

CURRENT AND FUTURE HABITAT SUITABILITY OF THE INVASIVE SPECIES *AILANTHUS ALTISSIMA* IN ROMANIA

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ABSTRACT

*Tree of heaven (Ailanthus altissima (Mill.) Swingle), originally from Asia, has spread to all inhabited continents and has been declared as one of the most problematic invasive species in Europe. As of 2022, the tree of heaven is recognised as one of four plant species of EU concern that have already become widely established across Romania. This study models the current and future habitat suitability of tree of heaven in Romania under two Shared Socioeconomic Pathways (SSPs), based on the primary climatic drivers of its European distribution. The bioclimatic variables with the most relative importance on the distribution of the tree of heaven were BIO15-Precipitation Seasonality, BIO4-Temperature Seasonality, BIO9-Mean Temperature of Driest Quarter and BIO14-Precipitation of Driest Month. Under present climate conditions, suitable habitat areas (above the 0.76562 threshold) cover 1.3% of the country (around 3400 km²), and areas with excellent climate habitat (above 0.80) cover around 700 km². Based on levels of suitability, no current or future areas where the climate conditions correspond to an unsuitable habitat (below 0.20) were found. Under the SSP2-4.5 scenario, the land area with excellent climate suitability for *Ailanthus altissima* is projected to reach approximately 1,700 km² during 2061–2080, before dropping sharply to around 500 km² by 2081–2100. Under SSP5-8.5, there are no areas where climate conditions correspond to excellent habitat suitability, but for the 2081-2100 period, the climate conditions are projected to improve so that areas with poor (0.20- 0.40) habitat suitability will also disappear, leaving only areas with fair (0.40-0.60) and good (0.60-0.80) habitat suitability levels. Mapping the future distribution of *Ailanthus altissima* can help forest managers develop better strategies to control this invasive species.*

KEY WORDS: species distribution models, *Ailanthus altissima*, invasive species, SSPs, Tree of heaven

INTRODUCTION

“Biological invasion” is the phenomenon in which an exotic species arrives in a new ecosystem (naturally or artificially) and rapidly expands its distribution (Wang et al., 2013). This can damage the local environment and ecosystems (Vitousek, 1990; Wang et al., 2013). Biological invasions are among the major causes of global biodiversity decline and reduced ecosystem services worldwide (due to ecosystem degradation) (Pyšek and Richardson, 2010; Courchamp et al., 2017; Pile et al., 2017).

Tree of heaven (*Ailanthus altissima* (Mill.) Swingle) is non-native and invasive and has been declared as one of the most problematic invasive species in Europe (Enescu et al., 2016). Originally from China and North Vietnam, the species has spread to all inhabited continents, where it thrives in temperate and subtropical climates (Kowarik and Säumel, 2007; Nunes, 2022; Bastl et al., 2025). It has been used as an ornamental species, for erosion control, and industrial habitat reconstruction (Dumitrașcu et al., 2013; Enescu et al., 2016; Sîrbu and Oprea, 2011). Vacant lands in urban areas were found to be hotspots of the species’ dispersal (Gavrilidis et al., 2023).

It is sensitive to frost and early frost, preferring a mild climate and sheltered locations in regions with a long growing season (Șofletea and Curtu, 2007). It is resistant to drought (Trifilò et al., 2004) - but only to a point (Șofletea and Curtu, 2007), and air pollution (Zhang et al., 2016).

Given its allelopathic properties, it outcompetes native plant species by damaging or killing them, releasing the phytotoxic compounds found in its stems, roots and leaves (Gómez-Aparicio and Canham, 2008; Bostan et al., 2014; Bastl et al., 2025). Its pollen is also considered a highly relevant allergen (Cariñanos and Marinangeli, 2021; Werchan et al., 2024).

The list of invasive alien species of EU concern was adopted in 2016 (Commission Implementing Regulation (EU) 2016/1141 of 13 July 2016 adopting a list of invasive alien species of Union concern pursuant to Regulation (EU) No 1143/2014 of the European Parliament and of the Council, 2016) and most recently updated in 2025, including 114 species, of which 49 are invasive alien plants (Commission Implementing Regulation (EU) 2025/1422 of 17 July 2025 amending Implementing Regulation (EU) 2016/1141 to update the list of invasive alien species of Union concern, 2025). In 2022, it included 88 species, of which 41 were invasive alien plants (Anastasiu et al., 2024; Commission Implementing Regulation (EU) 2022/1203 of 12 July 2022 amending Implementing Regulation (EU) 2016/1141 to update the list of invasive alien species of Union concern, 2022).

The tree of heaven is one of the four plant species already established and widespread in Romania, among the 41 plant species of EU concern in 2022 (49 as of 2025) (Anastasiu et al., 2024).

Species distribution models (SDMs) are the foundational instrument used to quantify and visualize the threat of species invasion across a landscape (Jeschke and Strayer, 2008; Davis et al., 2024).

The objectives of this study were: to (i) Identify the climatic variables that influence the distribution of tree of heaven in Europe; (ii) predict potential areas with suitable climate conditions for this species in Romania under current conditions; (iii) predict areas with potentially suitable climate conditions for this species under three future periods (2041-2060, 2061-2080 and 2081-2100) and two distinct shared socioeconomic pathways (SSPs) – 2-4.5 and 5-8.5; and (iv) evaluate the range shifts.

MATERIAL AND METHOD

For the analysis of the habitat suitability of the tree of heaven, the 5201 occurrences were extracted from the dataset of Heisig and Hengl (2020).

The historical climatic data (from 1970-2000) were downloaded from the WorldClim dataset, version 2.1 (Fick and Hijmans, 2017), at a 10-minute spatial resolution, for the area between -26 - 40 degrees longitude and 28 - 60 degrees Northern latitude.

For the entire area, an average of six recent climate models was calculated for three future periods (2041-2060, 2061-2080, and 2081-2100) and two Shared Socioeconomic Pathways (SSPs) - 2-4.5 (middle of the road) and 5-8.5 (Fossil-fuelled development), which are updates to the RCP4.5 and RCP8.5 scenarios (*The SSP Scenarios*, no date), from which Romania was subsequently cropped. At a 10-minute spatial resolution, the grid cells along the national perimeter inevitably encompass geographic areas outside Romania's borders, given an analysed area of 257266 km².

The six recent climate models were: ACCESS-CM2 (Dix et al., 2019), EC-Earth3-Veg (EC-Earth Consortium (EC-Earth), 2019), HadGEM3-GC31-LL (Webb, 2019), IPSL-CM6A-LR (Boucher et al., 2020) MIROC6 (Takemura, 2019) and MPI-ESM1-2-HR (Gutjahr et al., 2019). To reduce computational demand, we selected a subset of the ten models previously used by Alexandru et al. for modelling *Larix decidua* habitat suitability (Alexandru et al., 2025).

The bioclimatic variables were checked for collinearity based on the Variance Inflator Factors and those with collinearity problems were excluded from the analysis.

We have generated a consensus habitat suitability model by averaging 30 individual models. These were derived using 5 distinct algorithms—GLM (generalised linear model (McCullagh, 2019)), BRT (boosted regression trees (Friedman, 2001)), RF (random forests (Breiman, 2001)), MaxNet (maximum entropy (Phillips et al., 2006; Phillips, 2021)) and FDA (flexible discriminant analysis (Hastie et al., 1994))—with three replications each for subsampling and bootstrapping. For model testing, 30% of the data was randomly subsampled. The models' performances were evaluated using TSS (True Skill Statistic (Landis and Koch, 1977)) and AUC (Area Under the Receiver Operating Characteristic Curve (Araújo et al., 2005)).

The predicted probabilities of occurrence (current and future ones) were transformed into 1s and 0s (suitable and unsuitable) based on the threshold that maximised both specificity and sensitivity. Thereafter, the shifts in the habitat suitability of the tree of heaven in Romania have been classified as: unsuitable, expansion, contraction and stable.

Using the limits proposed by Brown and Griscom (2022), the habitat suitability was also classified into: unsuitable (less than 0.20), poor (0.21–0.40), fair (0.41–0.60), good (0.61–0.80) and excellent (above 0.81).

RESULTS

Model evaluation. After excluding from the analysis the collinear variables, the linear correlation coefficients range between -0.039 (BIO15-Precipitation Seasonality with BIO8 - Mean Temperature of Wettest Quarter) and -0.723 (BIO15-Precipitation Seasonality with BIO14 - Precipitation of Driest Month). The remaining seven bioclimatic variables, as well as their Variance Inflation Factor (VIF), are presented in Table 1. BIO15 and BIO4 had the highest relative variable importance. BIO9 and BIO14 are the third or the fourth, depending on the correlation or the AUC metric (Figure 1). Except for BIO8 - Mean Temperature of Wettest Quarter, all bioclimatic variables have a normal, bell-shaped response curve (Figure 2).

TABLE 1. The bioclimatic variables and their variance inflation factor (VIF)

Code of the variables	Bioclimatic variables	Variance Inflation Factor (VIF)
BIO2	Mean Diurnal Range	4.086
BIO4	Temperature Seasonality	2.160
BIO8	Mean Temperature of Wettest Quarter	1.838
BIO9	Mean Temperature of Driest Quarter	4.874
BIO14	Precipitation of Driest Month	5.839
BIO15	Precipitation Seasonality	3.050
BIO19	Precipitation of Coldest Quarter	3.064

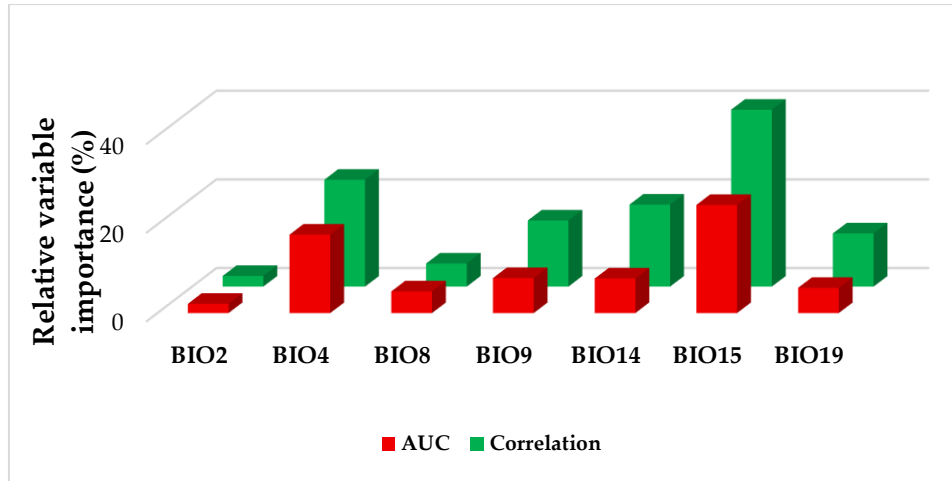


FIG. 1. Relative variable importance of the bioclimatic variables. The names of the bioclimatic variables are presented in Table 1. AUC - Area Under the Receiver Operating Characteristic Curve

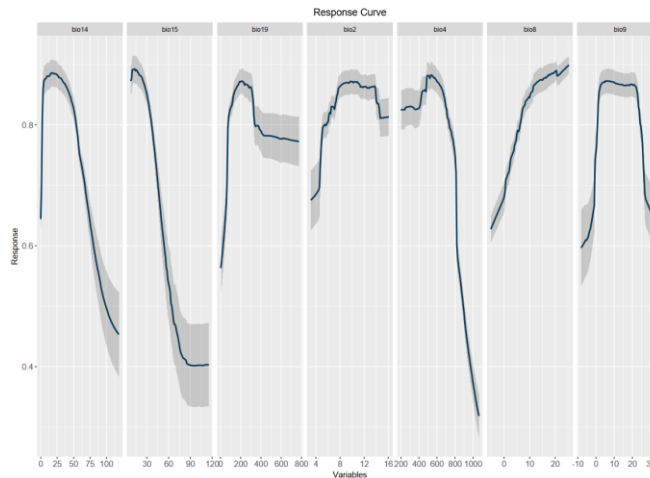


FIG. 2. The response curve of the bioclimatic variables. The names of the bioclimatic variables are presented in Table 1.

Analysing the Area Under the Receiver Operating Characteristic Curve (AUC), the performances of the models were fair, good and excellent (between 0.80 and 0.94) (Table 2). Based on the TSS, they were moderate and substantial.

TABLE 2. Model mean performance

Method	AUC	Correlation	TSS	Deviance
Generalised Linear Models (GLM)	0.80	0.54	0.51	0.73
Boosted Regression Trees (BRT)	0.88	0.67	0.64	0.67
Random Forest (RF)	0.94	0.76	0.74	0.43
Flexible Discriminant Analysis (FDA)	0.80	0.54	0.50	0.74
Maximum Entropy (maxNet)	0.87	0.66	0.62	0.95

AUC - Area Under the Receiver Operating Characteristic Curve, TSS - True Skill Statistic.

Based on the threshold method. The maximum threshold, based on which the habitat suitability was classified as suitable/unsuitable, was 0.76562. Applying this threshold, 1.3% of Romania represents areas with suitable habitat for *Ailanthus altissima*, around 3400 km² (Figure 3). The areas are in the south of Dobrogea and in the south-west of the country.

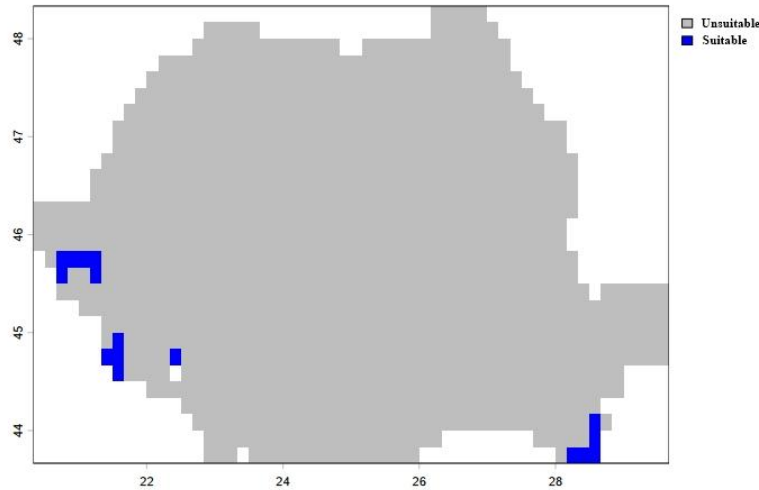


FIG. 3. Potential habitat suitability of tree of heaven in Romania

All the present suitable areas are predicted to become unsuitable in the future (contraction area) (Figure 4). The habitat suitability is predicted to improve in north-west of the country, for all periods and both SSPs, except 2081-2100 SSP5-8.5, reaching a maximum area of around 6000 km², under SSP2-4.5, for the 2041-2060 period (Figure 5). Under SSP5-8.5, the expansion area is lower than the contraction area.

Based on levels of suitability. One-third of the country has climate conditions representing a good or excellent habitat suitability for *Ailanthus altissima* (Figure 6). The excellent area is around 700 km², while the area with climate conditions corresponding to good habitat suitability for tree of heaven is around 84000 km². Our models found no areas where present or future climatic conditions correspond to unsuitable habitat (below 0.20). There were no areas with climate conditions classifying the habitat as unsuitable (under 0.20), neither for the present nor the future predictions (Figure 7). Under SSP5-8.5, there are no areas with climate conditions corresponding to excellent levels of habitat suitability, but for the 2081-2100 period, there will also be no areas with climate conditions corresponding to poor habitat suitability.

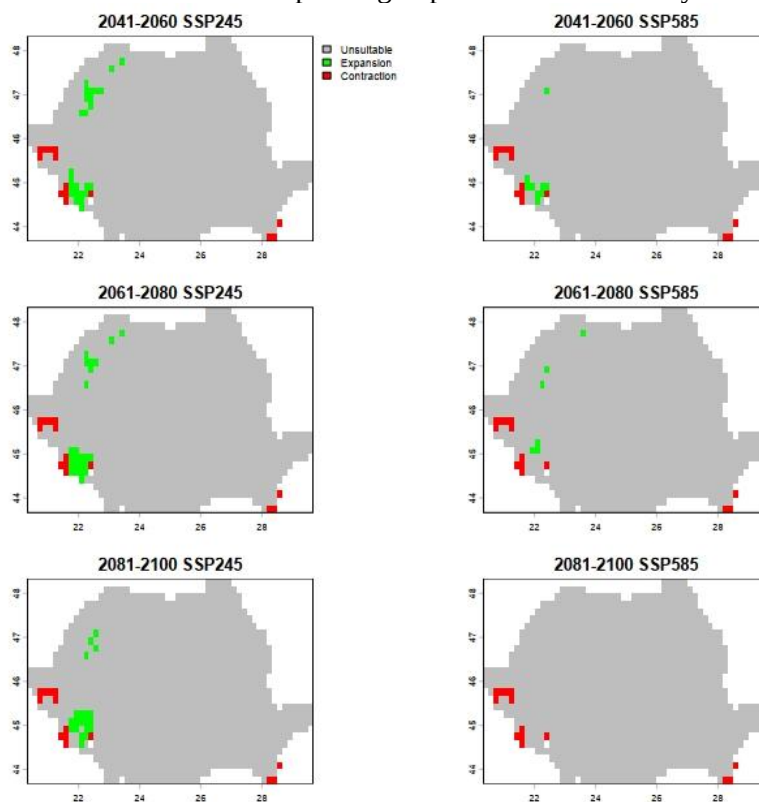


FIG. 4. Predicted shifts of the habitat suitability for *Ailanthus altissima* in Romania, for three periods and two Shared Socioeconomic Pathways

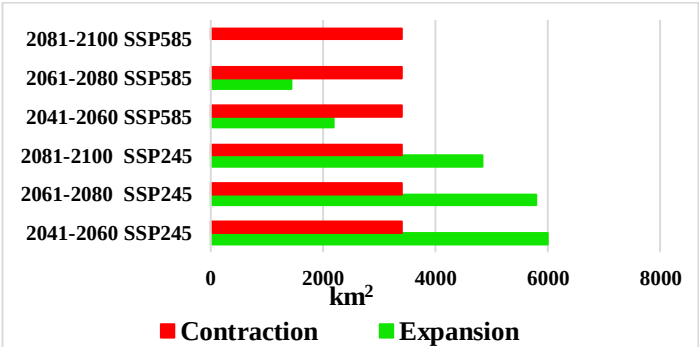


FIG. 5. Predicted shifts of the habitat suitability for *Ailanthus altissima* in Romania, for three periods and two Shared Socioeconomic Pathways

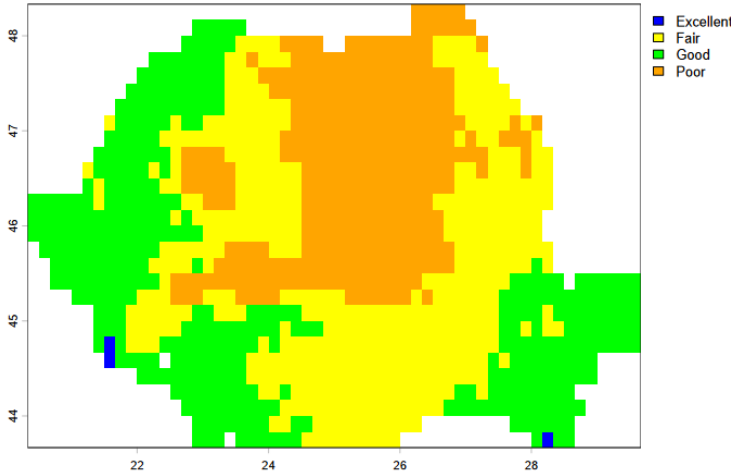


FIG. 6. Present levels of habitat suitability for *Ailanthus altissima* in Romania

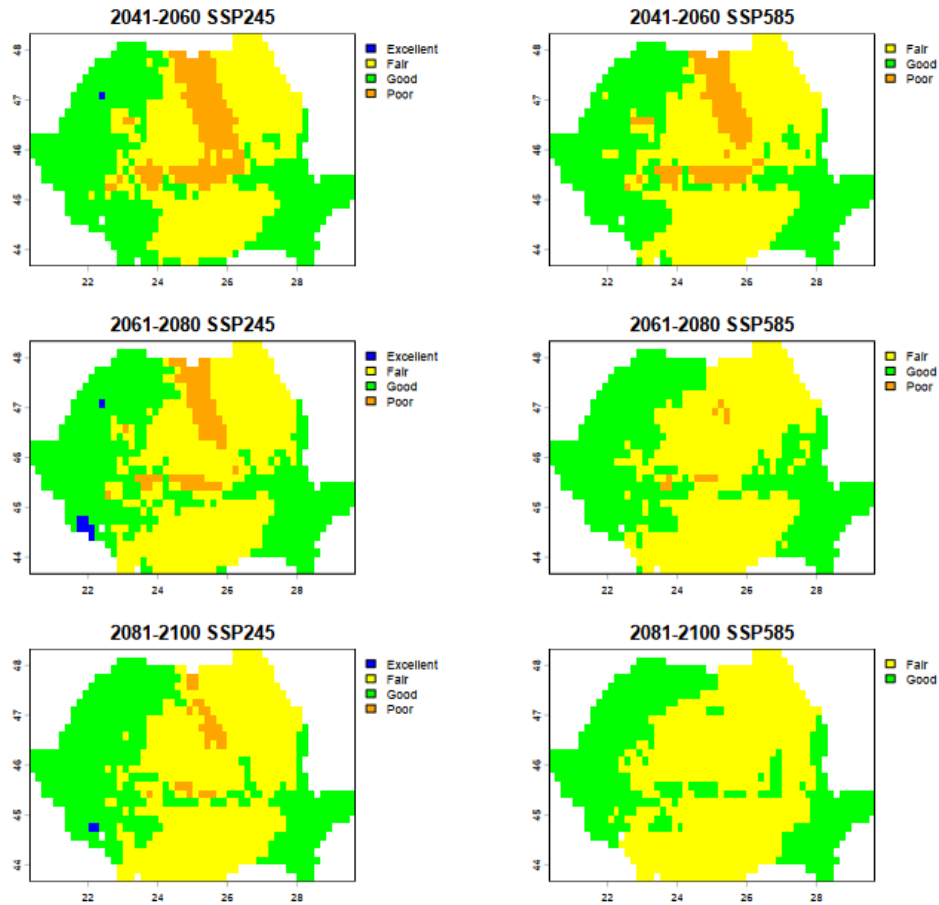


FIG. 7. Predicted levels of habitat suitability for *Ailanthus altissima* in Romania, for three periods and two Shared Socioeconomic Pathways

The area with climate conditions corresponding to poor habitat suitability will continuously decrease under both SSPs, while the area with fair habitat suitability will slowly grow (Figure 8). Areas with good habitat suitability based on climate variables are predicted to be relatively stable, around 105000 – 120000 km², reaching a maximum in the 2061-2080 period, then decreasing.

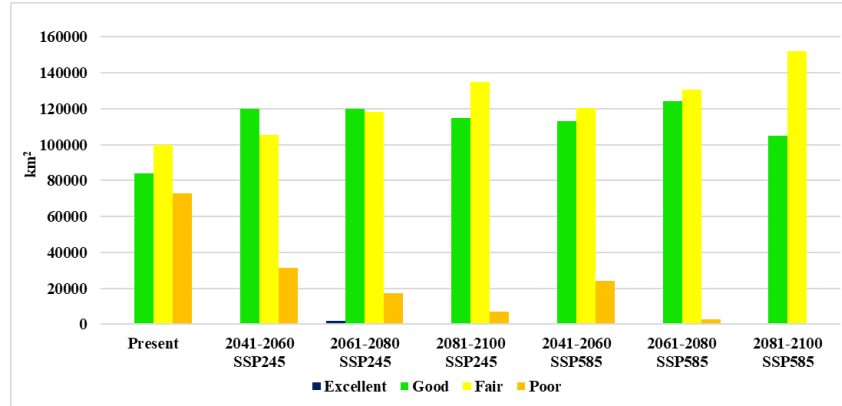


FIG. 8. Areas corresponding to the levels of habitat suitability of *Ailanthus altissima* in Romania

The ecological niches described by the four bioclimatic variables with the highest relative importance are presented in Figures 9-13. The habitat suitability for *Ailanthus altissima* is best in areas where:

- BIO15-Precipitation Seasonality is below 60 (Figures 9 and 10)
- BIO4-Temperature Seasonality is below 750 (Figures 10, 12 and 13)
- BIO9-Mean Temperature of Driest Quarter is between 4 and 25 °C (Figures 9, 11 and 12). The suitability drops swiftly above 25 °C BIO9(see also Figure 2).
- BIO14-Precipitation of Driest Month is at least 3-4mm (Figures 11 and 13)

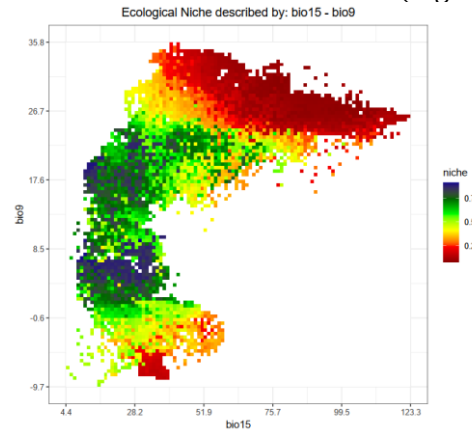


FIG. 9. Ecological niche described by BIO15-Precipitation Seasonality and BIO9-Mean Temperature of Driest Quarter

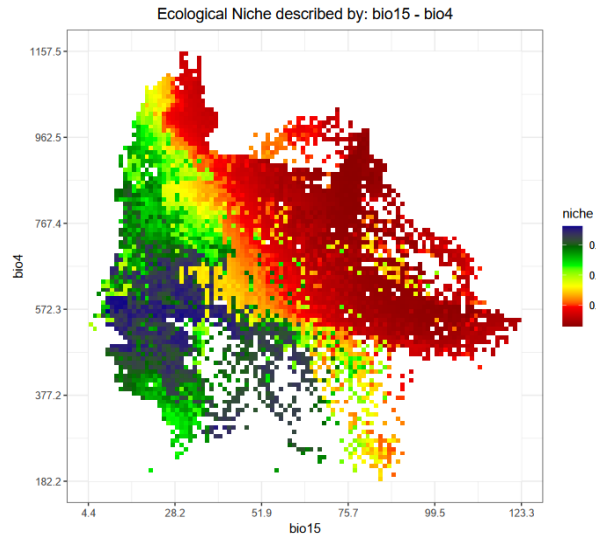


FIG. 10. Ecological niche described by BIO15-Precipitation Seasonality and BIO4-Temperature Seasonality

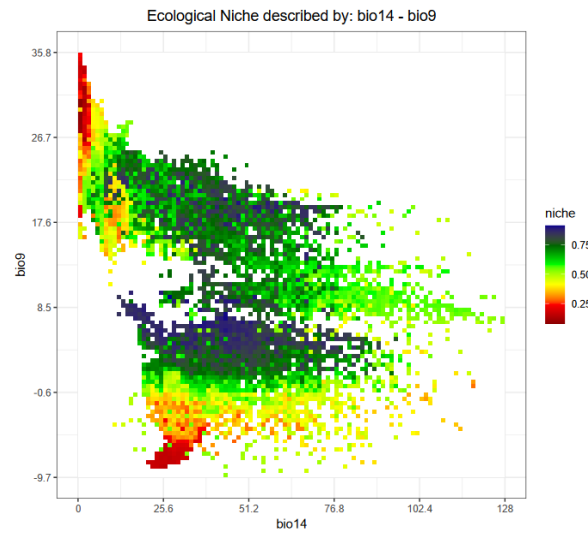


FIG. 11. Ecological niche described by BIO14-Precipitation of Driest Month and BIO9-Mean Temperature of Driest Quarter

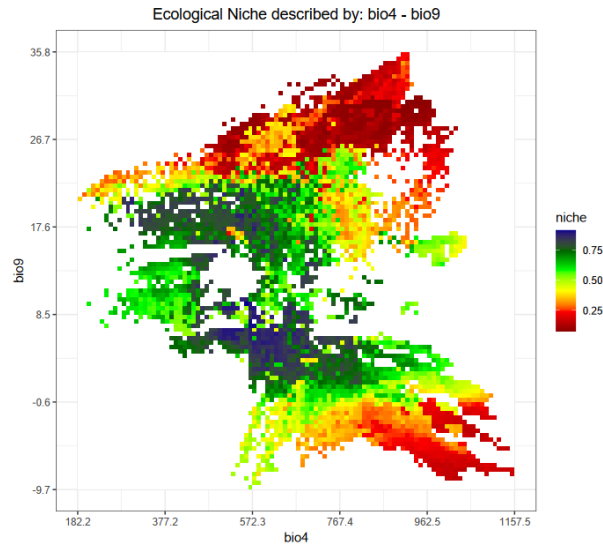


FIG. 12. Ecological niche described by BIO4-Temperature Seasonality and BIO9-Mean Temperature of Driest Quarter

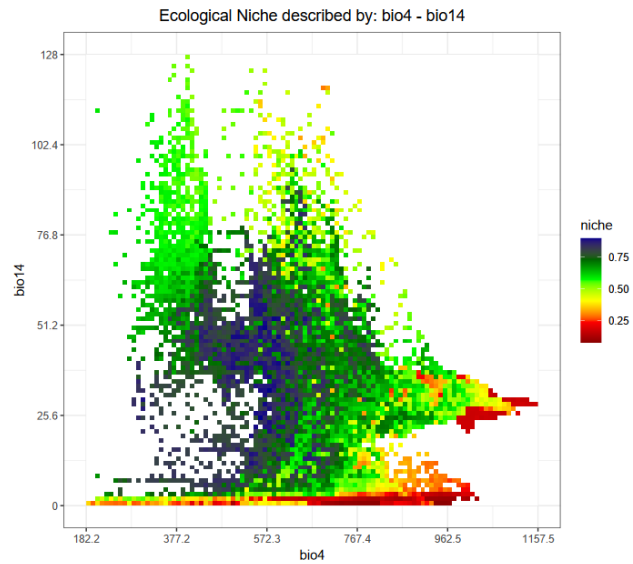


FIG. 13. Ecological niche described by BIO4-Temperature Seasonality and BIO14-Precipitation of Driest Month

DISCUSSIONS

In this study, the potential current and future habitat suitability of *Ailanthus altissima* in Romania were assessed, based on climate variables.

Analysing current climate conditions, the area with climate conditions that correspond to at least good habitat suitability for the species (above 60%) covers around 33% of the country. Under the future scenarios, this area could reach 48% (2061-2080 SSP5-8.5) and at least 40% (2081-2100 SSP5-8.5).

Although the current areas with potential suitable climate conditions for *Ailanthus altissima* are predicted to contract in all three periods and both SSPs, new areas are predicted to appear, mostly in the southwest and northwest of the country, in all periods and both SSPs, except in 2081-2100 under SSP5-8.5.

The climate conditions for the 2081-2100 period are predicted to correspond to a good habitat suitability for *Ailanthus altissima* in the Southern Carpathians, more so for the SSP5-8.5, indicating the expansion of the species to higher altitudes as well.

The climatic variables with the highest relative variable importance for the modelling of *Ailanthus altissima* in Europe were BIO15-Precipitation Seasonality, BIO4-Temperature Seasonality, BIO9-Mean Temperature of Driest Quarter and BIO14-Precipitation of Driest Month.

Our results confirm that *Ailanthus altissima* is resistant to drought, but not to extreme droughts (Șofletea and Curtu, 2007), a value of 0 of the BIO14-Precipitation of Driest Month indicating a low niche for the species (Figures 11 and 13).

In Tunisia, BIO19-Precipitation of Coldest Quarter and BIO8-Mean Temperature of Wettest Quarter were the climatic variables with the highest importance (Soilhi et al., 2024). In our study, they ranked fifth and sixth, with a relative variable importance of 12% and 5.2%, based on the correlation metric, and 5.7% and 4.9% under the AUC metric.

In southern Italy, it was concluded that the spread of *Ailanthus altissima* is not possible in areas where the BIO1-Annual Mean Temperature is lower than 11.1 °C (Motti et al., 2021). In western Slovenia, Čarni et. al. have found BIO11-Mean Temperature of the Coldest Quarter as the most discriminating variable for the identification of the habitat of *Ailanthus altissima*; based on BIO11, there are two suitable conditions: BIO11 higher than 3.8 °C coupled with seasonal precipitation, or BIO11 lower than 3.8 °C, BIO4-Temperature Seasonality and BIO17-Precipitation of Driest Quarter are low, altitude is below 655 m and inclination is under 23.8° (Čarni et al., 2017). In another study, for the entire Slovenia, altitude, insolation, land use and distance to water bodies

were the most important variables, while for the Slovenian forests, the most important variables were altitude and distance to railways (Groot *et al.*, 2024).

Isler *et al.* predicted an increase in the abundance of *Ailanthus altissima* in Switzerland in the short term (<100 years), but the species is becoming an additional admixed tree species in the long term (>200 years), not displacing other indigenous tree species (Isler *et al.*, 2023).

In our study, the response curve for the BIO8-Mean Temperature of Wettest Quarter variable was not bell-shaped, instead showing a continuous upward trend. This implies that low temperatures during the wettest quarter are a limiting factor for this species, but our model has not yet detected an upper thermal limit within our study area.

Methods of identifying the presence of the species. Deep learning and satellite imagery recognition were used to generate reliable and comprehensive maps of *Ailanthus altissima* distribution in the USA (Gao *et al.*, 2025).

Applying a potential distribution model, ITPS-PODISMOD, Grigorescu *et al.* found that 14% of the Măcin Mountains National Park (southeastern part of Romania) present high and very high potential distribution for *Ailanthus altissima*, using six factors: soil type, soil texture, land use/land cover, hypsometry, slope declivity, and slope exposure (Grigorescu *et al.*, 2016).

Methods of combating. Başnou and Vilà recommend some measures to combat the expansion of this species, of which we retain the following: avoiding planting the species as ornamental and the use of fungal pathogens (*Verticillium dahliae* and *Fusarium oxysporum*) (Başnou and Vilà, 2009). Miles *et al.* provide a review of potential biological controls for this species, focusing on *Verticillium nonalfalfae*, *Eucryptorrhynchus brandti* and *Aculops ailanthi* (Miles *et al.*, 2025). Mechanical actions, combined with chemical control, seem to be better than chemical control alone (Constán-Nava *et al.*, 2010; Meloche and Murphy, 2006; Soler and Izquierdo, 2024).

CONCLUSIONS

This study assessed how current and future climate variables impact the habitat suitability of *Ailanthus altissima* in Romania.

The climatic variables that most influence the distribution of the tree of heaven in Europe were: BIO15-Precipitation Seasonality, BIO4-Temperature Seasonality, BIO9-Mean Temperature of Driest Quarter and BIO14-Precipitation of Driest Month.

Under the present climate conditions, 1.3% of the country (around 3400 km²) represents the area corresponding to a habitat suitability above the 0.76562 threshold (suitable area), and an area of 700 km² is with excellent conditions (above 0.80).

Only for the period 2081-2100, there will be no new areas with climate conditions corresponding to a habitat suitability above the 0.76562 threshold. For the other periods and both SSPs, the expansion area is between 1400 and 6000 km².

Based on levels of habitat suitability, under SSP2-4.5, the area where climate conditions correspond to excellent habitat suitability for *Ailanthus altissima* reaches around 1700 km² for the 2061-2080 period, but drops to around 500 km² in the 2081-2100 period.

Under SSP5-8.5, there are no areas where climate conditions correspond to excellent habitat suitability.

Under both SSPs, the area where climate conditions correspond to the poor category of habitat suitability (between 0.20 and 0.40) is predicted to decrease with each following period, reaching 0 for the 2081-2100 period under SSP5-8.5.

Projecting the future distribution of *Ailanthus altissima* may enhance forest management strategies in Romania by identifying forest ecosystems and regions that are potentially vulnerable to future invasion.

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