Response of an Invasive Plant Species (Cynanchum acutum L.) to Changing Climate Conditions and Its Impact on Agricultural Landscapes

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Abstract: Forecasting the distribution patterns of invasive weed species under changing climate conditions is critical for the early identification of especially vulnerable regions and the implementation of effective preventive measures. In this study, the current and potential range of stranglewort (Cynanchum acutum L.)—an invasive alien species (IAS) in certain regions—are predicted under various climate scenarios, using the maximum entropy algorithm. Species occurrence data representing the natural distribution of C. acutum and 15 of the WorldClim bioclimatic variables are used. With an ensemble method, the impact of climate change on the distribution of the species is predicted according to five CMIP6 climate change models and three scenarios (optimistic: SSP245; middle of the road: SSP370; and pessimistic: SSP585). According to the findings, it is predicted in all scenarios that C. acutum could expand its range to the north, particularly in agricultural landscapes. Therefore, the invasive status of this species will likely continue in the future. This emphasizes the need to determine the priority of conservation targets, especially for agricultural areas, to ensure food safety and protect biodiversity.

Keywords: biological invasion; climate change; stranglewort; maxent; ecological niche modelling

1. Introduction

Urbanization, which is among the major causes of habitat destruction, triggers biological invasions in Mediterranean ecosystems [1]. Globally, the spread of invasive species into new regions causes major economic damage, sets irreversible ecological changes in motion, and triggers adverse effects on public health [2]. The harmful effects of invasive alien species (IAS) have been described as the second greatest threat to the survival of species worldwide after habitat destruction [3]. IAS can cause irreversible changes to ecological communities, in some cases altering their composition by affecting the abundance of the constituent species [4,5]. IAS tend to get intermixed with the native flora as a result of afforestation or agricultural production, causing significant environmental stress on other species [6,7]. They are considered a main factor in the population decline of 3862 species listed as extinct or endangered worldwide—16.6% of the total number of species in these two categories [6]. Moreover, IAS cause billions of dollars of agricultural losses each year [8]. For example, the economic losses in China due to IAS were estimated to be approximately USD 15 billion [9]. Moreover, the increasing populations of these species in rangelands lead
to significant losses in livestock production. The secondary metabolite contents of these species also facilitate their rapid spread in natural areas [10].

The proliferation of invasive species is an important concern due to the great ecological and economic destruction they cause [11]. Since these species disrupt ecosystem services and harm natural communities, the economic costs of biological invasions are massive. For instance, one study conducted in the United States shows that reported costs of US biological invasions from 1960 to 2020 were at least USD 1.22 trillion [12]. Predicting the potential distribution of an IAS represents an important step towards its management and control. IAS can form populations that can persist in new habitats or niches, encouraging biological infestation [11]. With the help of future climate projections, ecological niche modelling methods can be used to predict the potential geographical extent of species’ future distributions [13]. Based on ecological assumptions and theories, ecological niche models have been used to investigate the spatial and temporal effects of species distributions under climate change [14]. A large body of studies have been conducted on the potential and future distributions of invasive alien species [8]. For instance, under the projected climate scenarios for Sri Lanka, it was shown that entire agricultural areas are at risk of potential plant invasions of varying dimensions. In Australia, babul (Acacia nilotica (L.) Delile), a thorny-woody legume, is expected to expand its range due to climate change and an increase in its water-use efficiency [15]. Prosopis juliflora (Sw.) DC., one of the world’s 100 worst invasive alien species according to the IUCN Red List, has spread at a rate of 25 km² per year in Pakistan, occupying five million decares, equivalent to 2% of the total agricultural land [16–18]. Aside from plants, invasive alien animal species native to the Mediterranean region have also caused irreversible ecological consequences, such as the Eurasian collared dove (Streptopelia decaocto), which has spread to North Africa [19].

Weeds threaten crop production and global food security worldwide [20]. Invasion of weeds has significant negative impacts on natural habitats, among which are the forced migration of native plants, loss of biodiversity, and destruction of habitat functions [21]. The genus Cynanchum (Apocynaceae) encompasses approximately 200 species that are native across Europe, Africa, and Asia [22]. The invasive weed species C. acutum, vernacularly referred to as stranglewort, has a height of 1–2 m, wraps around other plants and competes strongly for light, water, and nutrients [23]. The species is highly toxic; however, its milky latex acts as an antidiabetic, anti-inflammatory, and antioxidant agent [24]. Cynanchum infestations have severely affected orchards due to lacking effective control methods and regeneration impacts [23]. It has also been defined as an invasive plant across the globe [25]. Additionally, C. acutum have severe allelopathic effects on other plant species, facilitating its rapid overtaking of new habitats [26]. In addition, an increased prevalence of Cynanchum is likely to occur due to its strong adaptability to different environmental conditions in different habitats (e.g., its tolerance to salinity and drought stress), favorable vegetation/rare native plant species, etc. Its invasion can be promoted due to the management challenges arising from its perennial nature [25]. Cynanchum regrows root buds too rapidly for manual management methods such as pruning and removal to be practical and effective [23]. It has been widely identified as a harmful invasive weed in Iran, especially in orchards [27]. In certain provinces of Turkey, namely Tekirdağ, Denizli, Manisa, Kırşehir, and Samsun, it has been defined as a weed in agricultural lands, [28] such as vineyards [29] and areas used for growing chickpeas [30] and thyme [31]. Pyrrolizidine alkaloids found in this species have lethal effects on grazing animals in rangeland and pasture areas [31].

Climate change may lead IAS with large ecological niches to adapt to new environmental conditions on, instead of for, their natural ranges [32]. In addition, the continued spread of invasive species due to their evolving logistics networks exacerbates the growing global biodiversity crisis [33]. Determining the potential distribution patterns of invasive species through an ecological niche modelling approach under various climate scenarios therefore contributes to the development of cost-effective solutions pertaining to the adoption of measures to curb the spread of these species. In this study, we aimed to determine the current and potential range of Cynanchum acutum L. and its impact on agricultural landscapes in light
of changing climatic conditions. This study contributes to the determination of conservation priority targets and to the protection of biodiversity and food security in agricultural areas.

2. Material and Method

2.1. Species

The IAS C. acutum is a perennial vine swallowwort with a climbing and herbaceous form. It is naturally distributed in the southern Mediterranean region and has spread to Asia, North and South America, other parts of the Mediterranean, Africa, and Europe [25]. The species can be found from 0 to 2300 m a.s.l., and generally invades sandy and salty areas, stony slopes, fallow farmland, and vineyards.

2.2. Study Area

We hypothesized the study area to be accessible to C. acutum during present and future periods [34]. The study area covered the natural range of C. acutum and the areas where the species could potentially be invasive (Figure 1).

![Figure 1. Geographic location of the study area and the distribution of occurrence data (spatially thinned).](image-url)

2.3. Occurrence Records and Environmental Variables

Point coordinates representing the geographical distribution of C. acutum were obtained from the online Global Biodiversity Information Facility (GBIF) database [35]. Potential errors and duplications in these occurrence data were removed from the sample. A 100 km buffer zone was then drawn around each occurrence record using the spThin
package [36]. Through this process, the total number of recorded locations was reduced from 5441 to 151.

Climate data at a spatial resolution of 2.5’ (~4.7 km) were obtained from the WorldClim v2.1 database [37]. The WorldClim variables are based on average monthly temperature/rainfall data from 1970–2000. Some studies identified apparent artifacts in four of the bioclimatic variables [38]: the mean temperature of the wettest quarter (BIO8), the mean temperature of the driest quarter (BIO9), the precipitation of the warmest quarter (BIO18), and the precipitation of the coldest quarter (BIO19). Consequently, we did not use these variables in our model and concentrated on the remaining 15 variables. Since multicollinearity among the climate variables can distort the analysis of species–environment relationships [39], we made use of the usdm package [40] in the R v.4.0.3 environment to investigate variance inflation factors (VIFs) based on correlation coefficients ($R^2$) obtained from regression analysis conducted among all the predictors. We then removed those variables with VIFs lower than 10 [41]. As a result, we used only the following six bioclimatic variables as environmental predictors: BIO2 [mean diurnal Range (mean of monthly (maximum temperature minus minimum temperature))]; BIO4 [temperature seasonality (standard deviation × 100)]; BIO5 [maximum temperature of the warmest month]; BIO13 [precipitation of the wettest month]; BIO14 [precipitation of the driest month]; and BIO15 [precipitation seasonality (coefficient of variation)].

In order to account for a reasonable degree of uncertainty in the climate model projections [42], the future habitat suitability of *C. acutum* was predicted with the aid of five different global circulation models: BCC-CSM2-MR [43], CNRM-CM6-1 [44], CNRM-ESM2-1 [45], CanESM5 [46], and MIROC6 [47]. Future datasets were obtained from the Sixth Climate Model Intercomparison Project (CMIP6, www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6, accessed on 17 March 2022) for 2021–2040, 2041–2060, 2061–2080, and 2081–2100. In each case, three shared socioeconomic pathways (SSPs) were considered: optimistic (SSP245), middle of the road (SSP370), and pessimistic (SSP585).

2.4. Ecological Niche Modelling

Ecological niche models (ENMs) were constructed for the purpose of predicting the suitability of environmental conditions, hence the potential geographical distribution of *C. acutum*, both in the present and future, across the entire study area. Using the MaxEnt algorithm (version 3.4.1), as well as the kuenm R package, which permits the exact calibration of ecological niche models [48], 2100 candidate MaxEnt models were generated in the R v4.3.1 environment, each based on a unique combination of parameter settings. These models were then analyzed according to 42 distinct sets of the six environmental variables, 10 regularization multiplier values (0.1, 0.5, 1, 1.5, 2, 3, 4, 5, 8, 10) [49] and five combinations of feature classes (l, lq, lqp, lqpt, and lqpth, where l = linear, q = quadratic, p = product, t = threshold, and h = hinge). The performance of the models were assessed on the basis of: (i) significance, i.e., partial ROC [50] with 500 iterations and 50% of data for bootstrapping; (ii) omission rates (E ≤ 5%) [51], and (iii) complexity, correcting for small samples using the Akaike Information Criterion (AIC) (AICc ≤ 2) [49,52]. The models to be used were then created using the parameters selected and the complete set of occurrences. A total of 10 replicates were implemented by means of bootstrapping, with clog log outputs and 10,000 background points.

The models were applied to the study area for the current and future scenarios using an ensemble method. We produced the ensemble rasters for the selected scenarios and periods. The final evaluations incorporated calculations of partial ROC and omission rates from the independent dataset. The median of all replicates was used to obtain the results for the species. In the outputs, the suitability of the habitat is represented on a scale of 0 (unsuitable) to 1 (suitable). The maps were converted into binary maps with a 10-percentile training presence logistical threshold as proposed by [53]. The RasterVis package was used to visualize the findings [54].
Overlay analysis was conducted in ArcMap10.7 to compare the agricultural areas in the potential range of the species with the areas of habitat suitability, and the relevant changes were calculated at the country level. In this way, predictions were made regarding the countries in which the species could become invasive over a wider area and those in which the scope of its invasiveness would likely be narrow.

The study used a dataset from 2019, produced by the Global Land Analysis and Discovery (GLAD) laboratory in the Department of Geographical Sciences at the University of Maryland, to analyze how the locations and overall range of the species will change in agricultural areas [35]. The data were provided in geographical coordinates using the WGS84 reference system in an 8-bit unsigned LZW-compressed GeoTiff format. The pixel size of the maps was 0.025 × 0.025 degrees (~3 km × 3 km at the Equator).

3. Results

3.1. Selection of the Model

As explained above, we created 2100 candidate models by combining three sets of environmental predictors, ten regularization multipliers, and five combinations of feature classes. We evaluated the performance of the candidate models in terms of statistical significance (partial ROC < 0.05), good performance (5% OR = 0.065), and low complexity (AICc = 4281.314). These statistics suggested two possible best models based on the three selection criteria (Appendix A, Table A1). Among these model sets, those with delta AICc values of ≤2 were chosen as the final models. We then retained the linear (l), quadratic (q), and product (p) features (with 0.1, 0.875, and SD = 0.011, respectively). The six bioclimatic variables were used to predict the distribution of the target species. Four of these were selected as predictors based on the results of the model performance evaluation (Table 1; Appendix A, Table A1: M_0.1_F_lqp_Set_26)—namely, the maximum temperature of the warmest month (BIO5, 48.6%), temperature seasonality (BIO4, 23.5%), the precipitation of the wettest month (BIO13, 15.6%), and the precipitation of the driest month (BIO14, 12.3%).

Table 1. Losses and gains of the species under different scenarios.

| Scenario   | Gain (km²) | Loss (km²) | Stable (km²) |
|------------|------------|------------|--------------|
| ssp245 2021–2040 | 2,634,605.35 | 1,490,184.82 | 10,985,402.89 |
| ssp245 2041–2060 | 3,123,948.08 | 1,868,191.87 | 10,607,395.83 |
| ssp245 2061–2080 | 4,222,180.29 | 2,396,831.93 | 10,078,755.77 |
| ssp245 2081–2100 | 4,935,024.08 | 2,744,423.34 | 9,731,164.36 |
| ssp370 2021–2040 | 2,696,045.60 | 1,593,444.20 | 10,882,143.50 |
| ssp370 2041–2060 | 3,507,823.75 | 1,920,419.49 | 10,555,168.21 |
| ssp370 2061–2080 | 5,865,243.74 | 2,868,879.52 | 9,606,708.18 |
| ssp370 2081–2100 | 6,826,764.28 | 3,680,999.46 | 8,794,588.25 |
| ssp585 2021–2040 | 2,664,147.07 | 1,522,821.45 | 10,952,766.24 |
| ssp585 2041–2060 | 4,074,629.67 | 2,159,356.30 | 10,316,231.39 |
| ssp585 2061–2080 | 6,468,715.67 | 3,410,208.87 | 9,065,378.84 |
| ssp585 2081–2100 | 7,111,382.35 | 4,504,907.16 | 7,970,680.54 |

3.2. Potential Habitats—Current Situation and Predicted Geographical Changes under Three Climate Scenarios

The areas with the greatest potential for the spread of *Cynanchum acutum* in the future, as determined by the ecological niche model, are identified by shades of yellow on the map in Figure 2. The map suggests that the species could potentially spread in Algeria, Morocco, and Saudi Arabia, on the Mediterranean coast of Egypt, in Turkey, Italy, Spain, Portugal, Russia, Bulgaria and Romania, on the Black Sea coast of Ukraine, and in Mongolia, China, Central Asia, Iran, Azerbaijan, Pakistan, Afghanistan, Iraq, Syria, and Kazakhstan (Figure 2).
The potential habitats of the species are likely to shrink along Africa’s Mediterranean coast, in Asia, the Mediterranean coast of Egypt, in Turkey, Italy, Morocco, and Saudi Arabia, on the Mediterranean coast of Egypt, in Turkey, Italy, and inland Italy, the north of Spain and Portugal, and Europe in general (Appendix A, Figure 1).

An examination of the change in the potential distribution of the species in the future under the optimistic (SSP245) climate scenario shows that \( C. \text{ acutum} \) is likely to expand its potential range along the Black Sea coasts of Romania, Ukraine, Bulgaria, Turkey, and Russia, in the north of Kazakhstan, on the northern and southern borders of China, in the south of Mongolia, in the northwest of Ukraine, in Tajikistan, and in Afghanistan. The potential habitats of the species are likely to shrink along Africa’s Mediterranean coast, in the Arabian Peninsula, Turkmenistan, and the southeast of Turkey (Figure 3).

![Figure 2](image1)

**Figure 2.** The present-time distribution of \( C. \text{ acutum} \) L. (ranges from 0 to 1) and occurrence data visualized by red dots used in ecological niche modelling.

![Figure 3](image2)

**Figure 3.** Average predicted climate habitat suitability maps for stranglewort (\( C. \text{ acutum} \) L.) under future climate scenarios. Average projections are presented for each of four periods (2021–2040, 2041–2060, 2061–2080, and 2081–2100) and three shared socioeconomic pathways (optimistic: SSP245; middle of the road: SSP370; and pessimistic: SSP585). The probability of occurrence ranges from 0 (dark blue, low probability) to 1 (yellow, highest probability).
Under the middle-of-the-road (SSP370) climate scenario, the model outputs show that *C. acutum* could spread over a large part of Russia, starting from the north, the northwest of Ukraine, the northern border and southeast of Mongolia, northern and southern parts of China, the Black Sea coasts of Turkey and Russia, Romania, Bulgaria, inland Italy, the north of Spain and Portugal, and Europe in general (Appendix A, Figure A1). By contrast, the potential habitats of the species could be contracted in Turkmenistan, the southwestern coast of Saudi Arabia, Afghanistan and Pakistan, the Mediterranean coast of Africa, and the southern inland of Spain (Figure 3).

Under the pessimistic (SSP585) climate scenario, *C. acutum* could spread to almost all of Russia and Mongolia, northern Kazakhstan, all parts of China, Tajikistan, Afghanistan, the Black Sea coasts of Turkey and Russia, the northern coasts of Spain and Portugal, Romania, Bulgaria and the western border of Greece, the inland regions and west of Italy, and Europe in general. By contrast, the areas suitable for the species are expected to decrease in Uzbekistan, Turkmenistan, the Arabian Peninsula, on the southeastern border of Turkey, the Mediterranean coast of Africa, and the southern coasts of Spain and Portugal (Figure 3).

### 3.3. Changes in the Extent of the Suitable Areas for *C. acutum* under Future Climate Scenarios by Continent

The degree of change predicted in the overall extent of the suitable areas for *C. acutum* under future climate scenarios varies from continent to continent. The largest predicted changes in the total suitable area are projected to occur in Europe, under both the SSP585 and SSP370 scenarios for 2081–2100. The smallest change in the total suitable area is projected to occur in Africa under the SSP585 scenario for 2081–2100 (Figure 4).

![Figure 4](image-url) Change in total area suitable for the species by continent.
In general, the degree of change predicted in the total area suitable for the species in Africa is similar under all climate scenarios. The degrees of change expected for the period 2021–2040 under the SSP245 and SSP585 scenarios are particularly close to one another. In Europe, the degrees of change expected under the SSP585 climate scenario in the periods 2061–2080 and 2081–2100, and under the SSP370 climate scenario in the period 2081–2100, are also very similar. In Asia, the degrees of change expected under all three climate scenarios for the period 2021–2040 are similar.

Under the SSP245 climate scenario, a decrease is predicted in the change in the total area of the potential habitats of *C. acutum* in all periods from the present day to the year 2100 in Central Asia, North Africa, and southern and western Asia, while in eastern, southern, and western Europe the change in area is expected to increase. Under this scenario, the species is predicted to spread most rapidly in eastern Europe, while southern Asia is predicted to witness the most rapid decrease (Appendix A, Figure A2).

When we compare the SSP245, SSP370, and SSP585 climate scenarios, the changes they predict in the potential distribution area of *C. acutum* in eastern Europe are most similar between 2081 and 2100. When we evaluate the SSP370 and SSP585 scenarios in reference to the SSP245 scenario, the results predict that the total area decreases in western Europe, western and southern Asia and Central Asia, as well as in East Africa. By contrast, the species is predicted to spread more widely in Eastern Europe.

### 3.4. Predicted Total Habitat Gains and Losses under Different Climate Scenarios

It was observed that the species will continue to be invasive in the future under different scenarios (Table 1). When the gains and losses in the extent of the suitable habitats of the species in the study area were examined, gains outweighed losses in all scenarios. In other words, under all scenarios, the total extent of the areas that are presently not suitable for *C. acutum* but are predicted to become so in the future (i.e., gains) exceeds the total extent of the areas which are suitable today but are predicted to become unsuitable in the future (i.e., losses). The most gains and losses are expected to arise in the SSP585 2081–2100, SSP370 2081–2100, and SSP585 2061–2080 scenarios, in that order. The scenarios in which the total extent of stable areas (i.e., areas that show neither losses nor gains) is the greatest are SSP245 2021–2040, SSP585 2021–2040, and SSP370 2021–2040, respectively.

### 3.5. The Potential Spread of the Species to Agricultural Areas

The changes in the potential distribution of *C. acutum* were also predicted on a country basis and with specific reference to agricultural areas under different climate scenarios (Appendix A, Figure A3).

Under the SSP245 climate scenario, the increase in the potential distribution area of the species in 2021–2040 and 2041–2060, compared with the present day, is predicted to be greatest in Kazakhstan. Meanwhile, the biggest decrease will be observed in Russia. Even so, Russia and China will continue to have the largest total areas of potential habitats. In all countries where the species can be found, except for Syria, Saudi Arabia, Russia, Pakistan, and Iraq, the potential range of *C. acutum* is expected to increase markedly in agricultural areas. In the periods 2061–2080 and 2081–2100, the largest gain in the total area of suitable habitats compared with the present day is predicted to occur in Kazakhstan and Russia. It is expected that the potential range of the species in agricultural areas will increase in all countries except for Tajikistan, Syria, Saudi Arabia, Russia, Pakistan, and Iraq.

In the SSP370 climate scenario, it is expected that the largest gain in the potential distribution of *C. acutum* in agricultural areas will be in Kazakhstan, while its greatest potential range will be in China and Russia, in all periods except for the 2021–2040 period. Under this scenario, the species is predicted to have a potential distribution in agricultural lands in all countries other than Pakistan, Libya, and Iraq in all periods investigated. However, the potential distribution area of *C. acutum* is likely to decline in Syria and Saudi Arabia in the periods 2061–2080 and 2081–2100.
Under the SSP585 climate scenario, the greatest gain in the total potential habitat of *C. acutum* in all periods, except for the 2021–2040 period, is expected to be observed in Russia and Kazakhstan. In the 2021–2040 and 2041–2060 periods, the species is predicted to have a natural distribution in agricultural areas in all countries other than Syria, Saudi Arabia, Pakistan, and Iraq. In the periods 2061–2080 and 2081–2100, the species is expected to completely lose its potential distribution areas in Syria, Saudi Arabia, Egypt, and Cyprus.

In all four periods and under all three climate scenarios, Russia, Kazakhstan, and China are predicted to be the countries in which the largest areas of agricultural land fall within the predicted potential habitats of *C. acutum*. In the case of Turkey, it is predicted that the potential range of the species will shift from south to north, and that its overall impact area will decrease, between the present and all future periods under all scenarios.

4. Discussion and Conclusions

Invasive plant species pose a major problem, particularly in agricultural areas and rangelands, due to the fact that they alter the natural vegetation cover and soil structure of areas they inhabit [56]. Invasive species are particularly difficult to control because they tend to multiply faster than other plant species, have higher levels of tolerance to unfavorable environmental conditions, and readily adapt to new habitats [57], all of which present negative implications for biodiversity. A major reason for the success of invading plant species is that they do not have natural enemies (herbivores that specialize on them) in the areas they invade. If their natural enemies were able to follow them to newly invaded areas, or were introduced deliberately by humans as biocontrol agents, they might not be much more fit than native vegetation. Climate change may render environmental conditions unfavorable for invasive species, negatively affecting their populations by reducing their competitiveness [58]. Additionally, the spread of certain invasive plants may be checked by extreme climatic events climate change can cause, such as severe floods and droughts. However, with their wide threshold values and adaptability, invasive species can also adapt to the effects of climate change faster than native species do, which is a highly advantageous trait in interspecific competition. This can increase the overall impact on biodiversity and make it more permanent.

In this study, the current and potential range of *C. acutum* were modeled with the help of the maximum entropy algorithm. Since these climate models possess higher predictive power and reliability, they are expected to generate more accurate results [59]. Under all climate scenarios used in the study, *C. acutum* is predicted to expand its range, particularly in agricultural areas, which could likely aggravate the economic and ecological impact of its biological invasion. However, climate-based ecological niche models have their limitations, as they only factor in certain essential conditions for the potential spread of an invasive species. Hence, partly due to topographic features not being included in the assessment, these predictions not only fail to produce a total representation, but they also potentially give misleading future projections. Over the past decades, substantial changes in the weed flora of arable ecosystems in Europe have been noted. The predicted effects of global climate change has rendered certain species that used to pose an insignificant threat to become major topics of concern in some regions [60]. In the US alone, the presence of these species in agricultural and rangeland ecosystems causes billions of dollars in losses [61,62]. The presence of IAS often reduces the variety, quality, and yield of agricultural products as well as the soil fertility by absorbing water and nutrients [63]. The balance of diseases and pests may also be upset due to the impact on the number of living creatures, such as arthropods and nematodes, in agricultural areas. The use of pesticides, especially for the control of invasive species that spread in agricultural areas, such as *C. acutum*, brings about both economic costs and toxic effects on the ecosystem [63]. Due to its morphological and physiological characteristics that make this species particularly difficult to control, its rapid biological invasion continues to cause problems in numerous countries [25]. Unfortunately, there are no existing attempts or plans for the use of biocontrol, i.e., introducing a natural enemy of the species from its native environment. This situation could eventually lead to the abandonment of particular
areas of agricultural production altogether. The use of herbicides as a control method may also affect other species in agricultural and rangeland ecosystems, which can lead to loss of biodiversity and threaten the survival of other perennial species [64]. Chemical applications can also cause groundwater contamination and lead to eutrophication [65]. Mechanical and physical control methods are often economically infeasible as they require extensive manual labor for large agricultural areas. Consequently, conservation priority targets need to be adopted to ensure food security and protect biodiversity.

Our models predict that the species could pose a threat to local ecosystems as it expands its range under future climate change scenarios. Assessing the threat of invasive species, combined with the impact of climate change, is crucial for the conservation and management of biological diversity. Before implementing any control measures, it is imperative to be familiar with the potential and future geographical distribution of these species [66]. In order to identify areas where invasive plant species will further spread, ecological requirements of the species and its past land-use are widely accepted as the key criteria [67]. Often, the range expansion of an invasive species presents a threat to the natural ecosystems of agricultural areas, as well as pastures, secondary shrubs, and coniferous forests. Mountain ecosystems remain relatively free of infestation by \textit{C. acutum} compared with lowland ecosystems, but this process could potentially be accelerated by climate change and anthropogenic disturbance. There is, therefore, a need for further research and better planning to assist early detection monitoring and habitat suitability assessment of the species so that appropriate measures can be promptly taken to prevent further infestation.

\textit{C. acutum} has been identified as a weed in areas with varying agricultural patterns in separate regions of Turkey [28–31]. The species wraps itself around other plants and strongly competes for light, water, and nutrients. The species is mainly known to invade sandy and salty areas, stony slopes, fallow farmland, and vineyards. In Turkey, it is most prevalent in vineyards and dry agricultural areas. Given the biology and ecological requirements of the species, it is expected to have the greatest impact in the Aegean, Mediterranean, and Central Anatolia regions of the country. Under all climate scenarios, the range of the species shifts from south to north. Consequently, the species may also increasingly affect the Black Sea region in years to come. However, upon closer inspection, the region’s climate, vegetation characteristics, and soil properties reveal that its agricultural patterns differ drastically from that of other regions, suggesting that \textit{C. acutum} may not have the same impact, even if it spreads into the area in the future. Nevertheless, the plains of Çarşamba and Bafra in the Black Sea region of Turkey need to be carefully monitored for the early detection of the emergence of areas suitable for the spread of the species.

Effective management of invasive species requires an integrated approach that includes mechanical, chemical, and biological control techniques. For example, infestations can be easily controlled when populations are small enough to be manually eliminated via physical methods, stopping the species from spreading further. Uprooting the plant before it flowers to control the propagation of seeds, flooding the area for short periods, using shade treatments, and applying herbicides are among effective control methods for invasive plant species. As the range of an invasive species expands, it becomes more difficult to control. Another strategy for managing invasive species involves finding alternative ways in which local communities can make use of it. In that sense, invasive species such as wild oats that invade wheat fields, circus grass in beet fields, millet grass in paddy fields, and purslane encountered on almost every type of agricultural land have all found a place for themselves in markets over time, and are currently used in the regional cuisines of many countries, including Turkey [68]. \textit{Commelina communis} L., a species naturally found in East Asia but also invasive in Turkey, especially in the Black Sea region, threatens tea plantations [69]. It likes rainy and humid weather. \textit{C. communis} tends to settle in areas it invades over time and is currently included in the natural vegetation.

As already noted, the potential range of \textit{C. acutum} in the future under the SSP245, SSP370, and SSP585 climate scenarios demonstrated a tendency to shift northward. The species is expected to spread mainly in northern Europe, the Black Sea coast, the north
and south of East Asia, and the south of Siberia. The outputs of the model predict that *C. acutum* will spread in Kazakhstan, Russia, and China, while suffering losses in the Arabian Peninsula. These results indicate that the main factors affecting the speed and direction of the spread of *C. acutum* are temperature and precipitation. In practice, however, the geographical spread of the species over time cannot be determined by climate change alone. In environmental conditions that are highly exposed to anthropogenic effects, some other factors may also influence the direction and speed of this shift. Species can be translocated not only by natural means (wind, ocean currents, via other organisms, etc.) but also by human activities, such as trade, exportation of forest products, and transportation systems [68]. Preventing human-mediated translocation is therefore crucial for controlling the infestation processes [70]. In order to successfully manage biological invasions, effective measures taken at the three crucial stages of control, namely prevention, early detection, and rapid response, can help prevent further spread of the species in question.

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**Appendix A**

**Table A1.** Performance statistics for the best models selected based on the user’s pre-defined criteria.

| Model             | Mean_AUC_Ratio | Pval_pROC | Omission_Rate_at_5% | AICc   | Delta_AICc | W_AICc | Num_Parameters |
|-------------------|----------------|-----------|---------------------|--------|------------|--------|----------------|
| M_0.1_F_lqp_set_26 | 1.361951528    | 0         | 0.065217391         | 4281.314 | 0          | 1      | 14             |
| M_0.1_F_lqp_set_39 | 1.355070872    | 0         | 0.065217391         | 4282.375 | 1.060487252 | 1      | 18             |
Figure A1. Cont.
Figure A1. Cont.
Figure A1. Habitat suitability (loss, stable, gain) of stranglewort for three scenarios.
Figure A2. Change in the area of distribution of the species by region under different climate scenarios.
Figure A3. Cont.
Figure A3. Changes in agricultural area by country under different climate scenarios.
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