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Effects of solar panels and management on pollinators and their interactions with plants in Southern French solar parks

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ABSTRACT

Pollination plays a key role in maintaining plant populations and structuring plant communities since most plants depend on pollinating insects. Habitat loss and fragmentation due to human activities has resulted in a decline of pollinators and reduced pollination. Solar parks may contribute to the loss of pollinators because the construction involves vegetation removal and solar panels change the microclimate. In our study, we evaluated potential negative effect of solar panels on pollinators and how solar park management by grazing or mowing affects pollinators. In twenty French solar parks, we compared the number of pollinators and plant-pollinator interactions under solar panels, in inter-rows between panels and outside panels in areas never shaded. We found that the number of pollinators and plant-pollinator interactions is 76 % and 86 % lower under panels, respectively, compared to areas outside panel with intermediate results in inter-rows. Grazing reduced the number of pollinators compared to mowing. Solar parks may thus contribute to the loss of pollinators if not compensated by a positive effect of inter-rows and non-shaded parts. Future research needs to focus on ecologically sound management of solar parks in order to avoid negative effects on pollinators.

1. Introduction

Pollination plays a key role in the structure of many ecosystems, and 87 % of angiosperm species depend on pollinating insects (Ollerton et al., 2011). It is a crucial ecological function for plant conservation as well as an important ecosystem service driving crop production. Economic benefits are estimated at 153–195 to 387–422 billion euros per year worldwide (Gallai et al., 2009; IPBES, 2016; Porto et al., 2020). It is well known that pollinators and pollination are declining and there is an urgent need to monitor, preserve or even restore them (IPBES, 2016). The major causes of this decline are habitat loss and fragmentation (IPBES, 2016; Potts et al., 2016; Xiao et al., 2016), and several groups are considered as endangered today (IUCN., Red List., SSC, Species Survival Commission, 2023).

The increasing construction of solar parks may further threaten pollinators since land occupation is higher than that of other renewable energy devices (Palmer-Wilson et al., 2019; Kim et al., 2021). Accordingly, solar parks may negatively affect plant communities, floral resource production and thus pollinator communities if parks are constructed in semi-natural habitats such as extensively used grasslands of high species-richness (Gang et al., 2014; Habel et al., 2013; IPBES, 2016; Lafitte et al., 2023). However, effects of solar parks on pollinators depend on climate, soil and technical characteristics (size, layout, panel height and width), and may be influenced by solar park management (Bai et al., 2022; Jeal et al., 2019; Uldrijan et al., 2022). On the other hand, solar parks may also have positive effects on biodiversity if

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constructed on degraded habitats such as arable fields or wasteland and if management allows the establishment of diverse plant communities (Lambert et al., 2022; Uldrijan et al., 2022).

Solar panels strongly change microclimatic conditions by excluding a large part of solar radiation and rainfall (Armstrong et al., 2016; Lambert et al., 2023). As a consequence, solar panels may change plant species composition and vegetation structure that shape pollinator communities. Solar panels influence further reduce the visibility of flowers attracting pollinators, and solar parks may represent a physical barrier for butterflies, beetles and flies at landscape scale (Guiller et al., 2017; Grodsky et al., 2021). Furthermore, solar parks require management by grazing and/or mowing to avoid overgrowth of solar panels. Management changes plant communities and thus also the associated pollinator communities.

So far, few studies have analyzed pollination in solar parks, and present knowledge is based on a small number of solar parks. Guiller et al. (2017) found that solar parks may hamper the movement of butterflies and recommend to revegetate areas between and under solar panels and to adapt the frequency of mowing to plant phenology. Grodsky et al. (2021) showed a negative effect of solar parks on non-bee flower visitors in solar parks of the Mojave desert. However, solar parks may potentially enhance pollinator biodiversity by managing the vegetation without negative effects on pollinator foraging and floral resources (Blaydes et al., 2021). In solar parks located in agricultural landscapes, pollinator abundance, diversity, and richness were lower under panels but flower visitation rates were not affected (Graham et al., 2021). Ecologically sound management including the establishment of pollinator-friendly habitats in solar parks may even result in positive effects increasing flower diversity, pollinator abundance and pollinator diversity (Walston et al., 2024). Menta et al. (2023) found a significant negative effect of solar panels on hymenopteran species only in grazed, but not in mown solar parks. However, studies in semi-natural grasslands showed higher abundance and diversity of pollinators under grazing than under mowing because grazing keeps grasslands more open whereas mowing favors tall-growing grasses at least until the first cutting (D'Aniello et al., 2011; Tälle et al., 2016). The effect of grazing depends on the intensity and period of herbivory and varies from year to year (Davidson et al., 2020; Goosey et al., 2024). However, there is a lack of studies on management and its interaction with solar panels (Blaydes et al., 2022). Furthermore, the Mediterranean region is underrepresented in such studies.

In order to better understand the effects of solar panels on pollination and to improve recommendations for biodiversity-friendly solar park management, we analyzed the effect of solar panels and management by grazing and mowing on pollinators in two Southern French regions (Mediterranean and South Atlantic). We hypothesized that (1) the abundance of pollinators and the number of plant-pollinator interactions decrease under solar panels compared to areas between (inter-rows, partially shaded) and outside panels (no shading); (2) grazing favors plant-pollinator interactions compared with mowing and (3) the effect of management depends on solar panels because this effect may change grazing/mowing conditions.

2. Methods

2.1. Field sites and sampling

The study was set up in two Southern French regions differing in climate, soil and vegetation (Atlantic, Mediterranean). Atlantic is characterized by oceanic climate and sandy podzols, while Mediterranean is characterized by a sub-Mediterranean to Mediterranean climate and calcic leptosols to cambisols. In each region, we selected ten solar parks, of which five were managed by mowing and another five by grazing (Fig. 1). The vegetation was dominated by spontaneously occurring species established from the seed or bud bank and seed rain. Only 5 out of 20 parks were initially sown with cultivars of grasses and legumes that mostly disappeared until our vegetation analysis. The cutting period was May/June and October/ November for mown solar parks using brush cutter with rotary mower. The hay was not removed. Sheep grazing from April to September of similar intensity was the second management treatment. Most solar parks were constructed in artificial forests, in particular in the Atlantic region characterized by a dominance of *Pinus maritima*. In the Mediterranean region, pre-construction habitats were more variable including quarries, industrial wasteland and abandoned crop fields. Accordingly, open habitats were also more common in the surroundings of Mediterranean solar parks (Table 1).

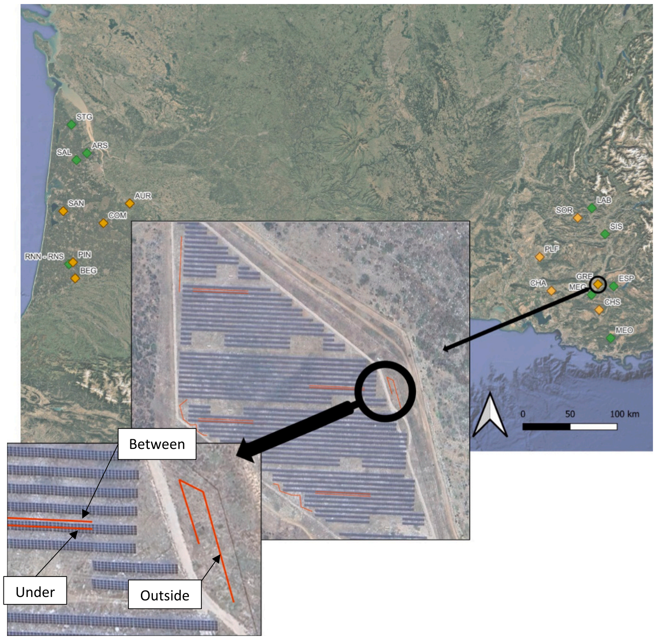

Fig. 1. Study sites and design using a zoom on one solar park and one block within this solar park. Blue strips: solar panel rows, orange lines: transects. Transect length is 100 m. The orange diamonds represent grazed and the green diamonds mown solar parks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

All solar parks are characterized by ground-mounted panels excluding sun tracker systems. Within each solar park, we analyzed three different positions corresponding to solar panel influence (treatments). Under solar panels ("Under") refers to the vertical projection of solar panels with full interception of rainfall. The alleys between solar panel rows ("Between") are shaded a part of the day (morning, afternoon) but receive the full amount of rainfall. Controls outside solar panels ("Outside") are neither affected by panel shadow nor by rainfall interception (Fig. 1). The three treatments were randomized in four blocks per solar park (Fig. 1). Since management treatment could not be replicated within solar park blocks, the design corresponds to a split-plot with vegetation management as whole-plot and solar park as split-plot factor. In total, the design included 3 locations × 4 blocs × 2 management types x 5 solar parks x 2 regions = 240 plots.

2.2. Insect visitation transects

For each treatment, pollinators were observed along a transect of 100 m length and 4 m width (400 m^2) for 10 min in walking along the transect edge. All insects that visited flowers were identified on sight to the following morpho-group level: honeybees, bumblebees, carpenter bees, large other solitary bees (>1 cm), small other solitary bees (<1 cm), wasps, hoverflies, bee flies, other diptera, ladybirds, other coleoptera, butterflies and other pollinators. In order to analyze interactions between flowers and pollinators, we focused on wild bees, butterflies

Table 1
Technical, geographical and climatic characteristics of solar parks. PACA corresponds to "Provence-Alpes-Côtes-d'Azur", Garrigue is Mediterranean shrubland, "Year" correspond to the year of commissioning.

Site	Region	Management	Area (ha)	Year	Width between panel rows (m)	Minimum height of panels (m)	Maximum height of panels (m)	Average annual rainfall (mm)	Average annual temperature (°c)	Past land use
BEG	Nouvelle-Aquitaine	Grazing	8.3	2016	3.6	0.9	2.2	978	14.0	Forest
RNN	Nouvelle-Aquitaine	Mowing	34.3	2021	4.2	0.8	2.8	899	14.0	Forest
RNS	Nouvelle-Aquitaine	Mowing	23.6	2021	4.2	0.8	2.8	899	14.0	Forest
PIN	Nouvelle-Aquitaine	Grazing	42.7	2014	4.4	1.0	2.5	899	14.0	Forest
COM	Nouvelle-Aquitaine	Grazing	26	2021	2.4	0.8	2.7	922	13.9	Forest
SAN	Nouvelle-Aquitaine	Grazing	26.4	2017	7.2	0.8	2.5	839	14.2	Forest
AUR	Nouvelle-Aquitaine	Grazing	8.5	2019	5.7	0.8	2.6	777	13.8	Industrial
SAL	Nouvelle-Aquitaine	Mowing	127	2017	3.0	0.8	1.9	782	13.8	Forest
ARS	Nouvelle-Aquitaine	Mowing	160	2015	5.3	0.7	2.8	782	13.9	Crop field
STG	Nouvelle-Aquitaine	Mowing	17.4	2016	3.5	0.8	1.9	774	13.9	Forest
MEO	PACA	Mowing	11	2014	5.4	0.7	2.5	709	13.5	Forest
CHS	PACA	Grazing	16.5	2013	8.0	0.8	3.3	737	13.1	Garrigue
MEG	PACA	Mowing	25	2017	5.0	0.8	2.2	742	12.8	Garrigue
GRE	PACA	Grazing	163.5	2017	3.5	0.8	2.2	689	12.5	Forest
ESP	PACA	Grazing	16.7	2011	7.7	0.8	3.8	689	12.5	Crop field
SIS	PACA	Mowing	6.9	2014	7.2	0.8	3.2	896	10.3	Woodland
SOR	PACA	Grazing	9.8	2017	3.7	0.9	2.2	1092	9.3	Forest
LAB	PACA	Mowing	20.1	2018	3.1	0.7	2.2	1092	8.2	Forest
CHA	PACA	Grazing	10.7	2013	6.5	0.8	3.3	682	14.1	Quarry
PLF	PACA	Mowing	3.2	2019	2.6	0.8	1.9	713	13.9	Quarry

and hoverflies, as these taxa are the most active pollinators in our study regions. We followed the path of flying individuals to count them only once per location. The visited plant species were identified to species or genus level.

2.3. Statistical analysis

All statistical analysis were run in R 4.1.0 (R Core Team, 2024). We tested the effect of vegetation management and solar panels on pollinator abundance and network metrics using the bipartite package (*networklevel* package "bipartite"). We used two network metrics: (i) the number of links per species (qualitative): sum of links divided by number of species (ii) the number of plant species visited by pollinators. Generalized linear mixed effect models were fitted using negative binomial error distribution and log-link function (*glmer.nb*, package "lme4") since models using Poisson distribution showed overdispersion. In order to account for the split-plot design, we tested vegetation management as the whole-plot factor against the interaction vegetation management x region x solar park. Region and vegetation management were fitted as fixed factors and solar park as random effect. The solar panel effect and its interaction with the vegetation management were tested against the global model error involving additionally block as a random effect. The significance of fixed effects was tested using ANOVA type II (package "car").

3. Results

3.1. Pollinator abundance

A total of 6002 pollinators were counted including 457 observations of honey bees (7,6 %). The mean number of pollinators per solar park was significantly higher in the Mediterranean region ($n = 31$) than in the Atlantic region ($n = 19$). In the Mediterranean region, pollinator abundance was significantly lower Under panels than Between panel rows (− 32,4 %) and Outside panels (− 71,3 %) (Fig. 2A). In the Atlantic region, pollinators were 24,1 % and 83,6 % less abundant Under panels compared with Between and Outside habitats, respectively (Fig. 1F). Grazing significantly reduced the pollinator abundance compared with mowing, independently of solar panel influence and region. Butterflies represent the largest proportion of pollinators with a total of 1910 individuals (32 % of total abundance) of which 72 % were flying in the period of observation. The effect of grazing and panels on flying butterflies was significant whereas region did not have any effect. The significant panel effect on butterflies was explained by a lower abundance Under panels compared with Outside and Between the panels (Fig. 3B).

3.2. Plant-pollinator interactions

A total of 3286 plant-pollinator interactions were recorded including 351 interactions with honey bees (10,7 %). The Mediterranean region showed significantly more plant-pollinator interactions than the Atlantic region (Table 2). In the Atlantic region, plant-pollinator interactions along transects were 43,2 % lower Under panels than Between panel rows and 90,7 % lower Under panels than Outside (Fig. 2B). In the Mediterranean region, plant-pollinator interactions were 39,4 % and 82,2 % less frequent Under panels than Between and Outside, respectively (Fig. 2F). The interaction management x solar panel was not significant in the two regions. Management by grazing significantly reduced the number of plant-pollinator interactions in both regions compared with mowing. The panel effect was stronger than the management effect being highly significant for all response variables (Table 2). A total of 1204 wild bee + hoverfly - plant interactions were found. For this group of insects, interactions with plants were only significant for the effect of solar panels (Table 2) but not for management or region. The reduction was very strong Under panels being 90 % lower than Outside panels (Table 2 & Fig. 3A).

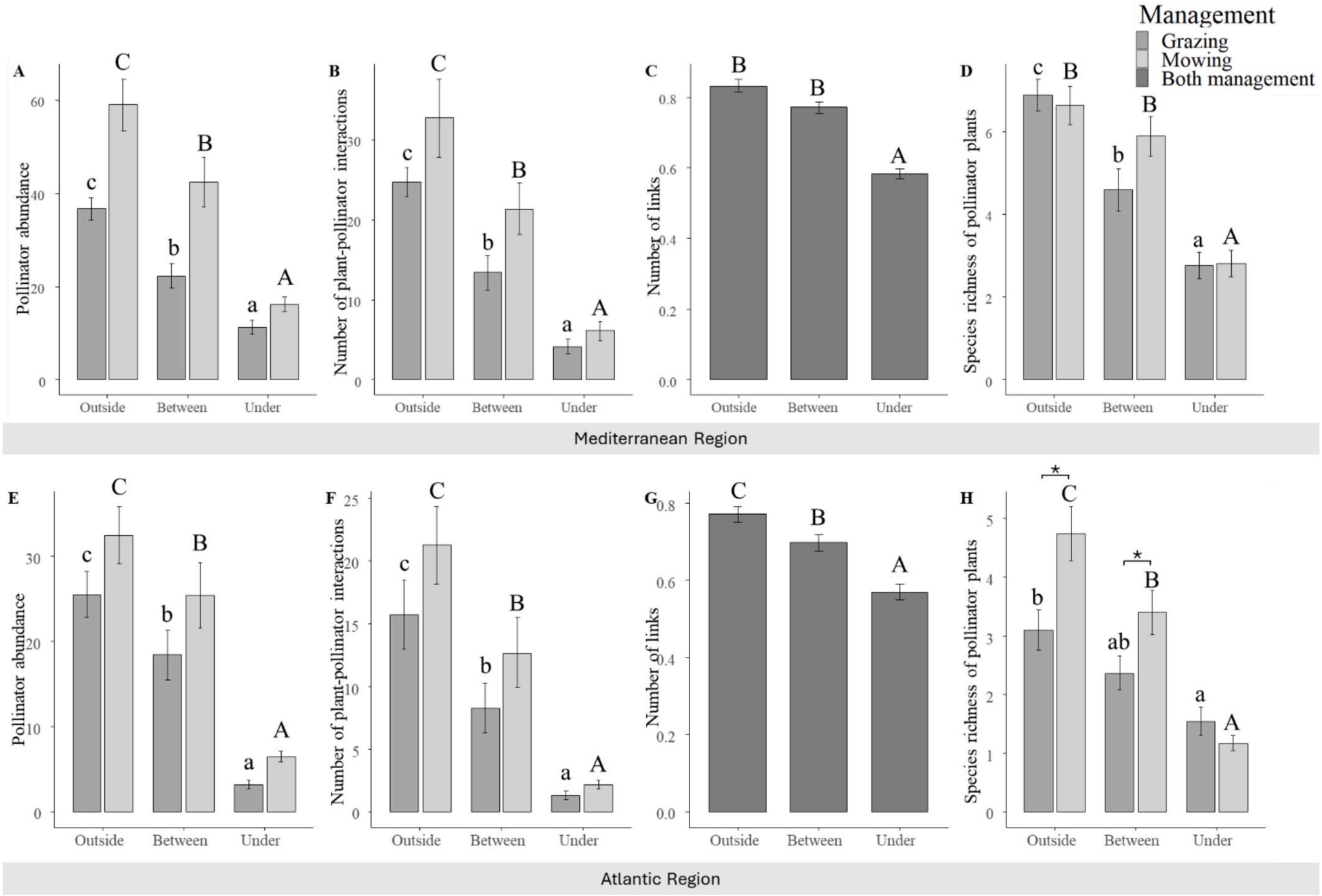

Fig. 2. Effects of management and solar panels on pollinators and plant-pollinator interactions in two Southern French regions (means ± SE). Species richness of plants (D, H) is the number of species visited by pollinators; different letters indicate significant differences (Tukey posthoc test, $p < 0.05$) in panel effects for mown and grazed plots, respectively. In absence of significant management effects (C,G), data were pooled for management and only uppercase letters were used to indicate differences in panel effects. The significance between management types is indicated as $* = p < 0.05$.

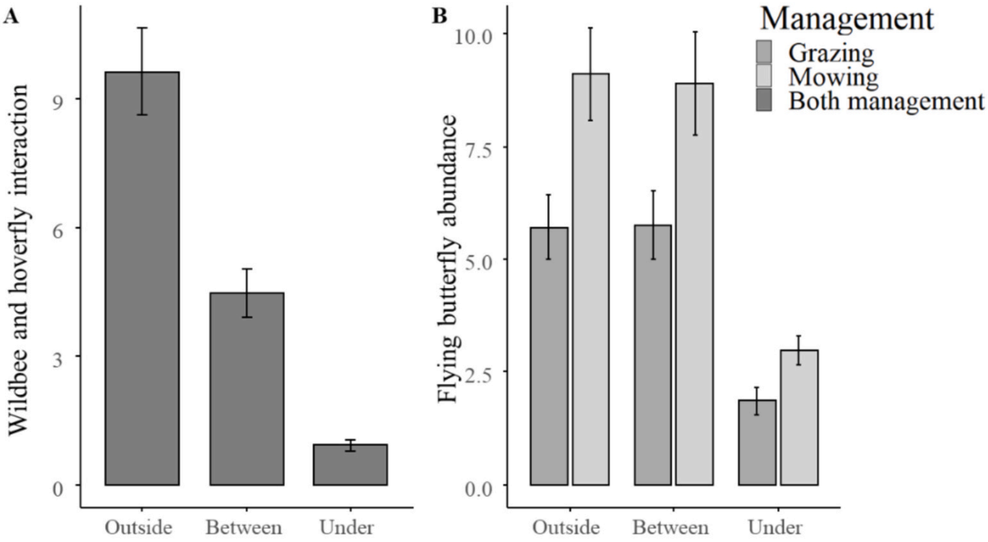

Fig. 3. Effect of solar panels and management on wild bees and hoverflies (A) and butterflies (B) (means ± SE); different letters indicate significant differences (Tukey posthoc test, $p < 0.05$) in panel effects (uppercase letters mown, lower case letters grazed plots); significance between two management types within solar panel effects is indicated as $* = p < 0.05$.

Table 2

Region, management and solar panel (SP) effects on pollinators and plant-pollinator interactions. Chi^2 values and significance resulting from generalized linear mixed models (GLMM). Significance: * = $p < 0.05$, ***$p \leq 0.01$*, ***$p \leq 0.001$.

	Region (df 1)	Management (df 1)	SP (df 2)	Management x SP (df 2)	Region x SP (df 2)	Region x management (df 2)
Pollinator abundance	28.21***	16.54**	388.8***	1.3	21.9 ***	0.34
Plant-pollinator interactions	18.73***	6.66**	308.5***	1.04	7.92 *	0.03
Wild bee and hoverfly interactions	0.38	1.15	163.8***	5.69	0.15	0.00
Flying butterfly abundance	1.05	5.22*	114.06***	0.20	13.57*	0.55
Number of links	11.83***	0.47	149.4***	1.04	2.17	0.72
Number of plant species attracting pollinators	36.37***	3.08 **	208.5***	6.76 *	1.19	0.51

3.3. Number of links and visited plant species

The analysis of flower visitation included 235 plant species, 187 in the Mediterranean and 67 in the Atlantic region. In the Atlantic region, the three most attractive species were *Hypochaeris radicata/glabra* (47 interactions), *Molinia caerulea* (31), *Pilosella_officinarum* (28) while in the Mediterranean region, *Dorycnium hirsutum* (79), *Dorycnium pentaphyllum* (58) and *Bituminaria bituminosa* (39) were the most visited species. The number of links per pollinator category was significantly affected by region being lower in the Atlantic than in the Mediterranean region. Solar panels had a significant effect on the number of links being negative Under compared to Outside panels in both regions and being negative Under compared to Between only in the Atlantic Region (Table 2 & Fig. 2C and G). The management effect was not significant. The interaction of solar panels and management was significant for the number of plant species interacting with pollinators (Table 2). This interaction was explained by a management – dependent panel effect (Fig. 2 D and H). The grazing effect on plant species attracting pollinators was positive Outside and Between panels but negative Under panels (Fig. 2 H).

4. Discussion

In our study on twenty solar parks in Southern France, solar panels significantly reduced the total abundance of pollinators, the number of plant-pollinator interactions, the number of plant-wild bee and plant-hoverfly interactions, the number of links between one plant species and one pollinator species and the number of plant species attracting pollinators. In contrast to our expectations, grazing negatively affected pollinator abundance and plant-pollinator interactions compared to mowing. The panels effect was not influenced by management except for the number of plant species in interaction with pollinators.

4.1. Solar panels negatively affect pollinators

Our results confirmed the first hypothesis and demonstrated that the effects of solar panels was particularly strong, with a decline of >77 % of pollinator abundance and 86 % of plant-pollinator interactions under solar panels compared to controls Outside. This strong reduction in pollinator abundance and activity under solar panels confirms the results of Menta et al. (2023) on hymenopteran species in northern Italy and of Graham et al. (2021) on pollinator abundance in general. Solar panels reduce solar radiation and air temperature during daytime (Adeh et al., 2018; Graham et al., 2021). These microclimatic effects change the pollinator abundance since pollinators avoid shaded and low temperature conditions (Herrera, 2010; Kilkenny and Galloway, 2008). Furthermore, solar panels affect pollinators indirectly through effects on plant communities (Lambert et al., 2023) including plant species composition, floral traits, flower density and phenology (Atlan et al., 2015; Zhao et al., 2012).

At landscape scale, the solar panels may create a physical barrier for the movement of sedentary butterflies (Grodsky et al., 2021; Guiller et al., 2017). The sensitivity of butterfly abundance to high quality habitats and species richness has already been demonstrated (Krämer et al., 2012) and flying butterfly abundance was not affected in inter-row plots compared with plots outside panels. This results suggests that there is no effect of inter-rows (Between) on the number of interacting plant species richness but the number of interactions was still lower than outside panels because plants were are less abundant (Blaydes et al., 2024; Lambert et al., 2023).

We observed a stronger effect of solar panels on plant-pollinator interactions than on pollinator abundance. One explanation could be that plant cover and diversity are lower under solar panels concentrating pollinators on fewer flowers (Lambert et al., 2023). Furthermore, the permanent shade of solar panels may lead to pollen limitation of female reproductive success in these flowers (Ushimaru et al., 2021) and to a negative effect on nectar production (Lambert et al., 2021; Villarreal and Freeman, 1990). Panel shading also affects soil moisture and temperature potentially reduces nectar secretion (Chabert et al., 2020; Wyatt et al., 1992). If nectar and pollen production are lower under solar panels, pollinators that nest on the ground (wild bees) or lay eggs on plants (butterflies, hoverflies) may be less attracted to areas under solar panels. The areas affected by solar panels are gradually becoming exclusion zones for nesting or egg-laying, but also for nectar and pollen feeding. Finally, the shading and lower visibility of plants under solar panels may directly affect pollinator visitations. Shade and cover of neighboring plants are known to reduce pollinator visits and reproductive success of plants (Ushimaru et al., 2021). Neighboring plants reduce the availability of light, water, and nutrient resources and consequently decrease the biomass and reproductive performance (the number of flowers, fruits, and seeds) of a given plant (Aschehoug et al., 2016).

4.2. Panel effects are robust across different pedoclimatic regions

As expected, the Mediterranean region showed a higher abundance of pollinating insects and more plant-pollinator interactions than the Atlantic region. The Mediterranean is a hot spot of plant diversity providing more niches for insects (Gómez-Martínez et al., 2022). The higher temperatures and lower rainfall during the flowering season may also directly increase pollinator abundance (Balzan et al., 2020; Herrera, 2010; Thompson, 2020). However, we did not observe strong region x panel interactions showing that the effects of solar panels are consistent over large pedoclimatic gradients.

4.3. Grazing negatively affects pollinators independent of solar panels

Solar parks are usually managed by mowing and/or grazing, and management type most likely affects pollinator communities. However, the effect of solar park management on pollinators has rarely been studied. Here, we showed that the effect of grazing on pollinator abundance and plant-pollinator interactions is negative compared with mowing. This is not in agreement with our hypothesis that grazing has a positive effect on pollinator abundance. Lázaro et al. (2016) and Tonietto and Larkin (2018) showed variations in the abundance of wild bees and hoverflies depending on grazing intensity and period. Contrary to our third hypothesis, the effect of management did not depend on solar panels. However, we could only analyze two management features without testing management intensity, future studies need to integrate different levels of grazing and mowing intensity to compare management strategies. Furthermore, sheep spend often more time in solar parks than in natural rangeland and grazing may be different under and outside panels (Kampherbeek et al., 2023). This higher intensity of grazing in solar parks compared to mowing leads to limited food resources and the destruction of nesting sites (Davidson et al., 2020; Kearns et al., 1998).

4.4. Future studies may help to understand how to mitigate negative solar panel effects

Our results suggest that solar panels may strongly reduce the ecological function of pollination. However, we estimated pollination using the number of plant-pollinator interactions rather than specific measurements of pollination success, that would be required to more precisely evaluate the pollination function (Bartholomée and Lavorel, 2019; Vázquez and Aizen, 2004). Using standard plants as pollination indicators ("pollinometers") may help to address this gap by comparing the reproductive success of flowers exposed to open pollination with those excluded from pollinator visitation (Albrecht et al., 2012; Theodorou et al., 2017). Due to the high magnitude of the observed effect, we still suggest that solar panels strongly change pollination. In order to evaluate this effect on pollination and to obtain species-specific responses, interactions between plants and pollinators need to be analyzed at species level. Blaydes et al. (2021) suggest that the microclimatic conditions created by solar panels provide niches and shelter that benefit pollinators. Partial shading by solar panels delays floral phenology potentially benefiting late-season foragers in water-limited ecosystems (Graham et al., 2021). A more detailed study of the interactions between pollinator and plant species would improve our understanding of the solar panel effects on community structure, and on the pollination function beyond a reduction in pollinator abundance.

Due to the highly negative effects of solar panels, the planned increase in solar park construction in Europe represents a new threat to pollinators. These impacts must be mitigated by pollinator-friendly management of solar parks, or else compensated for to ensure no net loss of pollinator biodiversity. However, a BACI (Before After Control Impact) study and comparison with reference sites are needed to assess the impact of solar park construction, including vegetation removal and soil disturbance. Increasing inter-row width or panel height are technical solutions that may reduce negative panel effects and improve pollinator conservation in solar parks. Ecological restoration techniques, such as increasing and diversifying floral resources, may complement these technical adaptations (Blaydes et al., 2024; Blaydes et al., 2022; Lambert et al., 2022). Solar parks management, particularly grazing practices, should better respect the flowering periods or even be shifted to autumn to minimize impacts on pollination (and fructification). Avoidance of natural or semi-natural habitats may further help to mitigate negative effects of solar parks and panels. Bigard et al. (2020) highlight the importance of strategic planning at landscape level for effective mitigation and a better integration of biodiversity in solar park construction. An improved understanding of solar park effects at park and landscape scale may help to develop ecovoltaic parks (Tölgyesi et al., 2023), that not only reduce negative effects on biodiversity but also enhance ecological functions, in particular if solar parks are constructed on degraded habitats.

CRediT authorship contribution statement

Arnaud Lec'hvien: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Louison Bienvenu:** Writing – review & editing, Investigation, Data curation. **Francis Isselin-Nondedeu:** Writing – review & editing, Methodology, Formal analysis. **Armin Bischoff:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Raphaël Gros:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Bertrand Schatz:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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