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FULL-LENGTH RESEARCH ARTICLE

A Global Estimation of Potential Climate Change Effects on Pollinator-Dependent Crops

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Abstract

Climate change poses a threat to global food security by significantly affecting agricultural products, both directly and indirectly. This study aims to assess the impact of climate change on the climate suitability of 61 pollinator-dependent crops worldwide under different climate change scenarios. Utilizing species distribution models (SDMs), we predicted climate suitability maps for these crops in the present and projected conditions for 2070. Our findings indicate that under the most pessimistic climate change scenario in 2070 (SSP585), 16, 31, 34, 29, 29, and 31 crops in Africa, Asia, Australia, Europe, North America, and South America, respectively, may experience a decrease in their suitable habitats. On average, crops in Africa, Asia, Australia, Europe, North America, and South America are expected to see a decrease of − 14.5%, − 11.2%, − 26.2%, − 4.7%, 5.5%, and − 14.4% in their suitability by 2070. Regional variations in the effects of climate change on crops highlight the vulnerability of certain areas, particularly Australia, where a substantial number of crops face a decline in suitable habitats. Conversely, North America may witness an increase in the distribution of specific products. Urgent action is needed to mitigate and adapt to the impacts of climate change, including the development of more resilient crop varieties and improvements in agricultural practices, especially for highly vulnerable pollinator-dependent crops in Asia and Africa.

Keywords Food security · Ecosystem · Warming globe · Species distribution models

Introduction

Around the world, human activities are rapidly changing land use patterns, resulting in the loss and fragmentation of natural habitats [14]. On the other hand, the increasing need for food has caused this process to continue and environmental management faces challenges and contradictions. By 2050, global agricultural production must be doubled to meet the needs of the world's population at that time [39]. However, agricultural activities cover one-third of the world's terrestrial land [14] and are known as one of the most important drivers of the loss and fragmentation of natural habitats around the world [29, 33]. The world is witnessing a growing shift toward urbanization, a trend expected to persist [36, 37]. The global urban area is estimated to cover approximately 4.2 million (km^2); however, projections suggest an additional 1.2 million km2 of urbanized land globally by 2030 [36]. This urban expansion may pose competition for agriculturally productive lands near human settlements [15]. Recent research is increasingly focusing on the significance of urban gardens, urban agriculture, and rooftop agriculture as viable solutions to address food security issues [30].

In 2005, the Millennium Ecosystem Assessment [6] published a global analysis of ecosystem services, reporting an almost 60% decrease in the assessed ecosystem services. It reaches 70% for regulating ecosystem services such as pollination. In this report, ecosystem services are divided into four categories: providing, regulating, cultural, and supporting services. The expansion of scientific studies on ecosystem services has led to a significant increase in the awareness of human effects on these services. For example, the role of biodiversity in ecosystem services and

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the factors affecting it, such as habitat loss and fragmentation, has received more attention. In 2018, East Africa experienced the most severe food insecurity, affecting 63% of the population (272 million), followed by Southern Africa with 54% (35 million), West Africa with 48% (183 million), and North Africa with 30% (70 million) [26]. In Asia, India, the largest and most populous country in the region, alone, accounts for a quarter of the world's total food-insecure population [23]. Currently, agriculture relies more heavily on pollinators, leading to a heightened demand for expanding cultivated land, particularly in developing nations. This suggests that as the reliance on pollination services grows, there is an increased need for expanding agricultural areas, particularly in less economically developed countries [3].

Using FAO data for the years 1961–2006, Aizen et al. [4] identified 87 pollinator-dependent crops and estimated that without the presence of pollinators, between 3 and 8% of the world's total crop production would decrease. Production and consumption of pollinator-dependent crops increased around the world between 1961 and 2006, especially in developed countries (16.7 versus 9.4% increase in developing countries) [2]. Global pollination benefits also had an increasing trend between 1993 and 2009 [19]. Approximately 50% of plant sources of Vitamin A are obtained from pollinator-dependent crops [10]. However, global warming could threaten food security by shifting the suitable growing areas of pollinator-dependent crops [20, 21, 31, 32]. For example, 57% of plants and 34% of animals will probably face a 50% change in their distribution by 2100 under climate change scenarios [44]. Climate change can have more destructive effects on plants in terms of spatial shifts because animals can migrate to suitable areas. However, as the rate of plant migration is very low, the plants have changed their position by 20–40 km per century [27].

Warming reduces the length of the growing season of some crops such that an increase of 0.5 °C in air temperature can shorten the growing season of winter wheat and soybean by 2–3 days [5]. In the case of 2 °C, winter wheat and soybean in northeastern Australia are predicted to mature 11 and 8 days ahead of expected. Some studies have investigated the effects of climate change on crops, especially cereals. for example, Teixeira et al. [38] investigated the effects of climate change on four crops: wheat, rice, corn, and soybeans on a global scale. They reported that agricultural areas in temperate and tropical regions will face a significant decrease in the productivity of crops. For winter wheat, a 2 °C increase in temperature leads to a 6% decrease in production, while it increases soybean production by 20% [5]. This disparity highlights the challenge and complexity of climate change effects on agriculture, as different crops respond differently to changes in temperature.

Basche et al. [7] also predicted the effects of climate change on maize and soybeans in the Midwestern US in 2060. They reported that there would be a 1.6 and 2.7% reduction in the production of the crops. In India, Mall et al. [20] showed that between 10 and 20% production of soybean crops will decrease as a result of global warming. Byjesh et al. [8] also predicted that because of climate changes, the production of monsoon maize in the southern parts of India and the mid-Indo-Gangetic Plains would decrease by 35% and 55% in 2050, respectively. Maize crop production also is predicted to decrease by 20% in 2050 due to climate change in Ethiopia compared to the period of 2009–1980 [17].

Although the effects of climate change on pollinator-dependent crops such as soybeans [5, 20], rapeseed, and sunflowers [12] have been estimated in different parts of the world, little attention has been paid to comprehensively studying the effects of climate change on all pollinator-dependent crops on a global scale. As far as we know, there is no comprehensive study in this regard. By determining the upper and lower temperature limits of pollination-related products, a relative estimate of the decrease or increase in their production can be obtained. However, we also need to estimate the potential climate suitability change of these products in the future. Therefore, the present study aims to estimate the effects of climate change on the future distribution of pollinator-dependent crops under climate change scenarios on a global scale. In this regard, we used species distribution models (SDMs) to estimate the changes in the habitat suitability of 61 pollinator-dependent.

Materials and Methods

Pollinator-Dependent Crops

By examining 115 of the leading global food crops, Klein et al. [18] found that 87 of these crops require animals for pollination. This latter set accounts for 35% of the world's food production. The degree of dependency of these crops on pollination is different, and they are classified into four groups. (1) Essential, in the absence of pollination, crop production decreases by more than 90%, (2) High, in the absence of pollination, crop production decreases between 40 and 90%, (3) Modest, in the absence of pollination, crop production can decrease between 10 and 40%, and (4) Little, in the absence of pollination, crop production decreases between 0 and 10%. In the present study, we only examined the effects of climate change on the first three groups. Out of 87 pollinator-dependent crops, 13 are in the essential group, 30 in the high-dependence group, and 27 in the modest dependence group [2, 18]. In the current study, we only had access to the data of 61 crops, of which 10 are in the essential group, 24 in the high-dependence group, and 27 in the modest dependence group (Table 1).

Species Distribution Models (SDMs)

For estimating the potential effects of climate change on the world's pollinator-dependent crops, species distribution models were used (SDMs). These models require two categories of dependent and independent data (1) presence and absence points of species as dependent data and (2) predictor variables like climatic data as independent data. Most species distribution models use the presence and absence of species data. Since it is difficult and time-consuming to prepare absence data for a species, most studies use background points or pseudo-absence points [31, 40]. In the current study, presence data for pollinator-dependent crops freely available on the Global Biodiversity Information Facility (GBIF) website (www.gbif.org) were used.

Table 1 List of studied crops and their pollination dependency

Pollination dependency	Scientific name	Name	Pollination dependency	Scientific name	Name
Essential	*Actinidia deliciosa*	Kiwifruit	Modest	*Abelmoschus esculentus*	Okra
	Bertholletia excelsa	Brazil nut		*Brassica napus*	Rapeseed
	Citrullus lanatus	Watermelon		*Brassica nigra*	Mustard
	Cucumis melo	Melon		*Castanea sativa*	Chestnut
	Cucurbita maxima	Pumpkin		*Cocos nucifera*	Coconut
	Cucurbita moschata	Pumpkin		*Coffea arabica*	Coffee
	Cucurbita pepo	Pumpkin		*Coffea canephora*	Coffee
	Theobroma cacao	Cocoa		*Coffea liberica*	Coffee
	Vanilla planifolia	Vanilla		*Fragaria ananassa*	Strawberry
	Vanilla pompona	Vanilla		*Fragaria chiloensis*	Strawberry
High	*Anacardium occidentale*	Cashew		*Fragaria moschata*	Strawberry
	Cola acuminata	Cola nut		*Fragaria vesca*	Strawberry
	Cola nitida	Cola nut		*Fragaria virginiana*	Strawberry
	Cucumis sativus	Cucumber		*Fragaria viridis*	Strawberry
	Elettaria cardamomum	Cardamom		*Glycine max*	Soybean
	Fagopyrum esculentum	Buckwheat		*Glycine soja*	Soybean
	Malus domestica	Apple		*Gossypium arboreum*	Cotton seed
	Mangifera indica	Mango		*Gossypium barbadense*	Cotton seed
	Myristica fragrans	Cardamom		*Gossypium herbaceum*	Cotton seed
	Persea americana	Avocado		*Gossypium hirsutum*	Cotton seed
	Prunus armeniaca	Apricot		*Helianthus annuus*	Sunflower
	Prunus avium	Sour cherry		*Ribes nigrum*	Black currant
	Prunus cerasus	Sweet cherry		*Ribes rubrum*	Red currant
	Prunus domestica	Plum		*Sesamum indicum*	Sesame
	Prunus persica	Peach		*Sinapis alba*	Mustard
	Prunus spinosa	Plum		*Solanum melongena*	Eggplant
	Pyrus communis	Pear		*Vicia faba*	Broad Bean
	Rubus chamaemorus	Cloudberry		–	–
	Rubus flagellaris	Dewberry		–	–
	Rubus idaeus	Raspberry		–	–
	Vaccinium angustifolium	Cranberry		–	–
	Vaccinium corymbosum	Blueberry		–	–
	Vaccinium myrtillus	Cranberry		–	–
	Vaccinium oxycoccus	Blueberry		–	–

Modest: 10–40% reduction without pollinators, High: 40–90% reduction without pollinators, and Essential: reduction > 90% without pollinators

For this purpose, all species of these crops listed in Table 1 were downloaded. Therefore, a total of 61 crops were downloaded on a global scale.

Data Cleaning

To ensure the accuracy of the data, the presence points were carefully examined to eliminate any duplicate records or those located outside the study area boundary. In addition, to prevent biased results due to the clustering or overrepresentation of certain areas in the presence records, a technique called spatial thinning was employed using the spThin package [1]. The distance applied for spatial thinning was 34 km, which was chosen based on the scale or pixel of the predictor layers of the model, as the spatial thinning distance should be equal to or greater than this scale to effectively minimize any spatial autocorrelation [35]. The ''rgbif'' package is an R package that provides a convenient interface to access biodiversity data from the Global Biodiversity Information Facility (GBIF). The rgbif package allows users to query and retrieve biodiversity data from GBIF's extensive database directly within the R environment [9]. The rgbif package was utilized to filter the data, and records located in the ocean were also excluded as they are not relevant to the terrestrial research question being investigated.

Environmental Variables

The Bioclimatic data in the WorldClim database include 11 temperature variables and eight precipitation variables, which have a spatial resolution of approximately 1 km. These 19 variables often have a high correlation with each other, and therefore, it is not recommended to use all these variables in species distribution modeling. For this purpose, we used the usdm [24] package to exclude the highly correlated variables from the set through a stepwise procedure based on variance inflation factor (VIF). The remaining variables include Mean Diurnal Range (Bio 2), Temperature Seasonality (Bio 4), Max Temperature of Warmest Month (Bio5), Mean Temperature of Wettest Quarter (Bio 8), Precipitation of Wettest Quarter (Bio 12), and Precipitation of Driest Quarter (Bio 17).

Estimating Climate Change Effects on Crops

In this study, we employed the ''FLEXSDM'' R package [41] in R software to model the distribution of the studied species. For this purpose, the MaxEnt model was used to prepare habitat suitability maps based on the presence and climate data. The MaxEnt model has been used by many studies to model the distribution of species and estimate climate change effects, especially on crops [34, 42]. We also generated 10,000 pseudo-absences points to be used together with the presence points for modeling with the MaxEnt model. Next, we used the climate change scenarios of SSP585 (the shared socio-economic pathway) to model the future distribution of bees in 2070. The SSP585 is known as the worst scenario of climate change, in which CO_2 emissions triple by 2075 and temperature increase to 4.4 by 2070 [25].

In the present study, we classified the climate suitability map into two classes of low and high suitability, and the high-suitability class included values greater than 0.6 [32, 43]. Therefore, we only measured range changes for the high-suitability class. Subsequently, we computed the percentage of change using the following formula:

Percentage of change = ((number of cells in the future under the suitable class)–(number of cells in the current under the suitable class))/(number of cells in the current under the suitable class)) * 100.

Model Assessment

To evaluate the effectiveness of outcomes generated by diverse models, we utilized three performance metrics: inverse mean absolute error (IMAE), the area under the ROC curve (AUC), and Boyce Statistic (BOYCE), employing the ''FLEXSDM'' R package [41]. AUC values falling within the 0.7–0.9 range are considered acceptable, while values surpassing 0.9 are deemed excellent, indicating highly accurate predictions. Higher IMAE and Boyce Index values signify enhanced model accuracy. Model performance underwent evaluation through fivefold cross-validation [13].

Results

Model Assessment

Table 2 shows the results of model validation metrics for all crops. According to this table, the average value of AUC for all crops is 0.95, which indicates that the results of the models are perfect. According to the other statistics, our predictions also fall within the excellent range. The

Table 2 Model validation metrics including AUC, BOYCE, and IMAE generated using the MaxEnt algorithm for bees

	AUC	BOYCE	IMAE
61 crops	0.95 (0.02)	0.96 (0.03)	0.87 (0.06)

The standard deviations are presented in parentheses assessment outcomes regarding performance evaluation for each crop are made available in the supplementary data.

Table 3 presents the percentage changes in the area of the high-suitability class under the SSP585 climate change scenario for the year 2070. Crops that are either not cultivated or have a minimal predicted area are omitted and represented by ''-''. The table provides insights into the anticipated alterations in the high-suitability areas for the specified crops, offering a comprehensive view of the potential impacts of climate change on crop distribution.

Africa

The projected changes in crop suitability across Africa pose multifaceted challenges. The substantial decrease in *Cola acuminata* suitability is particularly significant, given its cultural and economic importance in various African societies. Cola nuts are often used in traditional ceremonies and beverages, and a decline in suitability could impact local traditions and livelihoods. The decreased suitability for *Fragaria virginiana*, the wild strawberry, raises concerns about the loss of biodiversity and potential effects on ecosystems that rely on these native plants. Additionally, the reduced suitability for *Prunus persica*, or peach, suggests potential challenges for the peach cultivation industry, affecting both local economies and nutritional diversity. The mean decrease in suitability for a variety of crops under the SSP585 climate change scenario by 2070 is − 14.5% on average.

Asia

Asia, with its diverse agricultural practices, faces notable challenges with changing crop suitability. The substantial decrease in *Brassica napus* suitability may impact the production of canola oil, a key ingredient in many Asian cuisines. This has implications for local cooking habits and regional culinary traditions. The decline in suitable areas for *Coffea arabica* raises concerns for the Asian coffee industry, which is gaining prominence. *Vaccinium corymbosum's* reduced suitability poses challenges for the cultivation of blueberries, impacting both local consumption and export markets. These changes may necessitate shifts in agricultural strategies and potentially impact food security in the region. Across Asia, the mean decrease in crop suitability is − 11.2% on average.

Australia

Australia's unique agricultural landscape is susceptible to the changing suitability of crops. The decrease in *Abelmoschus esculentus* suitability, a vegetable commonly used in Australian cuisine, could impact local diets and traditional dishes. *Actinidia deliciosa*, or kiwi, is a fruit that has become synonymous with Australia's fruit industry. The reduction in suitable areas raises concerns for both local consumption and export markets. Additionally, the decreased suitability of *Coffea canephora* suggests potential challenges for coffee production in Australia, which has been steadily growing in recent years. These changes may prompt the need for agricultural diversification and adaptation strategies. Australia might face a substantial mean decrease in crop suitability, averaging − 26.2%, emphasizing the potential shifts in the country's agricultural patterns.

Europe

Europe's varied climates and agriculture face substantial challenges with the changing suitability of crops. The notable decrease in *Coffea arabica* suitability signals potential difficulties for Europe's emerging coffee industry. The reduction in suitable areas for *Vaccinium corymbosum*, the blueberry, is significant for both local consumption and the export market. Furthermore, the decrease in suitability for *Prunus persica* raises concerns about the future of peach cultivation in European regions, affecting local fruit industries and consumer choices. These changes highlight the importance of sustainable agricultural practices and the potential need for adjustments in crop choices. In Europe, the mean decrease in crop suitability is − 4.7% on average.

North America

North America, with its vast agricultural output, is expected to encounter challenges with the changing suitability of crops. *Fragaria ananassa*, the cultivated strawberry, is a widely consumed fruit with a significant economic impact. A decrease in its suitability may affect the strawberry industry, impacting both local and international markets. *Theobroma cacao*, crucial for chocolate production, faces challenges with reduced suitability, posing potential risks for the cocoa industry in North America. Additionally, the decrease in suitability for *Brassica napus*, a major oilseed crop, may impact cooking oil production and related industries. North America experiences a mean increase in crop suitability with an average increase of 5.5%.

South America

South America's rich agricultural diversity is at risk due to the changing suitability of crops. *Coffea canephora*, the Robusta coffee plant, is essential for coffee production in the region. A decrease in suitability poses challenges for the coffee industry, impacting local economies and livelihoods. *Glycine max*, or soybean, a major crop in South

Table 3 The percentage of changes in the area of the high-suitability class under the SSP585 climate change scenario in 2070

	Africa	Asia	Australia	Europe	North America	South America
Abelmoschus esculentus	1.1	− 14.0	− 68.9	184.4	− 2.4	28.2
Actinidia deliciosa	–	− 53.5	− 46.8	− 29.2	–	–
Anacardium occidentale	31.5	− 14.2	− 31.9	–	− 16.1	− 12.0
Bertholletia excelsa	–	–	–	–	–	− 6.2
Brassica napus	− 61.0	− 28.3	− 27.6	− 17.5	− 6.4	− 20.8
Brassica nigra	–	–	–	− 4.5	–	–
Castanea sativa Mill	–	− 1.6	− 22.5	− 31.6	− 41.2	− 4.3
Citrullus lanatus	7.0	5.1	− 1.6	18.5	26.4	18.2
Cocos nucifera	104.9	26.3	1.0	–	− 2.2	104.3
Coffea arabica	− 58.3	− 55.6	− 59.6	–	− 56.7	− 57.2
Coffea canephora	− 64.8	− 62.4	–	–	− 61.5	− 74.5
Coffea liberica	− 40.2	− 53.2	–	–	− 40.6	− 71.6
Cola acuminata	− 79.5	–	–	–	–	− 68.1
Cola nitida	33.1	–	–	–	–	–
Cucumis melo	36.2	8.8	− 33.6	18.2	33.8	87.6
Cucumis sativus	− 61.2	− 12.9	− 12.6	4.6	10.2	− 1.5
Cucurbita maxima	− 68.2	− 44.0	− 22.8	− 6.1	− 36.8	− 45.4
Cucurbita moschata	− 38.1	− 37.9	− 56.5	111.8	− 23.1	− 26.3
Cucurbita pepo	− 50.2	− 23.8	− 24.9	− 2.2	− 1.5	− 39.1
Elettaria cardamomum	–	− 44.1	–	–	− 39.2	–
Fagopyrum esculentum	–	− 9.3	− 32.7	− 4.5	32.3	− 21.2
Fragaria ananassa	–	–	–	− 20.9	73.4	− 28.6
Fragaria chiloensis	–	–	–	− 5.9	− 38.3	− 31.6
Fragaria moschata	–	119.6	–	− 25.4	–	–
Fragaria vesca	–	30.5	–	− 10.2	1.9	–
Fragaria virginiana	–	− 86.0	–	− 37.6	103.1	–
Fragaria viridis	–	− 21.0	–	− 38.3	–	− 23.0
Glycine max	–	42.1	− 32.8	32.6	46.4	− 56.5
Glycine soja	–	29.8	–	–	–	–
Gossypium arboreum	113.7	18.4	47.7	–	91.9	113.5
Gossypium barbadense	− 12.7	− 24.7	− 31.5	–	− 22.8	− 29.0
Gossypium herbaceum	− 57.3	− 33.8	− 40.5	58.8	− 19.0	− 37.4
Gossypium hirsutum	33.3	16.9	− 25.3	–	39.9	31.6
Helianthus annuus	− 49.8	− 7.2	− 19.1	0.5	22.0	− 20.5
Malus domestica	–	11.2	− 27.8	− 25.7	− 10.4	− 10.6
Mangifera indica	35.8	− 2.1	− 35.9	–	− 11.7	1.7
Myristica fragrans	− 59.0	− 56.1	–	–	− 54.4	− 60.2
Persea americana	− 58.7	− 42.6	− 33.7	63.5	− 41.3	− 51.9
Prunus armeniaca	–	− 51.7	− 40.2	− 17.5	7.0	–
Prunus avium	–	69.7	− 19.7	− 7.9	42.6	–
Prunus cerasus	–	7.3	− 31.7	− 37.8	0.2	–
Prunus domestica	–	− 23.1	− 37.0	− 7.4	− 11.9	− 37.4
Prunus persica	− 94.7	− 10.9	− 22.2	− 30.9	− 17.6	− 20.5
Prunus spinosa	–	− 27.8	− 26.0	− 20.9	90.6	–
Pyrus communis	–	28.4	− 31.2	− 9.8	− 11.9	− 30.6
Ribes nigrum	–	− 45.7	–	− 48.9	58.5	–
Ribes rubrum	–	17.6	–	− 29.4	− 9.4	–
Rubus chamaemorus	–	− 24.9	–	− 59.1	− 17.2	–

Table 3 (continued)

	Africa	Asia	Australia	Europe	North America	South America
Rubus flagellaris	–	–	–	–	35.2	–
Rubus idaeus	–	− 33.3	− 26.7	− 38.8	1.9	–
Sesamum indicum	24.7	-0.8	− 29.4	-	9.5	39.9
Sinapis alba	–	17.3	− 31.4	− 31.9	139.2	− 35.1
Solanum melongena	30.5	2.2	− 24.2	49.3	22.8	− 4.3
Theobroma cacao	6.4	− 23.1	–	–	− 22.5	− 21.8
Vaccinium angustifolium	–	–	–	–	28.1	–
Vaccinium corymbosum	–	–	54.9	4.2	21.7	–
Vaccinium myrtillus	–	− 6.7	–	− 59.0	− 2.5	–
Vaccinium oxycoccus	–	− 28.2	–	− 50.8	11.3	–
Vanilla planifolia	26.3	9.3	− 16.1	–	− 8.9	9.1
Vanilla pompona	–	–	–	–	− 20.0	− 48.3
Vicia faba	− 51.3	− 28.6	− 47.7	− 24.8	− 10.5	− 12.7
Mean	− 14.5	− 11.2	− 26.2	− 4.7	5.5	− 14.4

America, faces a decrease in suitability, potentially impacting soybean production and related industries. *Theobroma cacao*, crucial for chocolate production, is expected to experience challenges with reduced suitability, affecting the cocoa industry in South America. In South America, the mean decrease in crop suitability is significant, with an average decline of − 14.4%.

Crop Distribution

Figure 1 depicts climatic suitability maps for four pollinator-dependent crops. Specifically, the distribution of *C. lanatus* is emphasized, showcasing its climatic suitability in a majority of global regions. However, cultivation in regions such as northern Canada and Asia seems impractical for this crop. Additionally, Fig. 1B and C illustrates distribution maps for *C. melo* and *C. maxima*, respectively. These crops are highly desirable in specific parts of the world, with moderate desirability observed across most regions. In contrast, *C. moschata* is predominantly distributed in the southern hemisphere, exhibiting high climatic suitability in Africa and South America.

Discussion

This research demonstrates that the impacts of climate change can lead to varied outcomes for different pollinator-dependent crops across distinct regions of the globe. For instance, in the face of the most severe climate change scenario, it is projected that 16, 31, 34, 29, 29, and 31 crops in Africa, Asia, Australia, Europe, North America, and South America, respectively, may witness a decline in their suitable habitats. On average, crops in Africa, Asia, Australia, Europe, North America, and South America are anticipated to experience a decrease of − 14.5%, − 11.2%, − 26.2%, − 4.7%, 5.5%, and − 14.4% in their suitability by the year 2070. Conversely, certain crops such as *Abelmoschus esculentus* (excluding Australia), *Citrullus lanatus* (excluding Australia), *Cocos nucifera* (excluding North America), *Cucumis melo* (excluding Australia), *Gossypium arboretum*, and *Vaccinium corymbosum* may encounter an augmentation in their suitability under future climate conditions.

Our results reveal that specific global regions could confront substantial adverse consequences due to climate change. Particularly, Australia, Africa, Europe, and Asia are poised to witness a reduction in the suitable habitat for pollination-dependent crops. Conversely, North America may observe an upswing in the average distribution of all crops. Consequently, it becomes crucial to prioritize an examination of the potential impacts of climate change on pollination-dependent crops in Asian and African nations. The forecasts for Australia imply that as many as 34 crops may, on average, lose -31.5% of their suitable habitat, posing a considerable threat to food security in this region. Consistent with our findings, Alexandrov et al. [5] utilized species distribution models to investigate the impact of climate change on crops's wild relatives of peanuts, potatoes, and cowpeas in Africa and South America. Their study revealed that approximately 16–22% of the analyzed species were likely to face extinction, with a majority losing up to 50% of their suitable habitats due to climate change. Specifically, among the 31 peanut species

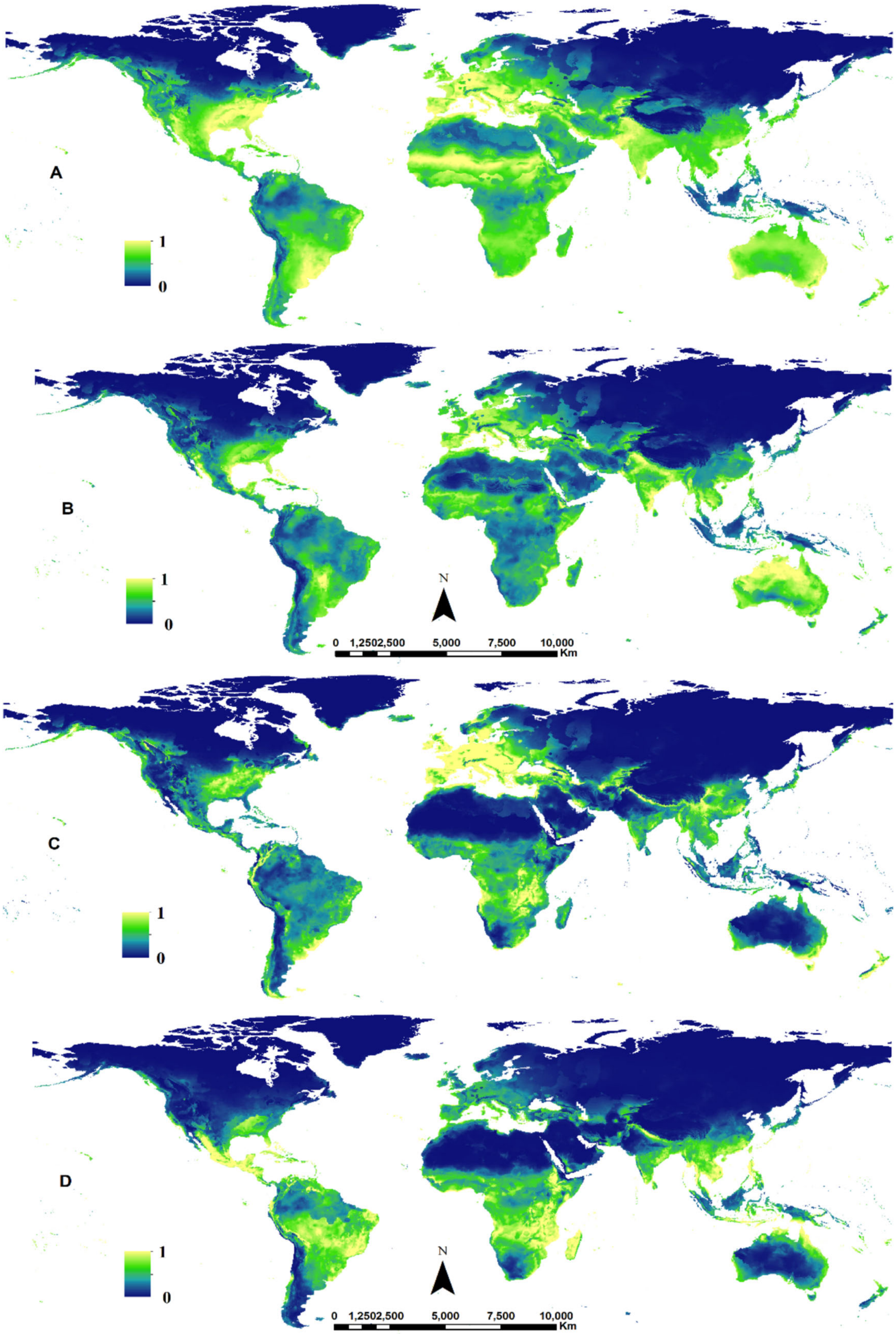

Fig. 1 Climate suitability maps of pollinator-dependent crops. (A) *C. lanatus*, (B) *C. melo,* (C), *C. maxima* and (D) *C. moschata*

examined, 24 were projected to become extinct, and the distribution range of Arachis species could shrink by 85–94% by 2055. Similarly, Reeve [34] predicted a substantial reduction, up to 50%, in the distribution range of walnuts in California between 2080 and 2100.

Soybean, despite being a pollinator-dependent crop with low reliance on pollinators for production, has been extensively examined regarding its susceptibility to climate change in various global regions. Our findings, about two soybean cultivars, *G. max*, and *G. soja*, indicate that these crops are expected to undergo an increase in their future distribution ranges, ranging from 32.65% in Asia to 46.4% in North America. Notably, studies on soybeans in India by Mall et al. [20] predicted a decline of 10–20% in soybean crops due to climate change. Teixeira et al. [38] conducted a global scale assessment and reported a substantial reduction in soybean cultivation in both temperate and tropical regions. Basche et al. [7] extended this evaluation to the Midwestern US, projecting a 1.6% and 2.7% decrease in soybean production by 2060. Interestingly, a study by Alexandrov et al. [5] highlighted a positive aspect, indicating that a 2-degree Celsius temperature increase could boost soybean production by 20%.

B. napus, characterized by low dependency on pollination, has been scrutinized for its response to climate change, particularly in European regions. Findings from Donatelli et al. [12] suggest a 5–30% yield reduction for this crop in France, Germany, and England by 2030. Our global analysis aligns with this trend, projecting a 17.5% decrease in habitat suitability for *B. napus* by 2070, with a notable impact on Europe. Similarly, sunflower crops, also with low pollination dependency, are anticipated to face challenges. Donatelli et al. [12] noted a 10–30% decrease in Eastern Europe, and our results show a marginal 0.5% increase in Europe. However, other continents, particularly Africa (− 49.8%), Australia (− 19.1%), and North America (− 20.5%), exhibit substantial decreases in habitat suitability for sunflower crops, emphasizing the diverse impacts of climate change on different regions.

A. deliciosa, a highly pollinator-dependent crop [2], faces significant challenges under the worst climate change scenario. Our results indicated that potential habitat suitability decreases of -53.5% in Asia, − 46.8% in Australia, and − 29.2% in Europe. Wang et al. [43] corroborate these findings, projecting a 40% reduction in suitable habitat for *A. deliciosa* in China by 2070 under RCP 8.5. Elevated temperatures, as observed by Warrick et al. [45] contribute to a substantial decline in flower numbers for this crop. On the other hand, watermelon (*Citrullus lanatus*), another highly pollinator-dependent crop, shows a contrasting pattern. Our study suggests that potential global increases in suitable habitats, ranging from 5.1% in Asia to 26.4% in North America. Rader et al. [28] highlight a nuanced response, indicating a 14.5% decrease in pollination by managed bees under the worst climate change scenario, offset by an increase in pollination by native bees. Melo et al. [22] found in Brazil that the development cycle of watermelon might decrease under climate change scenarios. These findings underscore the intricate interplay between climate change, pollinator-dependent crops, and the diverse responses exhibited by different crops globally.

While our study primarily focused on examining the displacement caused by climate change, it is essential to acknowledge that climate change impacts extend beyond spatial displacement. Climate changes can also influence the timing of natural events, such as crop growth and flowering. For instance, Cosmulescu et al. [11] investigated the effects of climate change on the phenological phases of *P. domestica* in Romania and discovered that in years with early spring and increased temperatures, phenological phases occurred much earlier than usual. Woznicki et al. [46] observed in a cool Nordic environment that climate warming led to accelerated flower formation, earlier blooming, and increased fruit size of *P. domestica*. Similarly, Jahan and Nassiri-Mahallati [16] modeled the response of *S. indicum* to climate changes, revealing that higher maximum temperatures in April and May resulted in the acceleration of flowering, grain filling, and physiological maturity. These findings highlight the broader impacts of climate change on the phenological aspects of crops, contributing to a more comprehensive understanding of the complexities involved.

Conclusions

In summary, this research underscores the profound implications of climate change on the global distribution of crops relying on pollination. While North America may experience an increase in the production of certain crops, Asia, Africa, Australia, and Europe are expected to witness diminishing suitable habitats for many such crops. This poses significant challenges to food security, particularly in regions already grappling with limited access to food. Urgent action is essential to mitigate and adapt to the consequences of climate change, including the development of more resilient crop varieties and advancements in agricultural techniques. Climate change can also have indirect effects on pollinator-dependent crops, primarily by influencing pollinator communities. Consequently, further investigations are warranted to comprehensively understand the multifaceted consequences of climate change on pollinators' distribution. It is crucial to delve into the effects of climate change on the pollinators of the studied crops, particularly insects, to gain more realistic insights into the repercussions of pollinator-dependent crops.

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Data Availability The Excel data and the list of crops presented in this study are openly available at https://github.com/ehsanrahimi666/Climate-Change-Effects-on-Pollinator-Dependent-Crops.git

Declarations

Conflict of interest The authors declare that they have no competing interests.

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