher JB. Long-term exposure of young spruce and beech trees to 2450-MHz microwave radiation. Sci Total Environ 180: 43–48; 1996.

Surducan V, Surducan E, Neamtu C, Mot AC, Ciorita A. Effects of long-term exposure to low-power 915 MHz unmodulated radiation on *Phaseolus vulgaris* L. Bioelectromagnet 41:200–212; 2020.

Thielens A, Bell D, Mortimore DB, Greco MK, Martens L, Joseph W. Exposure of insects to radio-frequency electromagnetic fields from 2 to 120 GHz. Sci Rep 8:3924; 2018.

Thielens A, Greco MK, Verloock L, Martens L, Joseph W. Radio-frequency electromagnetic field exposure of western honey bees. Sci Rep 10:461; 2020.

Vanbergen AJ, Potts SG, Vian A, Malkemper EP, Young J, Tscheulin T. Risk to pollinators from anthropogenic electro-magnetic radiation (EMR): evidence and knowledge gaps. Sci Total Environ 695:133833; 2019.

Vian A, Roux D, Girard S, Bonne P, Paladian F, Davies E, Ledoigt G. Microwave irradiation affects gene expression in plants. Plant Signal Behav 1:67–70; 2006.

Vijver M, Bolte J, Evans T, Tamis W, Peijnenburg W, Musters C, De Snoo G. Investigating short-term exposure to electromagnetic fields on reproductive capacity of invertebrates in the field situation. Electromagn Biol Med 33:21–28; 2014.

Waldmann-Selsam C, Balmori-de la Puente A, Breunig H, Balmori A. Radiofrequency radiation injures trees around mobile phone base stations. Sci Total Environ 572:554–569; 2016.

Woodgate JL, Makinson JC, Lim KS, Reynolds AM, Chittka L. Life-long radar tracking of bumblebees. PLoS One 11:e0160333; 2016.

Wyde ME, Horn TL, Capstick MH, Ladbur JM, Koepk G, Wilson PF, Kissling GE, Stout MD, Kuster N, Melnick RL, Gauger J, Bucher JR, McCormick DL. Effect of cell phone radiofrequency radiation on body temperature in rodents: pilot studies of the National Toxicology Program's reverberation chamber exposure system. Bioelectromagnet 39:190–199; 2018.

■■