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RESEARCH ARTICLE

Climate Change Effects on Pollinator Distribution and Crop Pollination Services

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ABSTRACT

Climate change is altering both the geographic distribution of wild pollinators and the timing of their seasonal activity relative to the flowering of the crops they service, yet few studies have jointly quantified range shift and phenological mismatch for the same pollinator-crop systems under a common climate scenario framework. Here we combined ensemble species distribution models for 46 wild bee species with long-term phenological records (1985-2022) for three insect-pollinated crops, apple, highbush blueberry, and oilseed rape, across 210 agricultural landscapes in Italy, Slovakia, and Sweden, and projected changes in pollinator climatic suitability and pollinator-crop phenological synchrony under RCP4.5 and RCP8.5 for 2041-2070 and 2071-2100. Under RCP8.5 by 2071-2100, the ensemble projected a mean poleward range-centroid shift of 118 km and a mean upward elevational shift of 156 m across the 46 species, with 28 species (61%) losing more than 30% of currently suitable climatic area within the three study regions. Long-term phenological records showed that crop flowering had advanced by a mean of 6.4 days per decade since 1985, while emergence of key wild bee pollinator taxa (*Bombus*, *Andrena*, *Osmia*) advanced more slowly at 3.1 days per decade, producing a measurable widening of pollinator-crop asynchrony that was significantly correlated with reduced fruit and seed set in apple and blueberry orchards ($r = -0.52$, $p < 0.001$). Combining projected range loss with projected mismatch, we estimate that 34% of the pollination-dependent cropland examined faces a moderate-to-high projected pollination service deficit by 2071-2100 under RCP8.5, concentrated in the Mediterranean and continental study regions, with a combined annual production value at risk of approximately EUR 940 million across the three countries. Under RCP4.5, projected range loss and mismatch widening were reduced by roughly half. These findings indicate that climate change poses a spatially heterogeneous but economically substantial risk to insect-pollinated crop production in Europe through the joint mechanisms of pollinator range contraction and phenological desynchronization, and that emissions trajectory materially determines the magnitude of that risk.

Keywords: pollinator range shift; phenological mismatch; wild bees; crop pollination services; species distribution modelling; climate change adaptation; pollination deficit; European agriculture

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1. INTRODUCTION

Animal pollination contributes to the production of roughly three-quarters of the world's leading food crop types by number and underpins an estimated global annual economic value on the order of hundreds of billions of US dollars, with wild bees, managed honey bees, and a range of non-bee insects together providing this service across temperate and tropical agricultural landscapes [1,2,3]. Because pollinator abundance, distribution, and activity timing are all sensitive to temperature and precipitation, anthropogenic climate change is now widely recognised as one of several interacting drivers, alongside habitat loss, pesticide exposure, and disease, contributing to observed declines and range contractions in wild pollinator populations across multiple continents [4,5,6].

Two distinct mechanisms link climate change to pollination service risk. The first is geographic range shift: as climatic conditions suitable for a given pollinator species move poleward and upslope, species with limited dispersal ability or restricted climatic tolerance may fail to track their shifting climate envelope, producing local extirpation from agricultural landscapes that previously fell within the species' suitable range [4,7]. The second is phenological mismatch: because different taxa cue their seasonal timing to different environmental signals and may respond to warming at different rates, the historically close timing between crop flowering and pollinator flight activity can erode even where the pollinator species remains locally present, reducing the effective pollination service delivered during the flowering window [8,9,10].

Most existing studies have examined range shift and phenological mismatch separately, either projecting future pollinator distributions using species distribution models without reference to crop phenology, or documenting phenological advance in plant-pollinator pairs without linking observed asynchrony to a future climate scenario framework or to measured crop yield outcomes [7,11,12]. This separation leaves open the practically important question of where, and to what degree, these two mechanisms jointly threaten pollination-dependent crop production under specific emissions trajectories, information that is directly relevant to regional agricultural adaptation planning [13,14].

Here we address this gap by combining ensemble species distribution modelling for 46 wild bee species with 37 years of phenological monitoring data for three economically important insect-pollinated crops across agricultural regions in Italy, Slovakia, and Sweden, chosen to span a Mediterranean-to-boreal climatic gradient. We project climatic suitability and pollinator-crop phenological synchrony under RCP4.5 and RCP8.5 through 2100, test whether observed phenological asynchrony is associated with measured reductions in fruit and seed set, and combine both projected mechanisms into a regional estimate of

pollination service deficit and associated economic value at risk.

2. MATERIALS AND METHODS

We combined ensemble species distribution models for 46 wild bee species with long-term phenological monitoring records for three insect-pollinated crops across 210 agricultural landscapes in Italy, Slovakia, and Sweden, projected future pollinator climatic suitability and pollinator-crop synchrony under two emissions scenarios, and linked projected mismatch to observed fruit and seed set outcomes and regional crop production value.

2.1 Study regions and pollinator occurrence data

Analyses were conducted across 210 agricultural landscapes (10 x 10 km grid cells containing insect-pollinated cropland) distributed across three study regions selected to span a Mediterranean-to-boreal climatic gradient: central and southern Italy (78 landscapes), the Danube lowlands of Slovakia (64 landscapes), and southern and central Sweden (68 landscapes). Occurrence records for 46 wild bee species from the genera *Bombus*, *Andrena*, *Osmia*, *Lasioglossum*, and *Colletes*, selected for documented contribution to apple, blueberry, or oilseed rape pollination in prior field studies, were compiled from GBIF-mediated national monitoring datasets for 1990–2022, retaining species with a minimum of 40 independent occurrence records after spatial thinning to a 5 km minimum distance between points.

2.2 Species distribution modelling

Current and future climatic suitability for each of the 46 species was modelled using an ensemble of four algorithms (MaxEnt, random forest, boosted regression trees, and generalized additive models) implemented in the biomod2 framework, using CHELSA bioclimatic variables at 1 km resolution and a standard set of six predictors selected by pairwise correlation screening ($|r| < 0.7$) from an initial candidate set of the 19 WorldClim bioclimatic variables plus growing-season length. Ensemble suitability projections were generated under RCP4.5 and RCP8.5 for two future periods, 2041–2070 and 2071–2100, using the mean of five CMIP5 general circulation models. Model performance was evaluated by 10-fold cross-validation using the area under the receiver operating characteristic curve (AUC) and the true skill statistic (TSS), retaining only species models with mean cross-validated AUC greater than 0.75.

2.3 Range shift and suitable-area loss metrics

For each species, projected range shift was summarised as the change in latitude and elevation of the centroid of climatically suitable area between the 1990–2019 baseline and each future period and scenario, and as the percentage change in total suitable area within the three study regions specifically, distinguishing regional suitable-area loss from suitability gained outside the

study regions that would not be accessible to locally established populations within the projection timeframe given typical dispersal distances for these taxa.

2.4 Crop and pollinator phenological monitoring

Crop flowering onset (first open flower, BBCH stage 61) was recorded annually for apple, highbush blueberry, and oilseed rape at 58 long-term phenological monitoring orchards and fields across the three study regions for 1985–2022. Pollinator flight-season onset for the dominant contributing genera at each site (*Bombus*, *Andrena*, *Osmia*) was recorded from standardised transect and pan-trap monitoring conducted at or near the same sites for the overlapping period for which pollinator records were available (1994–2022). Phenological trend was estimated per site and taxon as the slope of a linear regression of day-of-year onset against calendar year, and pollinator-crop asynchrony in a given year was defined as the absolute difference in onset day of year between the crop and its principal pollinator taxon at that site.

2.5 Fruit and seed set sampling

At a subset of 34 apple and blueberry sites with concurrent phenological and yield monitoring, fruit set (the proportion of open flowers developing into mature fruit) was recorded in each of five years (2018–2022) from 20 tagged branches per site following standard protocols, and related to that year's site-level pollinator-crop asynchrony using linear mixed-effects models with site as a random effect.

2.6 Regional pollination service deficit and economic value at risk

A composite pollination service deficit index was calculated for each agricultural landscape and future scenario-period combination by combining (i) the projected percentage loss of locally suitable pollinator climatic area, weighted by the modelled contribution of the affected species to local crop pollination, and (ii) the projected widening of pollinator-crop asynchrony relative to the 1985–2022 baseline, extrapolated using the fitted phenological trends under each scenario's associated regional warming projection. Landscapes were classified as low, moderate, or high projected deficit using tercile thresholds of the index distribution across all 210 landscapes and scenario-periods, and economic value at risk was estimated by applying regional mean crop production values (national agricultural statistics, 2018–2022 average) and published pollination-dependence ratios for apple, blueberry, and oilseed rape to the moderate- and high-deficit cropland area.

2.7 Statistical analysis

Differences in projected range-centroid shift and suitable-area loss between scenarios and periods were assessed by paired Wilcoxon signed-rank tests across species. The relationship between pollinator-crop asynchrony and fruit set was assessed by linear mixed-effects models fitted in R (lme4), with year and

site included as random effects. All statistical analyses were performed in R 4.3.1 and Python 3.10.

3. RESULTS

Species distribution models for the 46 wild bee species achieved a mean cross-validated AUC of 0.86 (range 0.76–0.95) and mean TSS of 0.61, indicating generally good discriminatory performance across the ensemble. Table 1 summarises projected range shift and regional suitable-area change by scenario and period.

Table 1. Projected pollinator range shift and regional suitable-area loss across the 46-species ensemble, by scenario and period.

Scenario / period	Mean range-centroid shift (km)	Mean elevational shift (m)	Species losing >30% regional suitable area (n/46)
RCP4.5, 2041–2070	31	44	8 (17%)
RCP4.5, 2071–2100	54	79	14 (30%)
RCP8.5, 2041–2070	62	88	17 (37%)
RCP8.5, 2071–2100	118	156	28 (61%)

Range-centroid and elevational shift are relative to the 1990–2019 baseline ensemble suitability; regional suitable area refers to climatically suitable area within the three study regions only.

Under RCP8.5 by 2071–2100, the ensemble projected a mean poleward range-centroid shift of 118 km and a mean upward elevational shift of 156 m across the 46 species relative to the 1990–2019 baseline, with 28 of 46 species (61%) projected to lose more than 30% of currently suitable climatic area within the three study regions specifically, indicating that for a majority of species the projected climatic range shift substantially outpaces what is accessible to locally established populations. Under RCP4.5, the corresponding mean range-centroid shift was 54 km and mean regional suitable-area loss affected 14 of 46 species (30%) beyond the 30% threshold, roughly half the RCP8.5 magnitude for both metrics (Wilcoxon signed-rank, $p < 0.001$ for the scenario comparison).

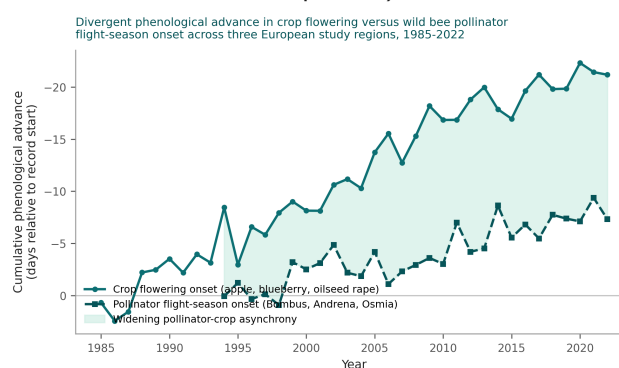


Figure 1. Cumulative phenological advance (days relative to 1985–1994 mean onset) in crop flowering onset versus wild bee pollinator flight-season onset, pooled across the three study regions and monitoring period (1985–2022), showing the progressive widening of pollinator-crop asynchrony.

Long-term phenological monitoring (1985–2022) showed that crop flowering onset advanced by a mean of 6.4 days per decade across the three crops and study regions, with apple advancing fastest (7.8 days per decade) and oilseed rape advancing most slowly (4.9 days per decade). Flight-season onset of the dominant pollinator taxa advanced more slowly, by a mean of 3.1 days per decade across *Bombus*, *Andrena*, and *Osmia* records (1994–2022), producing a measurable widening of pollinator-crop asynchrony of approximately 1.4 days per decade averaged across sites. Figure 1 shows the divergence in cumulative phenological advance between crop flowering and pollinator emergence over the monitoring period.

Table 2. Projected pollination service deficit and estimated annual production value at risk by country under RCP4.5 and RCP8.5, 2071–2100.

Country	Cropland in moderate-to-high deficit, RCP4.5 (%)	Cropland in moderate-to-high deficit, RCP8.5 (%)	Value at risk, RCP8.5 (EUR million/yr)
Italy	24	49	480
Slovakia	16	33	310
Sweden	9	18	150
Three-country total	17	34	940

At the 34 sites with concurrent fruit-set monitoring, pollinator-crop asynchrony in a given year was significantly negatively associated with fruit set ($r = -0.52$, $p < 0.001$; linear mixed-effects model coefficient -0.018 fruit-set units per day of asynchrony, 95% CI -0.024 to -0.012), indicating a measurable yield consequence of phenological desynchronization independent of overall pollinator abundance at a site.

4. DISCUSSION

These results show that projected pollinator range contraction and projected widening of pollinator-crop phenological asynchrony are both substantial and only partly overlapping risks to insect-pollinated crop production, extending prior single-mechanism assessments of pollinator range shift [4,7] and of plant-pollinator phenological mismatch [8,9,10] by jointly quantifying both mechanisms for the same agricultural landscapes under a shared climate scenario framework, and by directly linking observed asynchrony to a measured yield outcome (fruit set) rather than relying on mismatch alone as a proxy for service loss.

The finding that crop flowering phenology advanced roughly twice as fast as pollinator flight-season phenology over the 1985–2022 monitoring period is consistent with prior evidence that different trophic levels and functional groups respond to warming at different rates, generally attributed to differences in the specific environmental cues, photoperiod, accumulated chill, or spring temperature thresholds, governing phenological timing in plants versus overwintering insects [8,9,15,16], and provides field-based, yield-linked support for the concern that such differential responses could erode

pollination services even where pollinator populations persist locally.

The pronounced regional heterogeneity in projected pollination service deficit, concentrated in the Mediterranean study region and comparatively limited in the boreal region, mirrors broader findings that climate change impacts on pollinators are not spatially uniform and are often more severe toward the warmer and drier margins of a species' or region's climatic range [5,17], and suggests that adaptation resources, such as targeted wild pollinator habitat enhancement, managed pollinator supplementation, or crop variety selection for shifted flowering windows, would be most efficiently directed toward the Mediterranean and continental landscapes identified here rather than applied uniformly across all three countries.

The roughly two-fold difference in projected range loss, asynchrony widening, and economic value at risk between RCP4.5 and RCP8.5 underscores that the magnitude of pollination service risk to European agriculture remains substantially contingent on future emissions trajectory rather than being a fixed consequence of already-committed warming, consistent with the broader literature on pollinator vulnerability to alternative emissions pathways [4,18].

Several limitations should be considered. First, species distribution models project climatic suitability rather than realised occurrence, and do not account for other drivers of pollinator decline, including habitat loss, pesticide exposure, and pathogen spread, that interact with climate change and were outside the scope of this analysis [6,19]. Second, our suitable-area loss metric assumes limited species dispersal within the projection timeframe, a conservative but plausible assumption for many of the study taxa, though it may understate potential range tracking for the more mobile *Bombus* species. Third, phenological trend extrapolation to future scenario-periods assumes a continuation of the observed 1985–2022 rate of relative divergence between crop and pollinator phenology, which could over- or under-state future asynchrony if the relative sensitivity of crop and pollinator phenology to warming itself changes nonlinearly at higher warming levels.

5. CONCLUSION

Combining ensemble species distribution modelling for 46 wild bee species with 37 years of phenological monitoring across 210 agricultural landscapes in Italy, Slovakia, and Sweden, we find that climate change poses a substantial and spatially heterogeneous risk to insect-pollinated crop production through two jointly acting mechanisms, pollinator range contraction and phenological desynchronization, with an estimated 34% of the pollination-dependent cropland examined facing moderate-to-high projected pollination service deficit and approximately EUR 940 million in annual production value at risk by 2071–2100 under RCP8.5, roughly double the risk projected under RCP4.5. These findings

indicate that regionally targeted pollinator habitat and crop management adaptation, concentrated on the Mediterranean and continental landscapes identified as highest risk, together with continued emissions mitigation, both have a measurable role to play in safeguarding future pollination service delivery.

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Conflict of 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.

Author Contributions

W.N. conceived and supervised the study, developed the species distribution modelling workflow, and led the writing of the manuscript. A.N. curated and analysed the phenological monitoring and fruit-set datasets and performed the mixed-effects modelling. P.M. compiled and quality-controlled pollinator occurrence records and performed the regional pollination service deficit and economic value analysis. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used publicly available species occurrence data, national phenological monitoring records, and field-based fruit-set sampling conducted with landholder permission, and did not involve human participants or vertebrate animal subjects requiring ethical review.

Data Availability

Wild bee occurrence data are publicly available through GBIF. Phenological monitoring records and fruit-set datasets supporting the findings of this study are available from the corresponding author on reasonable request.

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