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Review

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

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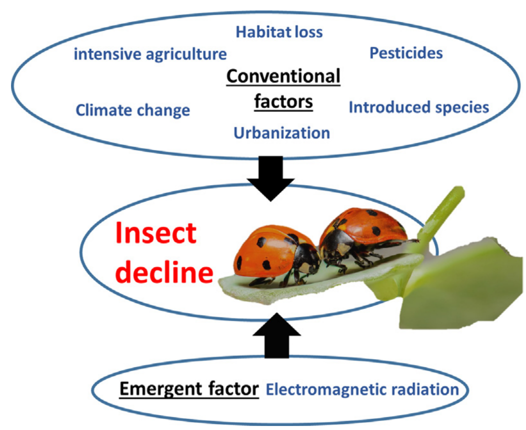
HIGHLIGHTS

- Biodiversity of insects is threatened worldwide.
- These reductions are mainly attributed to agricultural practice and pesticide use.
- There is sufficient evidence on the damage caused by electromagnetic radiation.
- Electromagnetic radiation may be a complementary 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 insects 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 cascading 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.

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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 broadband 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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Declaration of competing interest

The author declare that have no conflict of interest.

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