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ORIGINAL PAPER

Electromagnetic radiation of mobile telecommunication antennas affects the abundance and composition of wild pollinators

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Abstract The exponential increase of mobile telephony has led to a pronounced increase in electromagnetic fields in the environment that may affect pollinator communities and threaten pollination as a key ecosystem service. Previous studies conducted on model species under laboratory conditions have shown negative effects of electromagnetic radiation (EMR) on reproductive success, development, and navigation of insects. However, the potential effects that widespread mobile telecommunication antennas have on wild pollinator communities outside the laboratory microcosm are still unknown. Here we studied the effects of EMR from telecommunication antennas on key wild pollinator groups (wild bees, hoverflies, bee flies, remaining flies, beetles, butterflies, and wasps). We measured EMR at 4 distances (50, 100, 200 and 400 m) from 10 antennas (5 on Limnos Island and 5 on Lesvos Island, eastern Mediterranean, Greece), and correlated EMR values with insect abundance and richness (the latter only for wild bees and hoverflies). All pollinator groups except butterflies were affected by EMR. In both islands, beetle, wasp, and hoverfly abundance decreased with EMR, whereas the abundance of underground-nesting wild bees and bee flies unexpectedly increased with EMR. The effect of EMR on the abundance of remaining flies differed between islands. With respect to species richness, EMR only tended to have a negative effect on hoverflies in Limnos. As EMR affected the abundance of several insect guilds negatively, and changed the composition of wild pollinators in natural habitats, it might also have additional ecological and economic impacts on the maintenance of wild plant diversity, crop production and human welfare.

Keywords Bee flies · Beetles · Butterflies · Distance to the antenna · Electromagnetic smog · EMR · Hoverflies · Species richness · Wasps · Wild bees

Introduction

Pollinators play an important functional role in most terrestrial ecosystems and provide a key ecosystem service that is vital to the maintenance of wild plant communities and agricultural productivity (Klein et al. 2007; Kremen et al. 2007; Potts et al. 2010). Over the past decade, several studies have warned about the decline in pollinators (Biesmeijer et al. 2006; Pauw 2007; Goulson et al. 2008; Burkle et al. 2013) and the serious consequences this may have (e.g. Ashman et al. 2004; Burkle et al. 2013). This pollinator loss has been related to anthropogenic disturbances such as alterations in land use, habitat loss and climate change (Kearns et al. 1998; Aguilar et al. 2006; Hegland et al. 2009; Potts et al. 2010). At the same time, the use of mobile telephony has grown exponentially during recent years, resulting in a pronounced increase in electromagnetic fields in the environment. Detrimental effects of electromagnetic exposure have been shown for a

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variety of living organisms, from vertebrates to invertebrates, plants and bacteria (see reviews in Cucurachi et al. 2013; Balmori 2015).

The majority of studies on the effects of electromagnetic radiation on insects have been conducted on two model species: the fruit fly (*Drosophila melanogaster*) and the honeybee (*Apis mellifera*). The studies of electromagnetic radiation on the fruit fly have mostly shown developmental delays (Atli and Ünlü 2006) and negative effects on reproductive success (e.g. Panagopoulos et al. 2004; Atli and Ünlü 2006, 2007; Panagopoulos and Margaritis 2010; Panagopoulos et al. 2010; Chavdoula et al. 2010; but see Weisbrot et al. 2003 for a positive effect, and Vijver et al. 2013 for no effect) due to DNA fragmentation and reproductive cell death (Chavdoula et al. 2010; Panagopoulos et al. 2007, 2010). In honeybees, radiation decreases colony strength and oviposition rate (Sharma and Kumar 2010; Sahib 2011), and induces worker piping, a behaviour associated with swarming (Favre 2011). Electromagnetic radiation also interferes with honeybee navigation, as honeybees use compass mechanisms for orientation based on magnetite structures in their bodies (Kirschvink et al. 2001; Wajnberg et al. 2010; Válková and Vácha 2012; Balmori 2015). Due to electromagnetic smog, honeybees are often unable to return to their hives (Harst et al. 2006; Favre 2011; Sharma and Kumar 2010; Sahib 2011), and the resulting massive loss of workers then leads to a colony collapse (e.g. Harst et al. 2006; Sharma and Kumar 2010), which is why electromagnetic radiation has been suggested as one of the potential causes of the colony collapse disorder (CCD; e.g. Warnke 2009; Sahib 2011). Fewer studies exist in the literature regarding other insects, but it is known that radio frequency magnetic fields disrupt magnetoreception in the American cockroach (Vácha et al. 2009). In ants, electromagnetic radiation affects visual and olfactory memory, influencing their ability to associate cues to food (Cammaerts et al. 2012), as well as locomotion and orientation (Cammaerts et al. 2014; Cammaerts and Johansson 2014). Although most of these studies are conducted on model organisms and under laboratory conditions (Cucurachi et al. 2013), current evidence strongly indicates that insects in natural and protected areas may be negatively affected by the presence of base-station emitters of electromagnetic radiation (Balmori 2015). It still remains unknown, however, whether the presence of telecommunication antennas can modify wild pollinator communities by altering species abundance and/or species richness, thus threatening the maintenance of pollination as an ecosystem service.

In this study we investigate whether the electromagnetic radiation emitted by mobile telecommunication antennas affects the abundance and diversity of wild pollinators, as suggested by a preliminary study (Tscheulin et al. 2010) that indicated an effect of distance to the antenna on some pollinator groups. To do this, we measured the intensity of electromagnetic radiation at different distances from 10 telecommunication antennas in two Mediterranean islands, and correlated these measurements with the abundance and species richness of wild pollinators. Since the susceptibility of insects to radiation may differ, we hypothesized that electromagnetic radiation would modify the composition of the insect community and affect species richness negatively. Our specific questions were: (1) does electromagnetic radiation affect the abundance and richness of pollinating insects? And if so, (2) does the effect differ among taxonomic groups and nesting behaviours?

Materials and methods

Study sites

The study was conducted on two Mediterranean islands (Lesvos and Limnos) in the north-eastern Aegean (Greece), characterized by a variety of natural and managed habitats that support a great diversity of pollinators. In particular, the bee-friendly habitats the study was carried out in were phrygana (i.e. low scrub habitats with high pollinator diversity and abundance; Petanidou and Ellis 1993; Nielsen et al. 2011), which is dominant on Limnos and to a lesser degree on Lesvos; and olive groves (i.e. semi-natural habitats cultivated for centuries using non-intensive methods; Potts et al. 2006; Nielsen et al. 2011), which are co-dominant on Lesvos. Both these habitats have been shown to be equally rich in bee diversity and abundance (Potts et al. 2006; Nielsen et al. 2011).

In each island, we selected 5 mobile telecommunication antennas (antennas, hereafter; Fig. 1) as study sites, located in either phrygranic habitats or cultivated olive groves (Table 1). All study antennas were mobile telephony base stations, using frequency bands between 800 and 2,600 MHz, and were located at altitudes below 350 m in homogeneously flower-rich landscapes, and were separated by a minimum distance of 5 km. We have no reason to believe that antennas in the two islands differ in their emitted frequencies as all providers in Greece use similar frequency bands. Antennas located at high altitudes or in coniferous habitats were excluded in order to avoid pronounced differences in pollinator communities among antennas and sampling points (see below). Each of the study islands (and all the sites within them) is homogeneous in terms of climate and vegetation, and there are no apparent differences in land use management among sites (mostly light livestock grazing, beekeeping, and traditional ploughing of the olive groves).

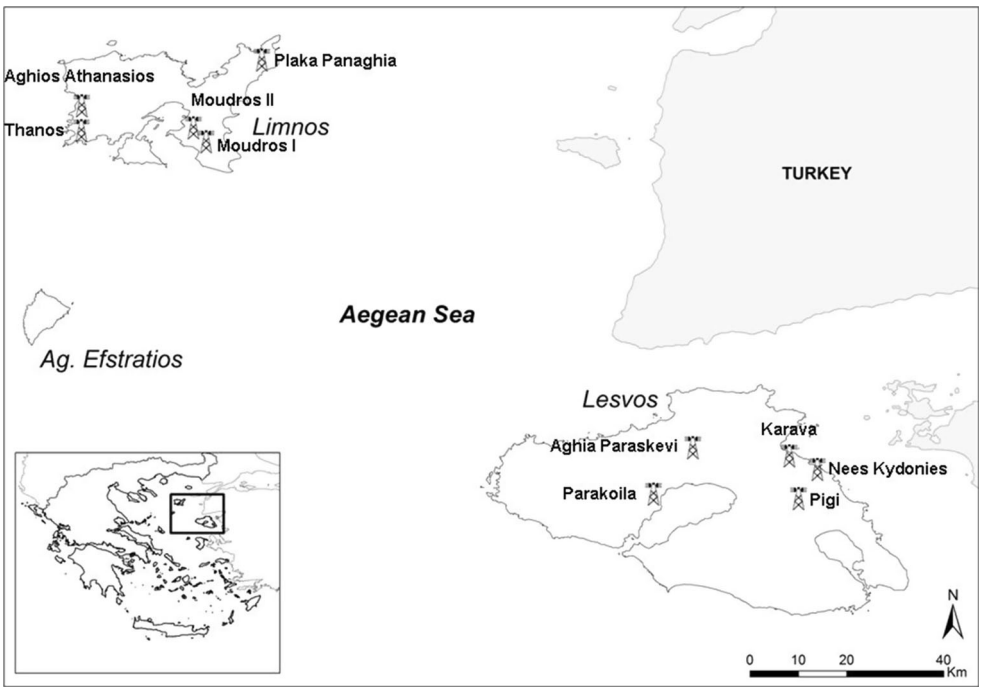


Fig. 1 Map of the study sites on Lesvos and Limnos Island (north-eastern Aegean, Greece)

Table 1 Study sites, respective habitat, coordinates, and mean EMR ± SD (V/m; see text for details)

Island	Site	Habitat	Latitude	Longitude	Mean EMR			
					50 m	100 m	200 m	400 m
Lesvos	Aghia Paraskevi	Olive groves	39°16′21.40″N	26°12′53.39″E	0.376 ± 0.042	0.313 ± 0.054	0.670 ± 0.015	0.271 ± 0.058
	Karava	Phrygrana	39°15′26.26″N	26°23′39.07″E	0.385 ± 0.012	0.341 ± 0.037	0.611 ± 0.030	0.632 ± 0.041
	Nees Kydonies	Phrygrana	39°13′56.74″N	26°26′46.09″E	0.516 ± 0.121	0.350 ± 0.049	0.069 ± 0.056	0.010 ± 0.004
	Parakoila	Phrygrana	39°11′11.95″N	26° 8′29.56″E	0.236 ± 0.112	0.149 ± 0.028	0.110 ± 0.184	0.118 ± 0.095
	Pigi	Olive groves	39°10′41.18″N	26°24′40.46″E	0.100 ± 0.054	0.077 ± 0.034	0.074 ± 0.028	0.061 ± 0.019
Limnos	Aghios Athanasios	Phrygrana	39°54′19.54″N	25° 4′44.66″E	0.512 ± 0.134	0.556 ± 0.057	0.169 ± 0.035	0.358 ± 0.085
	Moudros I	Phrygrana	39°50′20.06″N	25°18′36.30″E	0.083 ± 0.086	0.020 ± 0.055	0.084 ± 0.014	0.067 ± 0.012
	Moudros II	Phrygrana	39°51′52.57″N	25°17′11.64″E	0.139 ± 0.015	0.066 ± 0.043	0.010 ± 0.013	0.057 ± 0.030
	Plaka Panaghia	Phrygrana	39°59′25.80″N	25°24′49.30″E	0.278 ± 0.007	0.288 ± 0.014	0.386 ± 0.012	0.196 ± 0.023
	Thanos	Phrygrana	39°51′34.19″N	25° 4′41.59″E	0.327 ± 0.099	0.232 ± 0.247	0.132 ± 0.014	0.309 ± 0.078

Sampling points at 50 and 100 m were within the emission lobes of the antennas, except in Pigi (50 m + 100 m) and Moudros I (50 m)

Measurements of electromagnetic radiation

In April 2012, we measured the electrical field E component of electromagnetic radiation (EMR, hereafter) at 4 distances (50, 100, 200 and 400 m; sampling points, hereafter) from each of the 10 study antennas. These sampling points were selected in order to achieve a large range of EMR intensities at each study site, based on the inverse-square law, which states that an isotropic physical quantity or strength is inversely proportional to the square of the distance from the source of that physical quantity (Goldsmith 2005). However, the spatial structure of the electric field around the base station can be quite complex, and depend on factors such as topography, antenna vertical tilt and emission lobes (Balanis 2005; Goldsmith 2005). At each sampling point we also measured elevation with an altimeter, to account for differences in elevation with the distance to the antenna in the statistical analyses.

For the EMR measurements we used the device EMR-Narda (Narda EMR-300 Broadband RF Survey Meter; Flüge 2004) equipped with electric and magnetic probes. The electric field E probe has a wider frequency spectrum

response than the magnetic field B probe, namely 100 kHz–3 GHz and 80 MHz–1 GHz, respectively. In these frequency ranges, the EMR wavelength is much smaller than the measurement distances from the antennas, so one can safely assume that we are measuring in the far-field and consequently either E or B measurements are sufficient. We therefore chose to measure the E field, due to its wider frequency spectrum. E measurements in units of V/m are hereafter referred to simply as EMR measurements. The aforementioned frequency ranges contain all frequencies used by mobile telephony services. They also include radio and television communications, which are not serviced by the antennas at the locations monitored. In order to record potential diurnal EMR patterns, EMR was measured continuously during 24 h at the sites Karava, Kydonies, and Pigi on Lesvos Island, and at Aghios Athanasios, on Limnos Island. Following these measurements of EMR, shorter-term measurements (2 h) were carried out in all the remaining study sites. In total, between 115 and 1,400 measurements were recorded at each site and sampling point, each of these measurements corresponding to a 6-min average of electrical field.

Insect abundance and richness

At each sampling point we collected insects three times during the main flowering period (April, May and June) in 2012, using the pan trapping method (Westphal et al. 2008; Nielsen et al. 2011). Samplings were carried out under good weather conditions, i.e. temperature >15 °C, sunshine, low wind speed and relative humidity lower than 65 %. We arranged the pan traps in triplet units, with each triplet comprising three pan traps of a different UV-bright colour: blue, yellow, and white. These colours account for different colour preferences of pollinating insects (Westphal et al. 2008). Five triplets were set up at each sampling point of an antenna complex, on the ground, with any two triplets being separated by ca. 10 m. During each sampling round, pan traps were filled with 400 ml of water containing 1 drop of aroma-free kitchen detergent to break the water surface tension, and left for 48 h covering the entire flight activity period of diurnal and nocturnal pollinators.

Collected insects were transferred to small plastic zip-lock bags and refrigerated if they were to be processed within 24 h, otherwise deep frozen until pinning. After processing in the laboratory, bees and hoverflies were identified to species level (where necessary with the help of European specialists), while the remaining insects were assigned to one of the following taxonomic groups: beetles, butterflies, wasps, bee flies, and remaining flies that included all flies not belonging to hoverflies or bee flies (i.e. flies mainly belonging to the families Anthomyiidae, Muscidae, Calliphoridae, Nemestrinidae, Empididae, Tachinidae, Stratiomyidae, Asilidae, Rhagionidae, and Tabanidae). Honeybees were excluded from the analyses because they are managed, and their abundance is therefore biased by beekeepers' decisions. All identified insects are deposited in the Melissotheque of the Aegean (Petanidou et al. 2013).

Pollinator abundance at each sampling point for each group was estimated as the total number of individuals collected at that sampling point, pooling the data of the three sampling rounds together. Similarly, species richness was calculated as the total number of species collected at each sampling point during the three sampling rounds (e.g. Westphal et al. 2008; Nielsen et al. 2011; Lázaro et al. 2016).

Wild bees were categorized following their nesting behaviour, i.e. underground versus aboveground nesting, based on existing literature (Michener 2007; Müller 2015), and our own observations (see Table S1 for categories used).

Flower cover

Flower cover measurements were conducted in ten 1 m × 1 m squares selected at random at each sampling point and round, within the area where insects were collected. The total number of functional reproductive units, i.e., flowers or inflorescences depending on the species ('flowers' hereafter) for each plant species was counted within these squares. For each sampling point we calculated flower abundance as total number of flowers recorded in the ten squares, and flower richness as the total number of flowering species recorded. Plant specimens were deposited in the herbarium of the Laboratory of Biogeography and Ecology at the University of the Aegean.

Statistical analyses

All the statistical analyses were carried out using generalized linear mixed models (GLMM, library lme4) conducted in R 3.1.2 (R Development Core Team 2008), where site was included as a random variable to avoid pseudoreplication. To study how EMR varied with the distance to the antenna, the elevation and the island, we ran a model (Gamma distribution, log link function) with distance and elevation as continuous variables, and island as a categorical predictor variable. Full models on the abundance and species richness of insects were conducted separately for each taxonomic group and included EMR, distance, elevation (log transformed to improve model fitting), total flower abundance, and flower richness (to control for variations in the flowering community that could affect the response) as continuous predictor variables, island as a fixed predictor, and the interaction between EMR and

island, to detect any difference between islands in the response to EMR. For wild bee abundance and richness, we ran additional models in which the nesting behaviour of wild bees was included as a fixed categorical factor (underground vs. aboveground nesting), to test whether this factor affected the response to EMR. Due to the loss of some pan traps during sampling, and to control for the potential effects of these small changes in sampling effort on the results, we included the number of pan traps (log-transformed) as an offset in the models (Zuur et al. 2009). Due to the nature of the data, we used Poisson distributions and log link functions in these analyses. In some Poisson models we included an observation-level random intercept to cope with overdispersion (Zuur et al. 2013). Prior to analyses, we ran variation inflation factor (VIF) analyses to identify collinear predictor variables that should be removed from further analyses (Zuur et al. 2009). VIF values were smaller than 3 for all variables, thus none of the predictors needed to be removed (Zuur et al. 2009). Before the analyses, we also used Moran's I (library ncf; Bjørnstad and Falck 2001) to check for any spatial correlation in the data or in the residuals of the models (without random factor). Neither the data nor the residuals showed any spatial correlation, indicating that our mixed model approach was appropriate. Model selection was conducted using the 'dredge' function (package MuMIn; Barton 2014), including EMR in each model, and setting the maximum number of variables to 4 to avoid over-parametrization. Means and estimates are accompanied by their standard error throughout the text.

Results

EMR measurements

We found some diurnal-nocturnal patterns in EMR values in the sites measured continuously for 24 h (see Figure S1 in Electronic Supplementary Material). However, the patterns differed among sites, the effect of time was small compared to differences among distances and sites (Table 1; Figure S2 in Electronic Supplementary Material), and EMR values did not differ significantly when measured for only two or for 24 h ($\chi^2_1 = 2.53$, $p = 0.112$). Consequently, in our models we used the average EMR values measured per site and sampling point.

Overall, EMR values did not significantly differ between islands (Lesvos: 0.27 ± 0.05 V/m; Limnos: 0.21 ± 0.04 V/m; $\chi^2_3 = 0.08$, $p = 0.779$) and did not decrease with the distance to the antenna ($\chi^2_1 = 0.71$, $p = 0.398$), supporting the results of other studies (e.g. Vijver et al. 2013), possibly because some of the sampling points located close to the antenna may have been outside or at the edge of the emission lobes of the antenna. The interaction between island and distance was also non-significant ($\chi^2_1 = 0.95$, $p = 0.329$). Mean values (±SD) recorded at each sampling point are shown in Table 1.

EMR effects on insects

On Lesvos, we collected 11,547 insects in total: 1,334 wild bees (133 species), 41 hoverflies (9 species), 426 wasps, 75 bee flies, 2,857 other remaining flies, 6,758 beetles, and 84 butterflies. On Limnos, the total number of insects collected amounted to 5,544: 2,467 wild bees (108 species), 155 hoverflies (6 species), 357 wasps, 11 bee flies, 2,263 other remaining flies, 252 beetles, and 131 butterflies. Table S1 in the Supplementary Material shows the number of different wild bee and hoverfly species found at each study site.

EMR effects on the abundance of the different insect guilds

EMR had contrasting effects on the abundance of different pollinator groups, affecting some positively, while others negatively. In addition, for most pollinator groups the effects found were consistent in both islands.

Overall wild bee abundance increased significantly with EMR in both islands (Fig. 2a); however, the increase was steeper on Limnos than on Lesvos (Table 2A; Fig. 2a). When including the nesting behaviour of wild bees in the analysis, the triple interaction Island × Nesting behaviour × EMR was also significant ($\chi^2_1 = 7.47$, $p = 0.006$), showing that only underground-nesting wild bees were positively related to EMR, while aboveground-nesting wild bees were not affected on the study islands (Fig. 3). Again, the response was steeper in the case of Limnos.

Beetle abundance decreased significantly with EMR in both islands (Fig. 2b). However, as for wild bees, the relationship was more pronounced on Limnos than on Lesvos (Table 2B; Fig. 2b). There were significantly more beetles on Lesvos than on Limnos (Lesvos: 337.9 ± 62.8 cumulated insects per sampling point; Limnos: 12.6 ± 6.3; Table 2B).

The abundance of bee flies increased with EMR (Table 2C; Fig. 2c), while EMR was negatively related to the abundance of wasps (marginally non-significant relationship; Table 2D; Fig. 2d).

Wasp abundance also increased with flower richness (estimate: 0.140 ± 0.051; Table 2D) and decreased with flower abundance (estimate: -0.008 ± 0.004; Table 2D).

Hoverfly abundance was negatively related to EMR (Table 2E; Fig. 2e) and tended to increase with flower abundance (estimate: 0.009 ± 0.006; Table 2E).

The effect of EMR on the abundance of the broad group 'remaining flies' differed drastically between islands. Thus,

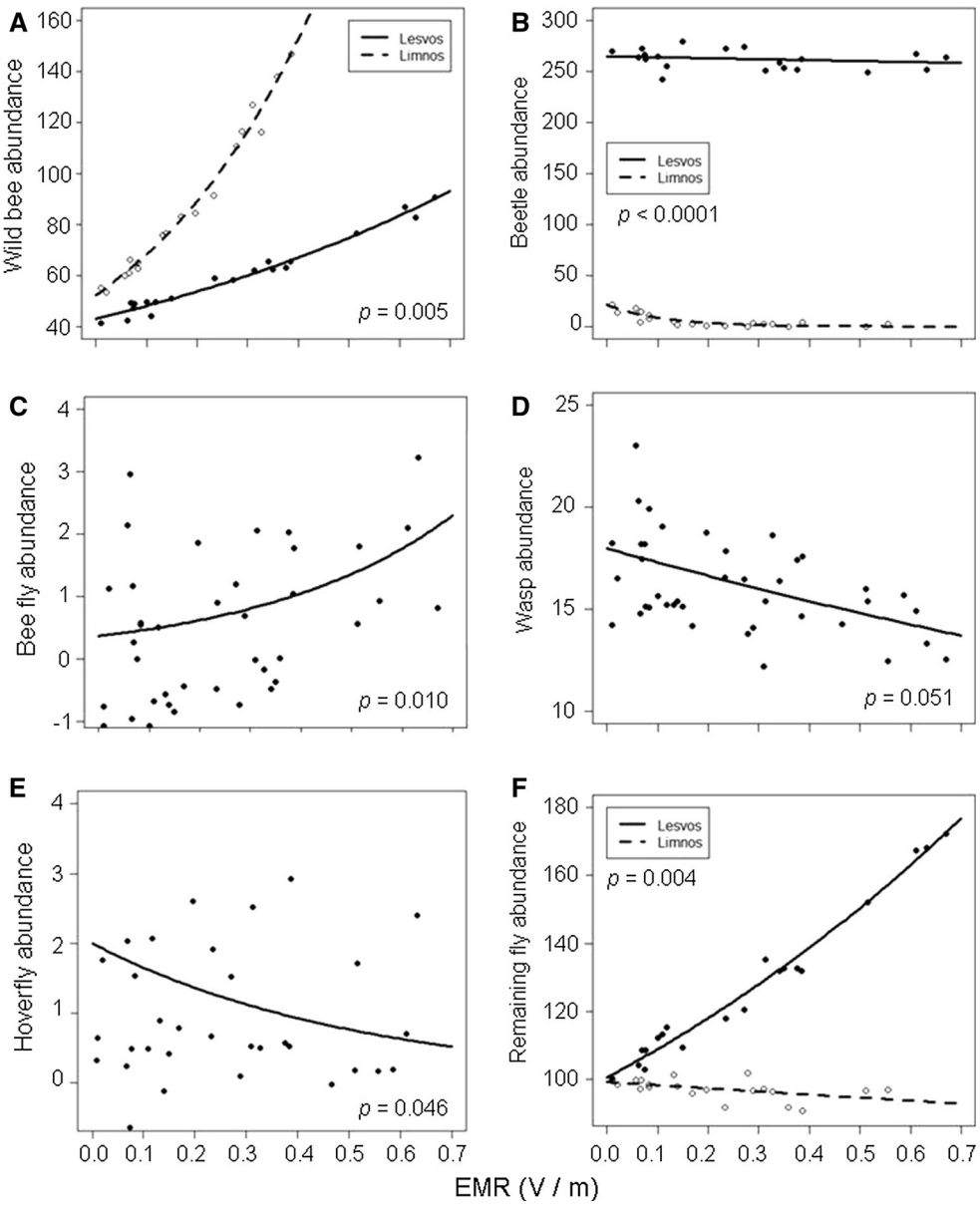


Fig. 2 Partial residual plots showing the significant relationships between EMR and the abundance of pollinating insects. When the interaction between EMR and island was significant, the relationships are depicted separately for each island. The *lines* represent the estimate of the best model and the *circles* represent partial residuals. Note that different graphs vary in y-axis scale

while EMR was positively related to the abundance of remaining flies in Lesvos, it was negatively related in Limnos (Table 2F; Fig. 2f).

Butterfly abundance (Table 2G) was not related to EMR, but was significantly higher in Limnos than in Lesvos (Limnos: 6.6 ± 1.0 cumulated insects per sampling point; Lesvos: 4.2 ± 0.8; Table 2G).

EMR effects on species richness of wild bees and hoverflies

EMR was not related to overall wild bee species richness (Table 2H), even when nesting behaviour was included in the model (Best model: EMR: $\chi^2_1 = 0.14$, $p = 0.71$; Nesting behaviour: $\chi^2_1 = 705.95$, $p < 0.0001$; 2.10 ± 1.24 vs. 1.88 ± 0.22 mean species/sampling point for underground- and aboveground-nesting wild bees respectively).

The interaction between EMR and island had a marginally non-significant effect on hoverfly richness (Table 2I). EMR tended to negatively affect hoverfly species richness but only in Limnos, whereas in Lesvos there was no significant relationship between these two variables (Fig. 4).

Discussion

For the first time to our knowledge, we have shown that electromagnetic radiation as typically emitted by telecommunication antennas affects the abundance and

Table 2 Results of the best models relating EMR to the abundance and richness of insects

Model	Variables tested	χ^2	*df*	*p*	Estimate for relationship with EMR
(A) Wild bee abundance	Island	1.79	1	0.181	
	EMR*Island	7.86	1	0.005	Lim (+), Les (+)
	Flower richness	12.97	1	0.0003	
(B) Beetle abundance	Island	5.49	1	0.019	
	EMR*Island	85.88	1	<0.0001	Lim (−); Les (−)
(C) Bee fly abundance	EMR	6.63	1	0.010	(+)
(D) Wasp abundance	EMR	3.78	1	0.051	(−)
	Flower richness	7.61	1	0.006	
	Flower abundance	5.05	1	0.025	
(E) Hoverfly abundance	EMR	3.98	1	0.046	(−)
	Flower abundance	2.86	1	0.091	
(F) Remaining flies abundance	Island	0.52	1	0.469	
	EMR*Island	8.33	1	0.004	Lim (−); Les (+)
(G) Butterfly abundance	Island	5.59	1	0.018	
	EMR	0.003	1	0.953	ns
(H) Wild bee richness	EMR	0.10	1	0.753	ns
(I) Hoverfly richness	Island	1.74	1	0.189	
	EMR*Island	3.13	1	0.077	Lim (−); Les (ns)

'+' a positive, '−' a negative, and ns: a non-significant relationship. When there was a significant interaction between island and EMR the sign of the estimate is given separately for Limnos (Lim) and Lesvos (Les)

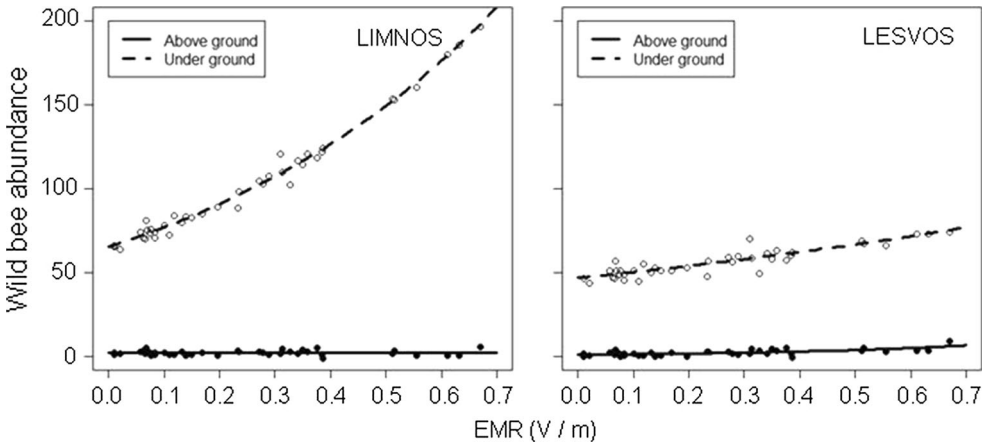


Fig. 3 Partial residual plots showing the relationship between EMR and the abundance of underground- and aboveground-nesting wild bees. As the triple interaction EMR × Island × Nesting behaviour was significant ($p = 0.006$), the relationships are depicted separately for each island. The *lines* represent the estimate of the best model and the *circles* represent partial residuals

composition of wild pollinators in natural habitats. In both study islands, beetle, wasp and hoverfly abundance decreased with EMR, whereas, to our surprise, wild bee and bee fly abundance increased with EMR. The effect of EMR on the abundance of remaining flies differed between islands. These differences in the response of insect guilds are likely due to differences in their susceptibility to radiation.

We expected telecommunication antennas to affect the abundance of wild pollinators because these animals rely on their cognitive and orientation abilities to forage and navigate (Chittka and Thomson 2001), and electromagnetic smog is known to affect cognition and orientation in insects (e.g. Cammaerts et al. 2012, 2014; Sharma and Kumar 2010; Sahib 2011). Our communities were similar in terms of habitat and human activities, and in our analyses we controlled for the variations in flower abundance and diversity among study sites (as these variables might directly affect the pollinator community); therefore, although we cannot totally discard the potential effect of an unmeasured variable, we are confident that our results reflect the effect of radiation on wild pollinator

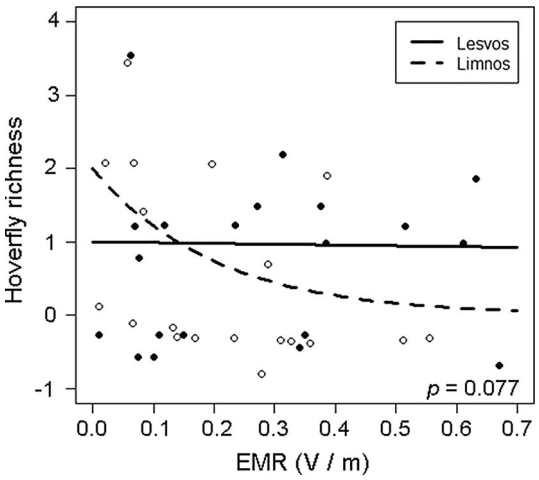


Fig. 4 Partial residual plots showing the significant relationships between EMR and the hoverfly richness. Since the interaction between EMR and island was marginally non-significant, the relationship is depicted separately for each island. The *lines* represent the estimate of the best model and the *circles* represent partial residuals

communities, either directly or indirectly. As expected, EMR modified the abundance of all the studied pollinator groups, with the only exception of butterflies; however, pan traps are not efficient tools for collecting butterflies (they accounted for only 1.3 % of the total specimens collected), and maybe a more adequate sampling method would have led to a different result. Interestingly, the effects of EMR on the abundance of pollinators were not always negative. More specifically, we found that overall wild bee abundance and bee fly abundance increased significantly with EMR, while hoverfly, beetle, and wasp abundance decreased with EMR in both islands. When looking closer at wild bees, we found that only the abundance of underground-nesting wild bees was positively related to EMR, whereas wild bees nesting aboveground were not affected by EMR. It is remarkable though, that the effects of EMR on insect abundance were consistent in both islands for all the pollinator groups except for the broad group 'remaining flies', which might have been due to differences in the composition of this group between the two islands. Previous studies have also shown that the effects of electromagnetic radiation vary for different animals. Within mammals, negative effects of radiation have been found in rats and mice (e.g. Maskey et al. 2010, 2012; Narayanan et al. 2015; Sahin et al. 2015), as well as in dogs, cats, and cows (Marks et al. 1995; Löscher and Käs 1998). Within insects, the effects on different species were also variable. For instance, negative effects of electromagnetic radiation have been reported on cognition, locomotion, and orientation in the ant *Myrmica sabuleti* (Cammaerts et al. 2012, 2014), and on worker piping and navigation in honeybees (e.g. Favre 2011; Sharma and Kumar 2010; Sahib 2011), and on development and reproductive success of the fruit fly (e.g. Panagopoulos et al. 2004; Atli and Ünlü 2007). Nevertheless, a field study on the effects of electromagnetic exposure on the reproductive capacity of several insects revealed no effects (Vijver et al. 2013). The authors suggest that this lack of effects could be at least partially attributed to short term exposures or to the length of waves in relation to the small size of the animals (Vijver et al. 2013). Our study, however, revealed alterations in the structure of the pollinator community. The negative relationship between EMR and the abundance of wasps, beetles and hoverflies might indicate a high sensitivity of these insects to electromagnetic radiation. In contrast, pollinators potentially more tolerant to EMR, such as underground-nesting wild bees and bee flies, may fill the vacant niches left by less tolerant species and thus result in an increase of their populations. One possible explanation for these results is that EMR may have particularly detrimental effects on the potentially more susceptible larval stages of these flower visitors. If so, larvae developing aboveground (many beetles, wasps, many hoverflies) may be more vulnerable than those developing underground (underground-nesting wild bees, i.e. the majority of Apoidea), because the former may be exposed to higher radiation levels. The fact that bee flies are mostly represented in our study by the genera *Phthiria* and *Cyllenia*, which are parasitoids of prepupal or pupal stages of moths and sawflies developing underground (Yeates and Greathead 1997), may also support our hypothesis. At any rate, these changes in the composition of pollinator communities may have important ecological consequences for the maintenance of pollination services and biodiversity, but also economic impacts in respect to potential effects on agricultural productivity (Gallai et al. 2009; Potts et al. 2010).

Reduced pollinator diversity in a community can reflect disturbances of the environment (Potts et al. 2010), and thus, we expected EMR to negatively affect overall pollinator species richness. However, our results on pollinator species richness were weak and not as conclusive as those on abundance, because we found no significant effect of EMR on wild bee species richness, and only a marginally non-significant negative effect on hoverfly species richness in Limnos, the study island where the overall effects of EMR were stronger. At any rate, the tendencies were always negative, and therefore, we cannot rule out that an increase in sampling effort in future research could reveal stronger effects of EMR on species richness.

Conclusions

Electromagnetic radiation from telecommunication antennas affected the abundance and composition of wild pollinators in natural habitats. EMR had contrasting effects on

the abundance of different pollinator groups (negative on beetles, wasps, and hoverflies; positive on underground-nesting wild bees and bee flies), which may be due to different susceptibilities to radiation particularly of the larval stages. Pollinators and their host plants constitute pollination networks. Although the architecture of these mutualistic networks can increase the capacity of pollinator populations to persist under harsh conditions, once a tipping point in human-induced environmental change is reached, pollinator populations may collapse simultaneously (Lever et al. 2014). Therefore, these changes in the composition of pollinator communities associated with electromagnetic smog may have important ecological and economic impacts on the pollination service that could significantly affect the maintenance of wild plant diversity, crop production and human welfare.

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