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Research Article

Climate change reduces pollination services and sunflower yields across Europe and Northern Africa

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ABSTRACT

Sunflower (*Helianthus annuus*) productivity is highly dependent on pollinators, yet the effects of climate on pollination services and crop yield remain poorly understood. In this study, we investigate how temperature gradients influence flower-visiting communities, pollination services, and sunflower productivity across Europe and Northern Africa. We conducted standardized two-year (2022 and 2023) pollination exclusion experiments across 36 sunflower fields spanning a broad climatic gradient, from temperate regions in Slovenia to arid conditions in Algeria. We found that sunflower production (seed set, seed number, and oil content) relied heavily on insect pollination. However, this benefit declined with rising temperatures, likely due to the observed decreases in wild pollinator diversity at high temperatures. Integrating these results with climate change projections suggests that southern Europe and northern Africa may soon face severe losses of pollination-mediated sunflower yield. Climate-driven reductions in pollination services pose a major risk to sunflower production in warm regions. These findings highlight the urgent need for pollinator conservation measures and the promotion of climate-resilient agricultural strategies to safeguard pollination services and ensure sustainable sunflower production under a warming climate.

Introduction

Animal pollination is crucial for the reproduction of most flowering plants (Rodger et al., 2021) and supports the yield of approximately 75% of global crops (Dicks et al., 2021; IPBES, 2016; Klein et al., 2007), contributing to 35% of global food production (Tscharntke, 2021). The economic value of these pollination services is estimated to range from US$ 195 to US$ 387 billion annually (Gallai et al., 2009; Porto et al., 2020). Insects, and bees in particular, are documented as the most important crop pollinators globally (Garibaldi et al., 2013; Requier et al., 2023). However, pollinator populations are in significant global decline due to habitat loss, widespread agrochemical use, and accelerating climate change (Delphia et al., 2022; Goulson et al., 2015; Koh et al., 2016; Potts et al., 2016; Vanbergen & the Insect Pollinators Initiative, 2013). This decline poses a growing threat to the productivity and economic viability of pollinator-dependent crops (Dicks et al., 2021; Potts et al., 2010).

Crop–pollinator interactions and the associated pollination services emerge from the interplay among plant reproductive traits, pollinator behaviour, and the timing of flowering relative to pollinator activity (Burkle & Alarcón, 2011). Temperature is known to simultaneously affect plants and pollinators. Heat can reduce plant reproductive success by lowering pollen viability and fertility regardless of the presence of pollinator (Rosenberger, 2024). Additionally, it can alter pollinator behaviour and activity patterns, influencing when and where they forage (Hegland et al., 2009; Stevenson et al., 2022). Warming may also

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shift the phenology of plant flowering and pollinator activity, leading to mismatches that reduce pollination success (Gérard et al., 2020; Peng et al., 2025). Despite these known mechanisms, how such changes translate into differences in pollination services and crop yield remains poorly understood across climates and crop systems.

In this study, we focus on sunflower (Helianthus annuus), a widely cultivated oilseed crop of global importance, particularly in Europe, where it is a primary source of edible oil (OECD/FAO, 2020). While multiple factors, including climate-driven changes in agroecological conditions such as shortened growth cycles and increased water requirements, may limit future productivity (Agüera & de la Haba, 2021; Gurkan et al., 2020; Kephe et al., 2024), sunflower production is also strongly enhanced by insect-mediated pollination (Bartual et al., 2018; Klein et al., 2007), particularly by honey bees and wild bees (Greenleaf & Kremen, 2006; Requier et al., 2023; Zaragoza-Trello et al., 2023). Experimental and field studies have shown that reduced pollination leads to measurable declines in sunflower seed set, reduced seed mass, and decreased overall production (Amarilla et al., 2025; Holland et al., 2020). Given the links between warming and pollinator declines, it remains unclear whether long-term temperature gradients are associated with variation in pollination services and potential deficits.

To address this gap, we conducted standardized flower visitor observations, pollination experiments, and sunflower production assessments across a climate gradient spanning four European countries (France, Croatia, Slovenia, Greece) and one North African country (Algeria) over two years (2022–2023). We examined how flower-visiting communities relate to local temperature measured during observations and how sunflower production metrics, i.e., seed set success, number of developed seeds (used here as a proxy for yield), and oil content, vary along gradients of long-term temperature derived from WorldClim (30-year averages; Fick & Hijmans, 2017) under different pollination treatments. We hypothesized that (1) higher local temperatures would alter the abundance and diversity of pollinator communities visiting sunflowers; and (2) sunflower production would vary along long-term temperature gradients, with warmer conditions associated with reduced seed set success, number of developed seeds, and oil content. Where significant associations between temperature and pollination services were detected for a given production metric, we projected the contribution of animal-mediated pollination to that metric under future climate scenarios.

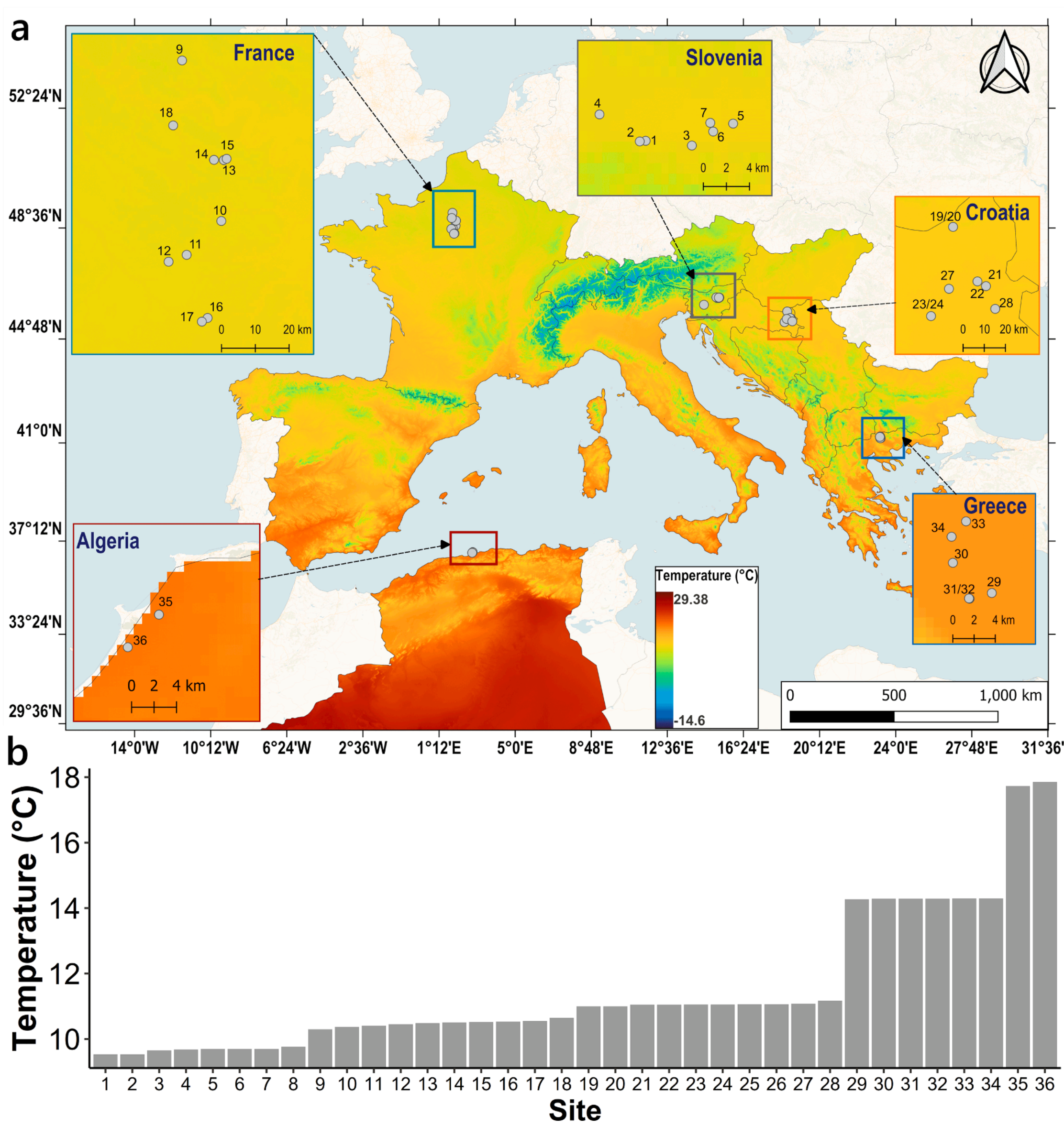

Fig. 1. Location of the study area (a) and the climatic gradient for the study sites (b). The background image is temperature as projected in 2011-2040 under the sustainable climatic scenario SSP 1-2.6. The light blue color is the ocean water extent.

Materials and methods

Study sites

The study was conducted over two consecutive years (2022 and 2023) in 36 sites distributed across four European countries (France, n=10; Slovenia, n=8; Croatia, n=10; Greece, n=6) and one North African country (Algeria, n=2; Fig. 1a). Each site represented a commercial sunflower field selected to capture a broad climatic gradient, ranging from temperate regions in Slovenia, which had the lowest mean temperatures, to arid conditions in Algeria, where the highest temperatures were recorded (Fig. 1b). To minimize spatial autocorrelation and ensure the independence of observations, all sites were located at least 5 km apart. Information on sunflower variety was not documented; however, all pollination treatments (exclusion, open, and open plus hand pollination) were applied within the same field to ensure comparability of results across treatments. Long-term temperature data for each site was extracted from the 30-year climatological averages available in WorldClim v2 (Fick & Hijmans, 2017).

We used climate projection data from CMIP6 models (Beck et al., 2023), to investigate spatial variation in pollination services under different climatic scenarios. Specifically, we projected near-future conditions for 2040 under a low-emission scenario (SSP1-2.6), representing a sustainable development pathway, and long-term conditions for 2100 under a high-emission scenario (SSP5-8.5), representing a fossil-fueled climate projection. Projections were based solely on temperature gradients and did not incorporate surrounding landscape variables. To avoid extrapolation beyond the empirical data, predictions were restricted to temperature ranges represented within the study locations.

Flower visitors' data

At each study site, 100 m transects within a fixed 1 m-wide box were established both inside and in adjacent habitats (outside transects) to monitor flower-visiting insects four times during the blooming period per year. Outside transects originated at the edge of the sunflower field and extended 100 m into the surrounding non-cultivated areas. In the outside transects, all flowering plants along the 100 m transects were first identified using the PlantNet mobile app (Goëau et al., 2013) to document floral resources available in the surroundings of sunflower fields. Subsequently, insect flower visitors were observed for 5 minutes at a steady pace along the transects. Flower visitors were classified into seven groups (Requier et al., 2023): honey bees, bumble bees, other bees, beetles, hoverflies, butterflies, and other flower visitors. The local temperature was recorded using a portable anemo-thermo-hygrometer device (Skywatch Atmos). In total, 142 transect surveys were conducted in both years, with 71 surveys inside sunflower fields and 71 in the surrounding habitats. Although we monitored the flower-visiting communities in adjacent non-cultivated habitats extending 100 m from the edge of the sunflower fields, we did not incorporate this data into the analyses as they were too restrictive to accurately describe the surrounding landscape.

Pollination experiments

At each study site, five sunflower plots were selected within the field, with a minimum distance of 20 m between them. Within each plot, three sunflower heads were assigned to one of three pollination treatments: (1) Pollinator exclusion (E): heads were enclosed in fine mesh bags (0.8 × 0.8 mm) to prevent access by pollinators. This treatment allows the assessment of geitonogamous self-pollination, i.e., pollen transfer between flowers of the same plant, and establishes the baseline seed set in the absence of insect visitors; (2) Open pollination (O): heads were left exposed to natural pollinators without interference; and (3) Open pollination with hand pollination (OH): heads received both natural and supplemental hand pollination. For the OH treatment, pollen was collected from 50 sunflowers in the same field on the same day as the experiment. The pollen was stored in a tube and applied to the stigmas of open flowers using a fine paintbrush. Hand pollination was conducted four times, at two- to three-day intervals, to ensure sufficient coverage of the flowering period. Hand pollination is commonly used in agriculture to supplement pollinators but requires skill and can be costly at larger scales (Wurz et al., 2021). In total, 550 sunflower heads were monitored across the three treatments.

Seed set success and number of developed seed (yield)

Upon maturity, sunflower heads were harvested and dried at 60°C for 48 hours to reduce moisture content before threshing to separate filled seeds from empty hulls. Achenes were classified as either 'fully developed' or 'empty' (containing only the embryo sac). Filled seeds were counted using a Contador Pfeuffer optical seed counter (PFEUFFER GmbH) and weighed to determine the number and mass of seeds per head. Oil content was determined by Pulsed Magnetic Resonance Analyser MQA7005 (Oxford instruments). The number of developed seeds per sunflower head was used as a proxy for yield, given the strong positive correlation between seed number and seed weight in sunflower (Radić et al., 2013). Pollination services were quantified as the difference between open pollination and pollinator exclusion treatments (O - E), while pollination deficit was calculated as the difference between open pollination with hand pollination and open pollination (OH - O). In total, sunflower production metrics were quantified from 550 harvested sunflower heads.

Statistical analysis

To examine the relationships between local temperature and pollinator communities, and between long-term temperature (climatic averages) and sunflower production metrics, all analyses were conducted in R (R Core Team, 2024). Generalized linear mixed models (GLMMs) were chosen for their flexibility in handling complex data structures and incorporating random effects to account for variability within groups (Madden & Ojiambo, 2024) and were implemented using the *glmmTMB* package (Brooks et al., 2017). In total, five response variables were analysed: (1) pollinator abundance, (2) pollinator group richness, (3) oil content, (4) seed set success, and (5) number of developed seeds (used as a proxy for yield).

For pollinators, we analyzed the association of local temperature, visitor group, transect type (inside vs. outside sunflower fields), year (2022 and 2023), and their interaction (explanatory variables) on flower visitor abundance and pollinator group richness (response variables) using a GLMM with a Poisson error distribution. To further explore differences in pollinator community composition between transect types, we conducted Non-Metric Multidimensional Scaling (NMDS) based on Bray-Curtis dissimilarities using the *metaMDS* function from the *vegan* package (Oksanen et al., 2025). Site and species scores were extracted using the *scores* function and visualized to assess compositional differences between inside and outside transects.

For sunflower production metrics, seed set success, number of developed seeds (yield), and oil content were modelled as response variables, with long-term temperature, year, treatment, and the interaction between temperature and treatment included as explanatory variables. Seed set success was calculated as the proportion of developed achenes relative to the total number of achenes (developed plus empty) and modeled using a binomial GLMM with the *cbind*(developed, empty) function. The number of developed seeds (yield) and oil content were modeled using linear mixed models (LMM) with Gaussian error distributions. All models included plots nested within sites and sites nested within regions as random effects.

Each model underwent a systematic evaluation process. The significance of predictors was assessed using Type II Wald chi-square tests implemented via the Anova function in the car package (Fox et al., 2024). Model assumptions were assessed using the *DHARMa* package (Hartig, 2024), which included visual inspection of residuals, testing for overdispersion with *testDispersion* function, and checking for zero-inflation with *testZeroInflation* function. No models showed evidence of overdispersion or zero-inflation, indicating that model assumptions were adequately met. Post hoc analyses (Tukey's HSD) were conducted only for models in which temperature or its interaction terms were significant. In such cases, the ggpredict function from the ggeffects package (Lüdecke, 2025) was used to estimate marginal effects. No post hoc analyses or predictions were conducted when temperature effects were not significant.

For spatial projection, animal-mediated pollination contribution to sunflower yield (number of developed seeds), model predictions were restricted to the temperature range observed across the study sites (9–18°C) to avoid extrapolation beyond the empirical data. Areas with projected temperatures below 9°C or above 18°C for both the near-future (2040) and future (2100) scenarios were therefore masked prior to prediction (Fig. 1b). To evaluate the robustness of the spatial projections, average predicted sunflower yield attributable to pollination per country was compared with long-term national yield averages (2011–2021) from FAO (FAOSTAT, 2025) using a Pearson correlation analysis with the *cor.test* function in the *base* package.

Results

Sunflower visitors' abundance and pollinator group richness

Our GLMM analysis showed that the flower visitor abundance differed significantly among visitor groups and across transects, with strong interactions between visitor identity and temperature as well as transect and temperature (Table S1). Only insects were observed as flower visitors and bar plots distribution showed that honey bees were consistently the most abundant taxon both inside sunflower fields and in surrounding habitats (Fig. 2).

Generally, flower visitor abundance was markedly higher within sunflower fields compared to the surrounding areas (Fig. 3a). In contrast, pollinator group richness was greater outside the fields than within (Fig. 3b), highlighting spatial variabilities in pollinator communities. Non-metric Multidimensional Scaling (NMDS) analysis revealed distinct species compositions between inside and outside of the sunflower field (Fig. 3c). Honey bees and bumble bees were predominantly associated with the sunflower fields, while other pollinator groups were exclusive to the surrounding habitats. With increasing temperature, flower visitor abundance slightly increased within sunflower fields but declined marginally in the surrounding habitats (Fig. S1).

Sunflower seed set success, number of developed seeds (yield), and oil content

Seed set success was significantly influenced by pollination treatment and its interaction with temperature (Table S2a). Seed set success was lowest under pollinator exclusion (E), while both open pollination (O) and open plus hand pollination (OH) showed higher values (Fig. S2a). Sunflower yield (number of developed seeds) was influenced by temperature, pollination treatment, and the interaction between these factors (Table S2b & Fig. S2b). Yield was consistently lowest under exclusion and highest under open pollination but declined with increasing temperature across all treatments, with a stronger decline observed under O and OH compared to exclusion (Fig. S2b). Oil content was influenced only by pollination treatment (Table S2c).

Post-hoc Tukey's HSD tests revealed distinct patterns across the three-yield metrics measured. For seed set rates, all three pollination treatments showed significant differences (Fig. 4a). Seed set under pollinator exclusion (E) averaged approximately 68%, compared with 87% in open pollination (O) and 89% in open plus hand pollination (OH). For developed seed number (Fig. 4b), the exclusion treatment produced an average of 809 developed seeds, which was substantially lower than both O (1269) and OH (1241). These differences between treatments were statistically significant, as indicated by distinct Tukey HSD groupings (Fig. 4a & b). For oil content (Fig. 4c), the exclusion treatment (E) differed significantly from open pollination (O), but no significant difference was found between exclusion and open plus hand pollination (E *vs.* OH; $p=0.53$). Across all metrics, the exclusion treatment consistently yielded the lowest values, underscoring the crucial role of insect pollinators in enhancing sunflower yield.

Pollination effectiveness declined with increasing temperatures, as both seed set (Fig. 4d) and developed seed counts (Fig. 4e) decreased at higher temperatures. This suggests that pollination services are more effective under cooler conditions. The pollination deficit was not significantly influenced by any of the factors (Fig. S3a & S3b).

Spatial predictions of pollinator contributions to sunflower seed count per head reveal substantial variability across the study region under both near-future and future climate scenarios (Fig. 5). These projections were derived by applying model relationships to gridded climate data and were restricted to the temperature range observed across the study sites (9–18°C) to avoid extrapolation beyond the empirical data (see Methods). At near-future (2040), contributions are highest in northern regions and progressively decline toward southern areas (Fig. 5a). Under the future (2100) high-emission projected climatic scenario, animal pollination contributions decrease markedly, rendering much of southern Europe and the Mediterranean increasingly unsuitable

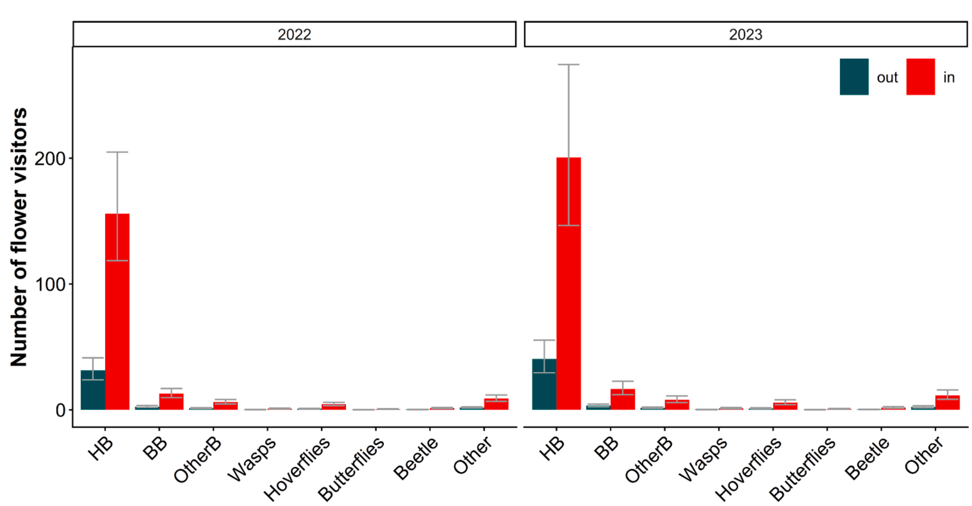

Fig. 2. Distribution of observed pollinator community composition per transect (in and out) per year. HB=Honeybees, BB=Bumble bees and OtherB=solitary bees.

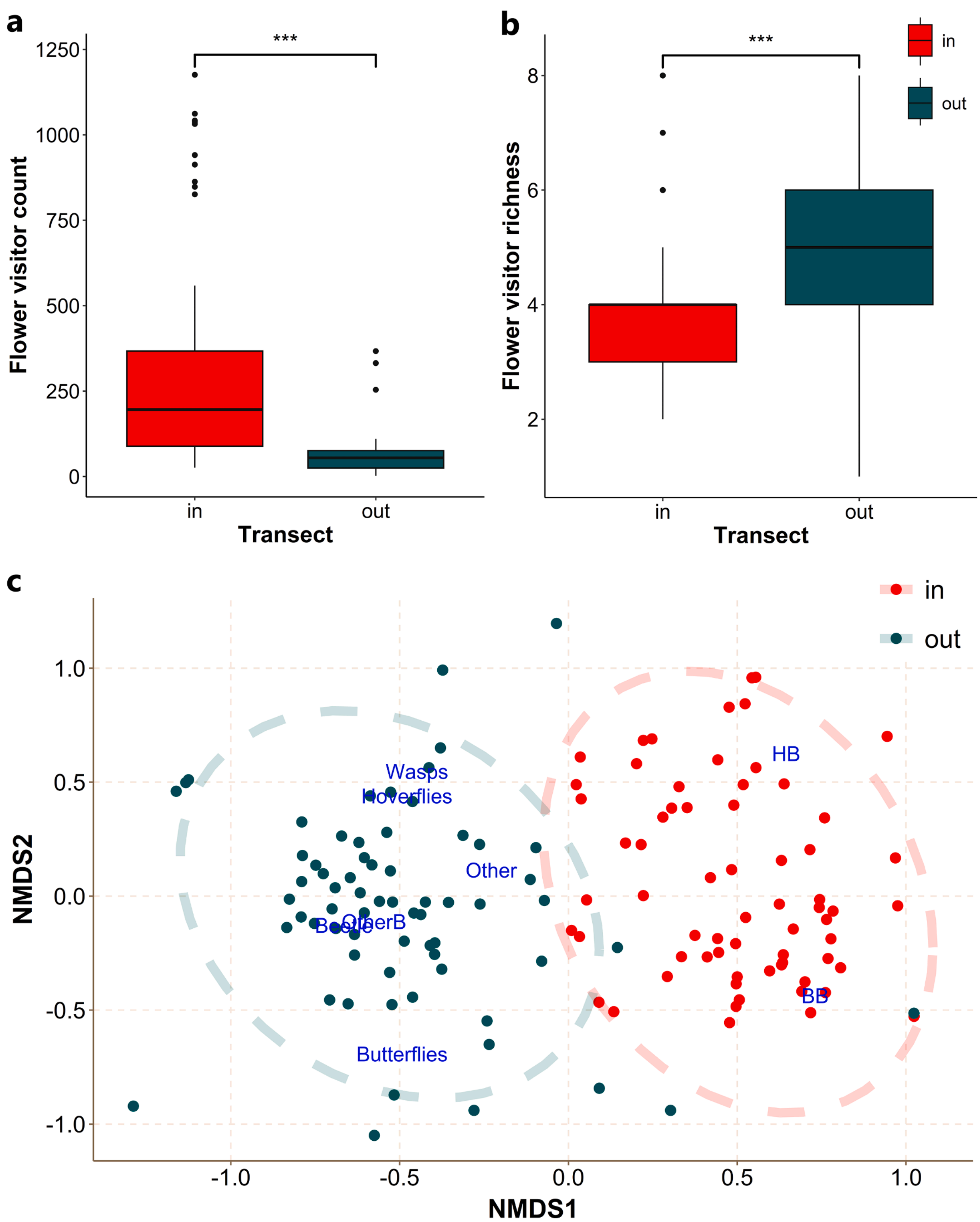

Fig. 3. Distribution of flower visitors abundance (a) and richness (b) inside and outside the sunflower fields. c) is the Non-metric MultiDimensional Scaling (NMDS) analysis showing where various species are found. Honey bees (HB) and bumble bees (BB) were more dominant inside the sunflower fields while other species dominated outside the fields.

for sunflower production (Fig. 5b).

Correlation analysis of predicted sunflower yield, averaged at the country level and compared with FAO long-term averages (2011–2021), revealed a significant positive relationship (Spearman's $\rho=0.59$, $p<0.01$; Fig. 6). This demonstrates a robust reliability of our predictions, effectively capturing the trends observed in historical data, and supporting their potential utility for future forecasting and decision-making in agricultural planning.

Discussion

This study assessed the combined effects of animal pollination and temperature on sunflower production across a climatic gradient from Northern Africa to Europe. Over two years and across 36 field sites, we found that sunflower production (quantified by seed set success, number of developed seeds (yield), and oil content) was strongly dependent on insect pollination. However, the magnitude of pollination benefits declined with increasing temperature. We also found that flower visiting insects were more abundant inside the sunflower fields, but pollinator group diversity was higher in adjacent habitats outside the crop fields.

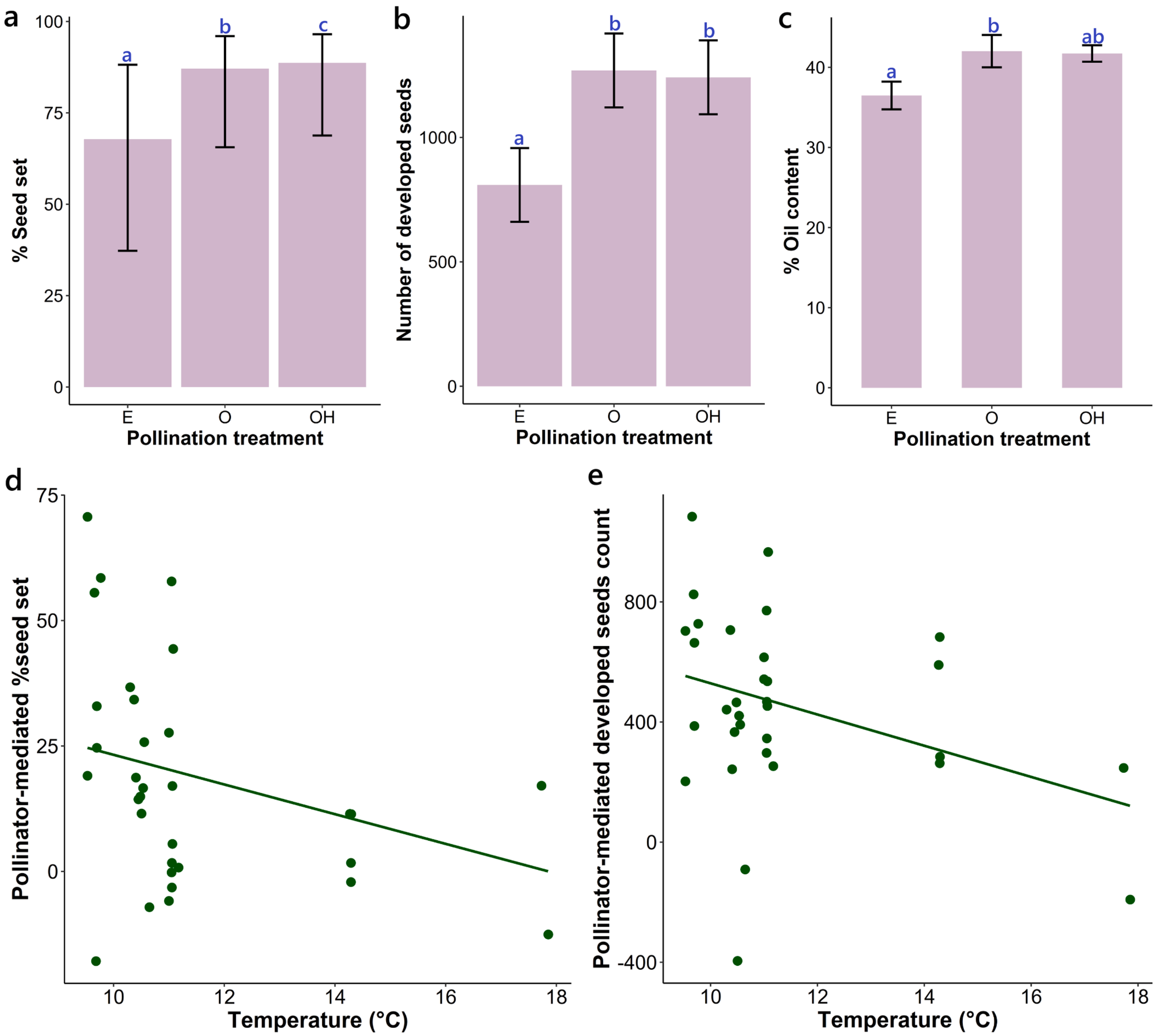

Fig. 4. Distribution and variability of sunflower seed set (a), number of developed seeds (b), and oil content (c), and temperature effects on pollinator-mediated seed set (i.e. difference between open pollination and excluded pollination treatments) (d) and pollinator-mediated developed seeds count (e). In a, b and c, thick lines represent the 95% confidence intervals (based on GLMM predictions) and letters within the bar plot indicate the results of pairwise comparisons between treatments. In d and e, thick lines show the GLMM predictions.

Sunflower yields are strongly enhanced by animal pollination, especially by insects (Lajos et al., 2021; Mota et al., 2024). In our study, pollinator-exclusion treatments resulted in an average seed set of approximately 68%, indicating that self-pollination (geitonogamy) can sustain a baseline level of reproductive success. However, this was substantially lower than seed set under open pollination (87%) and open plus hand pollination (89%), demonstrating that insect visitors contribute to improve sunflower yield. Similar patterns have been reported in other regions. In Argentina, insect-mediated pollen deposition enhanced sunflower yield (Chamer et al., 2015), and pollinator exclusion reduced seed set by ~20% and total production by ~30% (Amarilla et al., 2025), highlighting the importance of insects even in self-fertile cultivars. A study in France found that insect pollinators increased sunflower yields by up to 40% (Perrot et al., 2019). Additionally, insect pollination has been linked to higher oil content in sunflower seeds (Mallinger & Prasifka, 2017), underlining both its economic and agronomic importance.

Recent national-scale estimates illustrate the broader economic importance of insect pollination: in France, the total economic value of insect pollination in 2022 was €4.2 billion, with 12% of national crop production dependent on pollination and the southern and western departments identified as the most vulnerable to pollinator decline (Blili et al., 2025). In our study, we detected no pollination deficits, consistent with earlier results from sunflower fields in France (Chabert et al., 2022). While our results suggest that current pollinator populations are sufficient to support optimal sunflower productivity in our study regions, moderate deficits have been observed elsewhere in Europe (Holland et al., 2020). Therefore, conserving pollinator-friendly habitats is essential to safeguarding these ecosystem services under increasing environmental pressures (IPBES, 2016).

Honey bees emerged as the most abundant pollinator in our study sites (regardless of country or temperature gradient), a finding consistent with global evidence highlighting their key role in pollinating sunflower crops (Cerrutti & Pontet, 2016; Lajos et al., 2021; Susic Martin

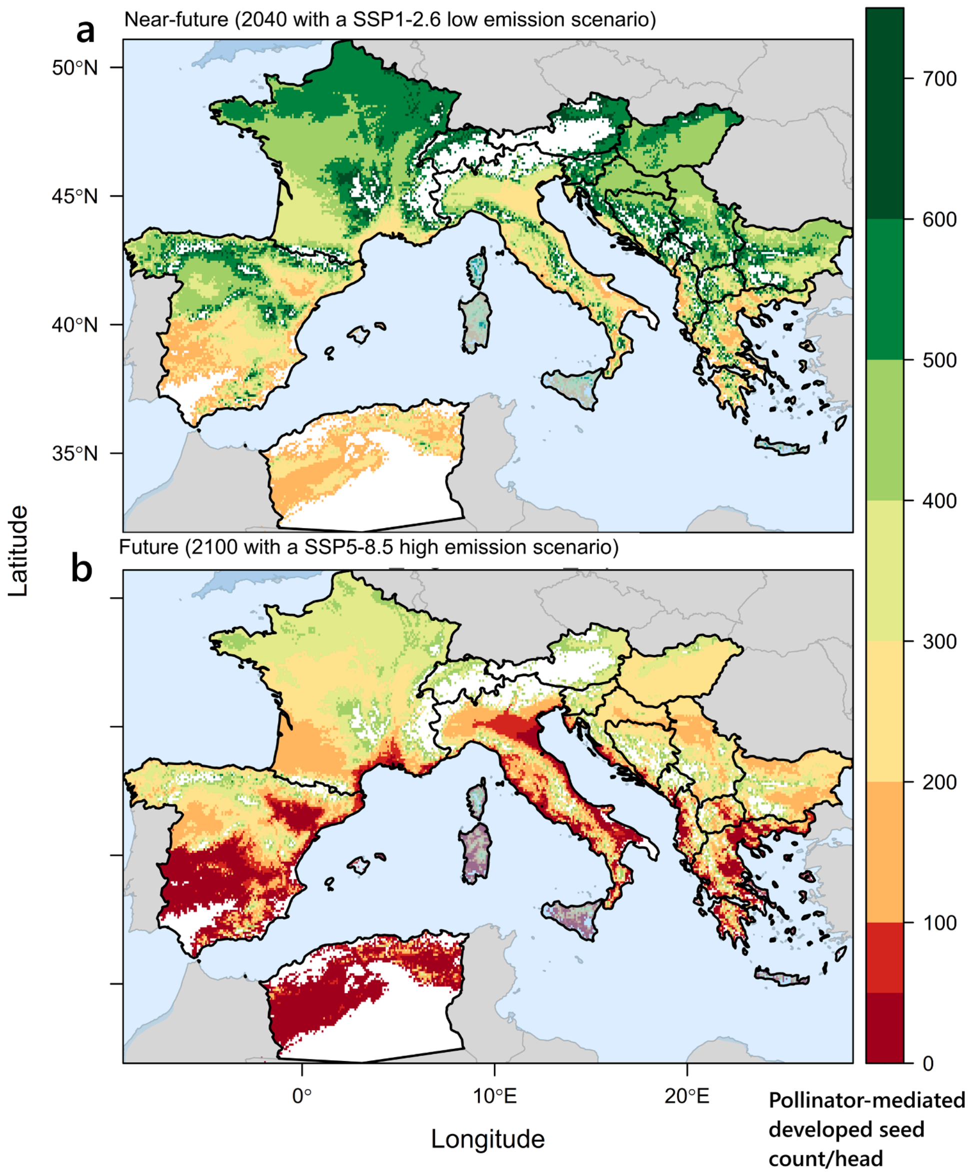

Fig. 5. Spatial predictions showing the contribution of animal pollination to sunflower yield (i.e. pollinator-mediated developed seeds count per head) under near-future (2040 with a SSP1-2.6 low-emission scenario) (a) and future (2100 with a SSP5-8.5 high emission scenario) (b) climatic conditions under the fossil-fueled high emission climatic projections pathways. The color gradient indicates the predicted seed count, ranging from low (red) to high (green). White areas represent regions with mean temperatures outside the observed range of the study sites (9–18°C), which were excluded to avoid extrapolation beyond the model's training data.

& Farina, 2016). Their high abundance is likely influenced by the presence of apiaries of honey bees in the surrounding of the study sites, potentially related to migratory beekeeping practices, where managed hives are brought into or near sunflower fields during the flowering period to optimize honey production while also supporting crop pollination (Charrière et al., 2010; Pilati et al., 2016). However, we did not get data on the location and the number of beehives in the study areas. Honey bees also have sophisticated social foraging strategies such as the waggle dance (Shackleton et al., 2023), which helps them to quickly mobilize nestmates to rich floral patches. While honey bees dominated overall visitation, other pollinator groups contributed more to community diversity, particularly in adjacent habitats. This greater diversity outside sunflower fields likely reflects the availability of semi-natural habitats, which provide a wider range of nesting sites and floral resources compared to monoculture crops. Similar patterns of elevated pollinator diversity at field margins declining towards the crop interior have also been documented in Hungary (Lajos et al., 2021) and Central California (Sardiñas et al., 2016).

In terms of temperature effects on pollinator communities, our findings reveal contrasting responses among flower-visiting insects. Inside the sunflower fields, where honey bees and bumble bees dominated, abundance increased with rising temperatures, whereas outside the sunflower field, the abundance of more diverse pollinator groups declined slightly, similar to patterns observed in Tanzania (Classen et al., 2015). Diverse communities of managed and wild pollinators are known to enhance pollination efficiency in both global crops (Reilly et al., 2024) and sunflower systems (Lajos et al., 2021). Comparable trends are projected elsewhere, such as in Brazil, where pollinator diversity in nut crops is predicted to decline by 20% under future climate scenarios, leading to productivity losses despite a projected 6% increase in suitable cropping areas (Sales et al., 2021). The observed small reduction in non-honey bee pollinators under warmer conditions (based on their abundance outside sunflower fields) may partly explain why, despite higher honey bee numbers, pollinator-mediated seed set and yield declined with increasing long-term temperatures. However, variation in floral resources and surrounding landscape context, which were

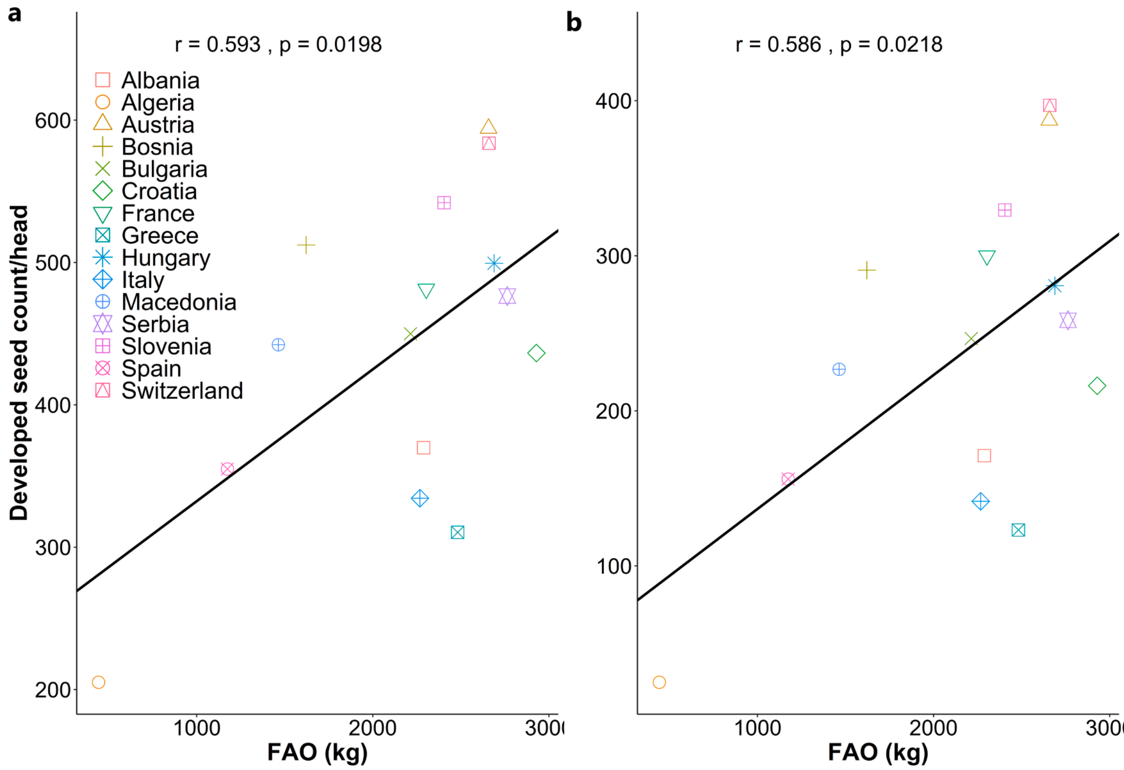

Fig. 6. Correlation between predicted pollinator-mediated sunflower seed counts per head and FAO national yield averages (2011–2021) under current low-emission (a) and future (b) high-emission climate scenarios. The black line represents the linear regression fit. Different shapes and colors denote individual countries.

not assessed in this study, may also have influenced these patterns. Therefore, we encourage future studies to investigate whether the surrounding landscape can influence pollinator communities, and whether it can mitigate or exacerbate the effects of climate change. Preserving floral resource diversity and promoting structurally heterogeneous landscapes, alongside integrated pollination management strategies, may be critical for sustaining pollinator communities and buffering pollination services against the adverse effects of climate warming (Isaacs et al., 2017; Vanderplanck et al., 2019).

Our spatial projections suggest that Northern Europe currently experiences greater pollination benefits than Mediterranean and southern European regions. However, under a high-emission climatic scenario (SSP585) projected for 2100, large areas of Southern Europe and the Mediterranean may become unsuitable for sunflower production, while Northern Europe could also face significant yield declines. The strong correlation (≈60%) between our spatial projections and FAO-derived yield estimates supports the reliability of these findings, suggesting that temperature is a key driver of pollination outcomes. However, these projections are correlative and do not account for potential confounding factors such as local soil conditions, farm management, landscape composition, or cultivar differences, which may also influence pollination and yield. Identifying climate-vulnerable areas can guide targeted interventions, including habitat conservation, promotion of pollinator-friendly landscapes, strategic placement of managed hives, and adoption of climate-resilient sunflower varieties. Considering multiple climate scenarios may further help stakeholders anticipate a range of possible outcomes and develop adaptive management strategies to safeguard pollination services and maintain sunflower productivity under future climate change.

Although our results reveal clear correlative associations between long-term temperature and pollination benefits, the observed patterns may be also linked to other country-level variables such as soil characteristics, irrigation, pesticide use, farm management, landscape composition, the presence of beehives, and variation in sunflower cultivars. Future studies should explicitly design experiments that disentangle the effects of these variables, both by testing their correlations with pollinator communities and pollination outcomes, and by investigating the physiological and ecological mechanisms through which they may interact with temperature to influence yield. Moreover, the causal links underlying the effect of temperature on pollination can involve a shift of flowering phenology and desynchronization with the phenology of pollinators (Fisogni et al., 2025; Peng et al., 2025), a decrease in floral rewards such as nectar quantity and sugar content (Alquichire-Rojas et al., 2024; Arrowsmith et al., 2025), and a heat stress that reduces or modifies pollinator foraging (Arrowsmith et al., 2025; Chang et al., 2024). Future work combining controlled temperature manipulations with explicit data on cultivar identity, floral resource dynamics, and landscape context, alongside detailed behavioral and physiological observations of pollinators will be needed to disentangle these mechanisms and refine predictions of how climate warming may reshape pollination services and sunflower yields.

Conclusion

This study illustrates the crucial role of insect pollinators in supporting sunflower productivity and highlights the growing risk that rising temperatures pose to this essential ecosystem service. While pollinators significantly enhance seed set and yield, our results show that their contribution diminishes with increasing temperature, identifying temperature as a key driver of pollinator-mediated declines in sunflower production. Although honey bees were the most abundant pollinators and their numbers increased under warmer conditions, pollinator-mediated seed set and yield still declined. This suggests that honey bees alone (given their high abundance inside the sunflower fields) may not be sufficient to ensure optimal sunflower pollination, particularly under warming conditions. Instead, a diverse pollinator community appears crucial for maintaining productivity under changing climatic conditions. Spatial projections under high-emission scenarios (SSP5-8.5) indicate that large areas of the Mediterranean and southern Europe may soon become unsuitable for pollination-dependent sunflower production. These projections, based on contrasting climate scenarios representing both near-future sustainable pathways and high-emission futures, highlight a range of potential outcomes under climate change. To mitigate these impacts, sustainable agricultural and land management practices, including habitat conservation and climate-adaptive strategies are crucial. These findings offer valuable insights for policymakers, emphasizing the urgency of targeted interventions to preserve pollination services and safeguard crop yields in a warming climate. Importantly, these conclusions are supported by standardized field experiments across sites, allowing consistent comparison of pollination responses along temperature gradients.

CRediT authorship contribution statement

Stella Gachoki: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Clémence Riva:** Writing – review & editing, Methodology, Investigation, Data curation. **Danilo Bevk:** Validation, Resources, Investigation, Funding acquisition. **Yamina Haider:** Investigation. **Noureddine Adjlane:** Validation, Resources, Funding acquisition. **Ioannis Manthos:** Investigation. **Bojan Stipešević:** Validation, Resources, Investigation, Funding acquisition. **Zlatko Puškadija:** Investigation. **Marin Kovačić:** Investigation. **Leonidas Charistos:** Investigation. **Fani Hatjina:** Validation, Resources, Funding acquisition. **Fabrice Requier:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, 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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.baae.2026.05.005.

Data availability

The data presented in this manuscript are available through the Zenodo repository at https://doi.org/10.5281/zenodo.19405047

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