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Forecasted changes in the suitability of the *Vanessa cardui* environment in agroecosystems of Ukraine under climate scenarios

V. Lohvynenko

Article info

Correspondence Author
V. Lohvynenko
E-mail:
vadym.lohvynenko@pdau.edu.ua

Poltava State Agrarian University,
Skovoroda Str., 1/3,
Poltava, 36000, Ukraine

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Modern climate change significantly transforms the functioning of agroecosystems and affects the spatial dynamics, abundance, and potential harmfulness of migratory phytophages in the temperate climate zone. In this regard, it is particularly important to study possible changes in the ecological niches of species capable of responding quickly to changes in climatic parameters. One such species is the painted lady butterfly *Vanessa cardui* (Lepidoptera: Nymphalidae), which is characterised by high migratory ability, broad ecological plasticity and the potential to form significant populations in agricultural landscapes. The aim of the study was to assess the current and projected suitability of the environment for Vanessa cardui and to determine possible changes in its potential range under different climate change scenarios. The analysis used georeferenced data on the species' localisation obtained from global biogeographical databases, which were combined with bioclimatic variables based on CMIP6 climate projections. Habitat suitability was modelled using the entropy maximisation (MaxEnt) algorithm, which is widely used to model the potential distribution of species based on presence-only data. The quality of the models obtained was assessed using AUC indicators and ROC curve analysis. The modelling results showed that the spatial distribution of Vanessa cardui is largely determined by temperature seasonality, the average temperature of the warmest quarter, and the amount of precipitation during the growing season. Forecasts indicate a possible redistribution of territories with varying levels of ecological suitability, an increase in the spatial mosaic of the environment, and fragmentation of optimal habitats under scenarios of more intense climate stress. At the same time, a significant part of the studied region retains a moderate level of environmental suitability for the species, which indicates not an unambiguous expansion or reduction of the range, but an increase in the variability of living conditions and potential instability of populations. The results obtained indicate a possible transformation of the balance between phytophagic pressure and natural ecological regulation in soybean agroecosystems, which is caused by changes in climatic parameters. The proposed approach to forecasting can be used in phytosanitary risk assessment systems, improving monitoring programmes and developing adaptive strategies for managing agroecosystems in conditions of climate uncertainty.

Keywords: climate change, environmental suitability, species distribution modelling, MaxEnt, soybean agroecosystems, migratory phytophagous insect, ecosystem services.

Прогнозовані зміни придатності середовища *Vanessa cardui* в агроекосистемах України за кліматичними сценаріями

В. В. Логвиненко

Полтавський державний аграрний університет,
м. Полтава, Україна

Сучасні кліматичні зміни істотно трансформують функціонування агроекосистем і впливають на просторову динаміку, чисельність та потенційну шкодочинність мігруючих фітофагів у помірній кліматичній зоні. У зв'язку з цим особливої актуальності набуває дослідження можливих змін екологічних ніш видів, здатних швидко реагувати на трансформацію кліматичних параметрів. Одним із таких видів є сонцевик будяковий *Vanessa cardui* (Lepidoptera: Nymphalidae), який характеризується високою міграційною здатністю, широкою екологічною пластичністю та потенційною здатністю формувати значні популяції в агроландшафтах. Метою роботи було оцінити сучасну та прогнозовану придатність середовища для *Vanessa cardui* і визначити можливі зміни його потенційного ареалу за різних сценаріїв кліматичних змін. Для аналізу використано геоприв'язані дані про локалізації виду, отримані з глобальних біогеографічних баз даних, які були поєднані з біокліматичними змінними, сформованими на основі кліматичних проєкцій CMIP6. Моделювання придатності середовища здійснювали за допомогою алгоритму максимізації ентропії (MaxEnt), що широко застосовується для моделювання потенційного розподілу видів на основі даних типу presence-only. Якість отриманих моделей оцінювали за допомогою показників AUC та аналізу ROC-кривих. Результати моделювання показали, що просторовий розподіл *Vanessa cardui* найбільшою мірою визначається температурною сезонністю, середньою температурою найтеплішого кварталу та кількістю опадів у вегетаційний період. Прогнозні оцінки свідчать про можливий перерозподіл територій з різним рівнем екологічної придатності, зростання просторової мозаїчності середовища та фрагментацію оптимальних зон існування за сценаріїв інтенсивнішого кліматичного навантаження. Водночас значна частина досліджуваного регіону зберігає помірний рівень придатності середовища для виду, що вказує не на однозначне розширення чи скорочення ареалу, а на підвищення варіабельності умов існування та потенційну нестабільність популяцій. Отримані результати свідчать про можливу трансформацію балансу між фітофагічним тиском і природною екологічною регуляцією в агроекосистемах сої, що обумовлюється змінами кліматичних параметрів. Запропонований підхід до прогнозування може бути використаний у системах оцінювання фітосанітарних ризиків, удосконаленні програм моніторингу та розробленні адаптивних стратегій управління агроекосистемами в умовах кліматичної невизначеності.

Ключові слова: кліматичні зміни, придатність середовища, моделювання розподілу виду, MaxEnt, агроекосистеми сої, мігруючий фітофаг, екосистемні дисервіси.

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Introduction

Climate change, accompanied by rising temperatures, changes in precipitation patterns and an increase in the frequency of extreme weather events, is having an increasingly strong impact on the spatial dynamics of phytophagous insects and, accordingly, on phytosanitary risks in agroecosystems [1–3]. One of the most sensitive components to such changes are migratory species, for which the climate determines the possibility of seasonal movement, the success of generational development and the formation of high-density populations. For *Vanessa cardui*, large-scale seasonal migration between Europe and Africa, including crossing the Sahara, has been proven, making this species a representative model for assessing climate-induced changes in range [4–6].

Recent studies emphasise that climate change is already causing noticeable shifts in the ranges of Lepidoptera and may alter the spatial structure of populations, particularly through changes in wind regimes, temperature thresholds for development, and seasonal resource availability. An important example is new data on the scale of *V. cardui* migrations and their connection with atmospheric processes, confirming the potential role of climatic factors as «transport» and «phenological» drivers of migratory insects [7].

To predict the spatial response of species to climate change, species distribution modelling (SDM) approaches are widely used in the world literature, in particular the MaxEnt algorithm, which allows assessing the suitability of the environment and constructing forecast maps for climate change scenarios [8–10]. The practice of using MaxEnt to assess the current and future potential distribution of insects, including economically significant pests, is actively developing and demonstrating its suitability for applied risk forecasting tasks in agriculture. At the same time, for the territory of Ukraine and, in particular, for agricultural landscapes where soybeans occupy an important place in the structure of agriculture, the issue of scenario forecasting of changes in the suitability of the environment for *V. cardui* using CMIP6 approaches remains insufficiently generalised and requires systematic analysis taking into account regional specifics [11, 12]. An important source of bioclimatic variables for such studies are global climate databases, in particular WorldClim, which provide high-resolution spatial data on temperature and hydrothermal characteristics of the climate [13].

For Ukraine, the issue of the impact of climate change on the spread of phytophagous insects and the structure of agroecosystems is particularly relevant, as changes in climatic conditions can significantly alter the phytosanitary status of agrocenoses and the stability of agricultural production. In particular, in the conditions of the Left-Bank Forest-Steppe, where soybeans occupy an important place in the structure of agriculture, climate change can affect the spatial dynamics of pest populations and related ecosystem risks [14–16].

In this regard, it is important to use modern methods of spatial analysis and environmental suitability modelling, which allow assessing possible changes in the potential range of species and their response to climate change [17, 18]. This approach provides a scientific basis for predicting phytosanitary risks and developing adaptive monitoring systems in agroecosystems.

The aim of the study

The aim of the study is to establish patterns of change in environmental suitability and spatial configuration of the potential range of *Vanessa cardui* (Linnaeus, 1758) under different CMIP6 climate scenarios using MaxEnt modelling to assess possible phytosanitary risks in soybean agroecosystems.

To achieve this goal, the following tasks were set:

• to create a database of georeferenced *V. cardui* findings and prepare input data for modelling;

• to select and justify a set of bioclimatic predictors and MaxEnt model parameters;

• to evaluate the quality of habitat suitability models using AUC and ROC indicators and determine the contribution of key climatic factors;

• to construct maps of current habitat suitability and forecast maps based on climatic scenarios;

• analyse spatio-temporal changes in environmental suitability and interpret them in terms of possible phytosanitary risks in soybean agroecosystems.

Materials and methods

To justify the selection of indicator groups of biota as indicators of ecosystem services and soybean agrocenoses, we used methods of analytical review and critical synthesis of scientific sources from the perspective of the concept of climate change in the conditions of the Left-Bank Forest-Steppe of Ukraine.

To form a list of indicator taxa and prepare initial data on their distribution, we collected and summarised information from open databases and literary sources, taxonomic verification, nomenclature standardisation, spatial validation of geographical references, filtering and elimination of duplicates, as well as bringing the data into a single spatial format for further analysis.

To assess the current and projected suitability of model species' habitats, species distribution modelling was applied based on presence data using multivariate suitability model algorithms, with model calibration and forecast quality assessment using standard accuracy metrics. GIS analysis of suitability maps and a scenario approach based on climate projections for different time intervals were used for spatial interpretation of results and comparison of scenarios. To summarise the impact of predictors and identify the leading factors in the dynamics, we used variable contribution analysis in models, response function interpretation, and comparison of determinants for groups representing regulatory services (entomophages), supporting services (pedobionts), and disservices (phytophages).

Results and discussion

Within Europe, *Vanessa cardui* is characterised by an extremely wide and almost continuous range, reflecting its high mobility and migratory life strategy (***Fig. 1***).

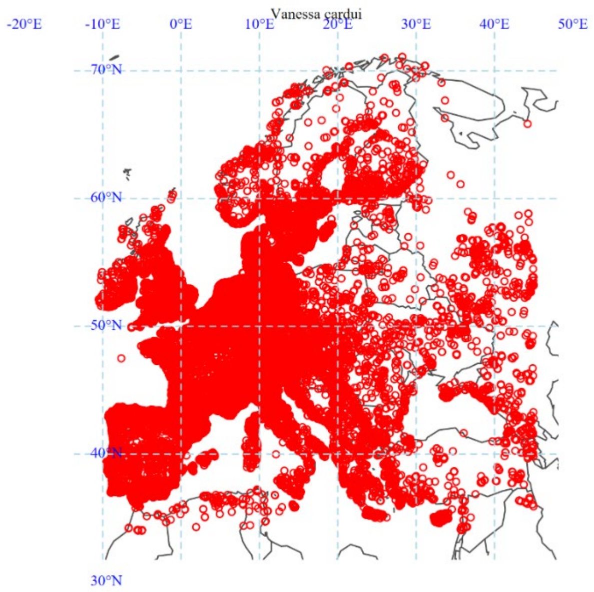

Fig. 1. Spatial distribution of *Vanessa cardui* (Linnaeus, 1758)
according to GBIF data (https://www.gbif.org/species/4299368)
(graphic representation by the author)

In general, the European distribution of *Vanessa cardui* should be interpreted not as a classic stable range, but as a dynamic spatial-temporal mosaic formed by regular interregional migrations, fluctuations in population size, and broad tolerance to climatic and landscape conditions.

Fig. 2 summarises the results of modelling the ecological niche of *V. cardui*, combining the assessment of the relative contribution of individual ecological factors and model quality indicators. Panel a (Variable contribution) shows that the formation of the species' ecological niche is primarily determined by the temperature characteristics of the cold season and indicators of thermal continentality. The average temperature of the coldest quarter has the greatest contribution, indicating the key role of winter temperatures in the spatial distribution of the species. The second position is occupied by isothermality, which reflects the ratio of daily and annual temperature variability and actually characterises the stability of the thermal regime. The minimum temperature of the coldest month and the annual temperature range also make a significant contribution, emphasising the importance of cold extremes and continental climate as limiting factors.

Among the second-order variables, bio04 (temperature seasonality) makes a noticeable contribution, which is consistent with the species' negative response to pronounced seasonal variability. Soil characteristics generally play a subordinate but not negligible role: the most significant of these are ocd_d5. This indicates an indirect influence of soil conditions through the structure of vegetation cover and the production potential of biotopes.

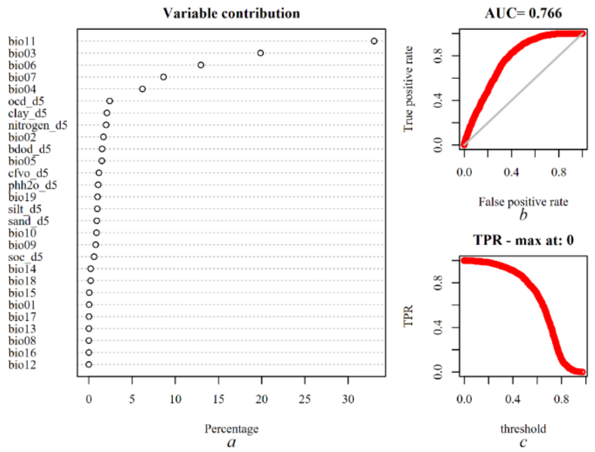

Fig. 2. Contribution of ecological factors to the formation of the ecological niche of *Vanessa cardui*

BIOCLIM climatic variables (temperature and hydrothermal regimes): bio01 – average annual air temperature (°C), bio02 – average daily temperature range (average difference between Tmax and Tmin), bio03 – isothermicity (bio02/bio07 × 100), bio04 – temperature seasonality (standard deviation × 100), bio05 – maximum temperature of the warmest month, bio06 – minimum temperature of the coldest month, bio07 – annual temperature range (bio05 − bio06), bio08 – average temperature of the wettest quarter, bio09 – average temperature of the driest quarter, bio10 – average temperature of the warmest quarter, bio11 – average temperature of the coldest quarter, bio12 – annual precipitation, bio13 – precipitation of the wettest month, bio14 – precipitation in the driest month, bio15 – precipitation seasonality (coefficient of variation), bio16 – precipitation in the wettest quarter, bio17 – precipitation in the driest quarter, bio18 – precipitation in the warmest quarter, bio19 – precipitation in the coldest quarter; soil variables (d5, 0–5 cm): bdod_d5 – bulk density of soil ($kg \cdot m^{-3}$), cfvo_d5 – volume fraction of coarse fragments (%), nitrogen_d5 – total nitrogen content in soil (%), phh2o_d5 – soil acidity (pH in water extract), sand_d5 – sand content (%), silt_d5 – silt content (%), clay_d5 – clay content (%), soc_d5 – soil organic carbon content (%), ocd_d5 – organic carbon stock density ($kg \cdot m^{-2}$).

Other soil variables and most precipitation indicators make a relatively small contribution to the model, which corresponds to the high ecological plasticity of the species in terms of moisture. The AUC value of 0.766 indicates good forecast quality, i.e. the model is significantly better than random guessing at distinguishing between conditions suitable and unsuitable for the species, but at the same time does not reach the level of almost deterministic prediction. This is a typical result for widespread, migratory species with a broad niche. Panel c (TPR depending on the threshold) shows the change in the proportion of true positive predictions as the threshold value increases. The maximum TPR value is achieved at a zero or near-zero threshold, after which the sensitivity of the model decreases sharply as the threshold increases. This curve shape means that the model reproduces the potential range of the species well, but with stricter selection criteria, it quickly «cuts off» a significant part of the territories, which again corresponds to the biology of *V. cardui* as a mobile, generalist species. The results in ***Fig. 2*** show that the ecological niche of

V. cardui is primarily structured by the thermal characteristics of the cold season and indicators of climatic stability, while precipitation and soil properties play a secondary, modulating role. This is consistent with the species' migration strategy and its ability to effectively utilise a wide range of landscapes in the absence of severe climatic constraints.

According to the modelling results (***Fig. 3***), the current potential range of *V. cardui* in Europe is characterised as wide, almost continuous and spatially slightly fragmented, which is consistent with the actual distribution pattern of this migratory species. The Maxent forecast map (left panel) shows high values of ecological suitability (green and yellow-green tones) across most of Western, Central and Southern Europe.

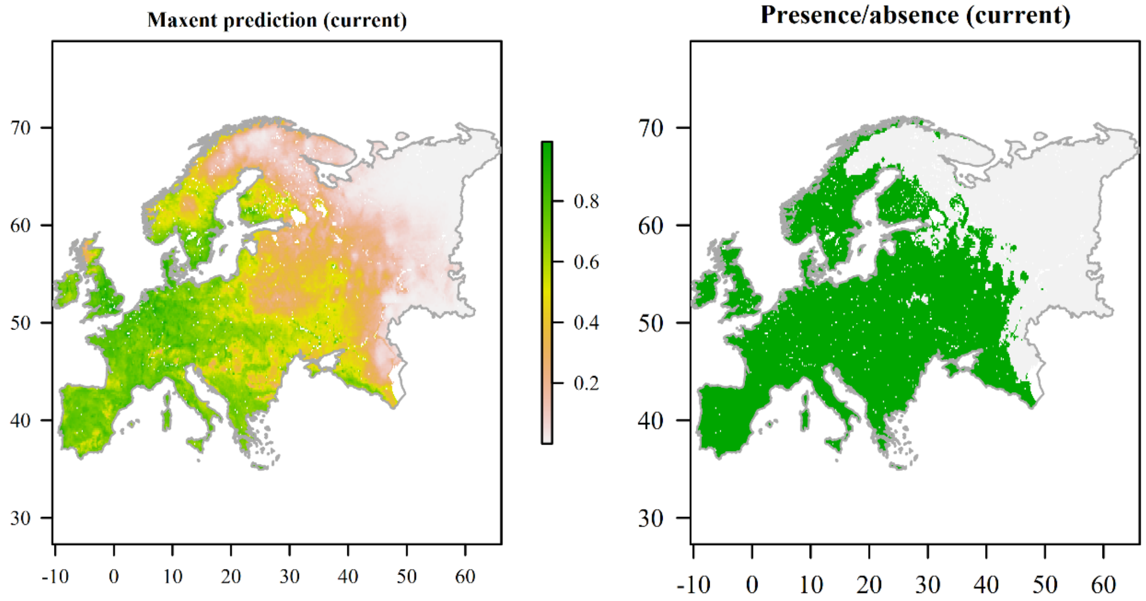

Fig. 3. Modelling of the current range of *Vanessa cardui*

The presence/absence map (right panel), obtained based on the model threshold value, shows an almost continuous potential presence of the species across most of Europe.

This spatial pattern confirms that the actual range of the species is determined not so much by rigid climatic barriers as by migration dynamics, interannual fluctuations in population size and the availability of temporarily suitable habitats, making Vanessa cardui one of the most ecologically plastic butterflies in Europe. According to the forecast (***Fig. 4***), *V. cardui* retains a wide potential range within Europe under all considered climate change scenarios, so the expected changes in populations are more likely to be related to the redistribution of suitable territories and changes in the spatial stability of habitats than to a sharp overall decline in the species. In the near future (2021–2040), the picture will remain almost unchanged from the present: most of Western, Central and Southern Europe will remain suitable, while in the north there is potential for regular incursions of the species and the maintenance of migration waves. This means that numbers and frequency of sightings in most regions should remain high, with possible changes manifesting themselves mainly as seasonal and interannual fluctuations typical of a migratory butterfly.

Time intervals: 2021–2040, 2041–2060 and 2061–2080, corresponding to the short-, medium- and long-term prospects for climate change in the 21st century. The calculations were made using Shared Socioeconomic Pathways (SSP) scenarios: SSP1-2.6 – a sustainable development scenario with low greenhouse gas emissions; SSP2-4.5 – a moderate scenario with an average level of climate impact; SSP3-7.0 – a scenario of regional fragmentation with high emissions; SSP5-8.5 – a scenario of intensive economic growth accompanied by very high greenhouse gas emissions. Green indicates areas classified by the model as suitable for the potential presence of the species under appropriate climatic conditions, while light areas correspond to zones with low predicted environmental suitability.

According to ***Table 1***, within the Forest-Steppe zone as a whole, a relatively stable background of habitat suitability for *V. cardui* can be observed in the short and medium term, while more significant changes are concentrated mainly in the distant interval 2061–2080 and are manifested mainly under high emission scenarios.

If we generalise the «core» of forest-steppe regions, for which the zone is directly designated as Forest-Steppe, the average current index level is about 0.58 and in 2021–2040 it remains virtually unchanged under SSP1-2.6 (also about 0.58), remaining very close to the current level under SSP3-7.0 and even increasing slightly under SSP5-8.5, while under SSP2-4.5 a slight ‘decline’ (by about one hundredth) is recorded. In 2041–2060, these fluctuations remain small: for SSP1-2.6 and SSP3-7.0, the average values remain close to the current level, and SSP2-4.5 and SSP5-8.5 show only moderate deviations without a clear trend towards a systematic decline.

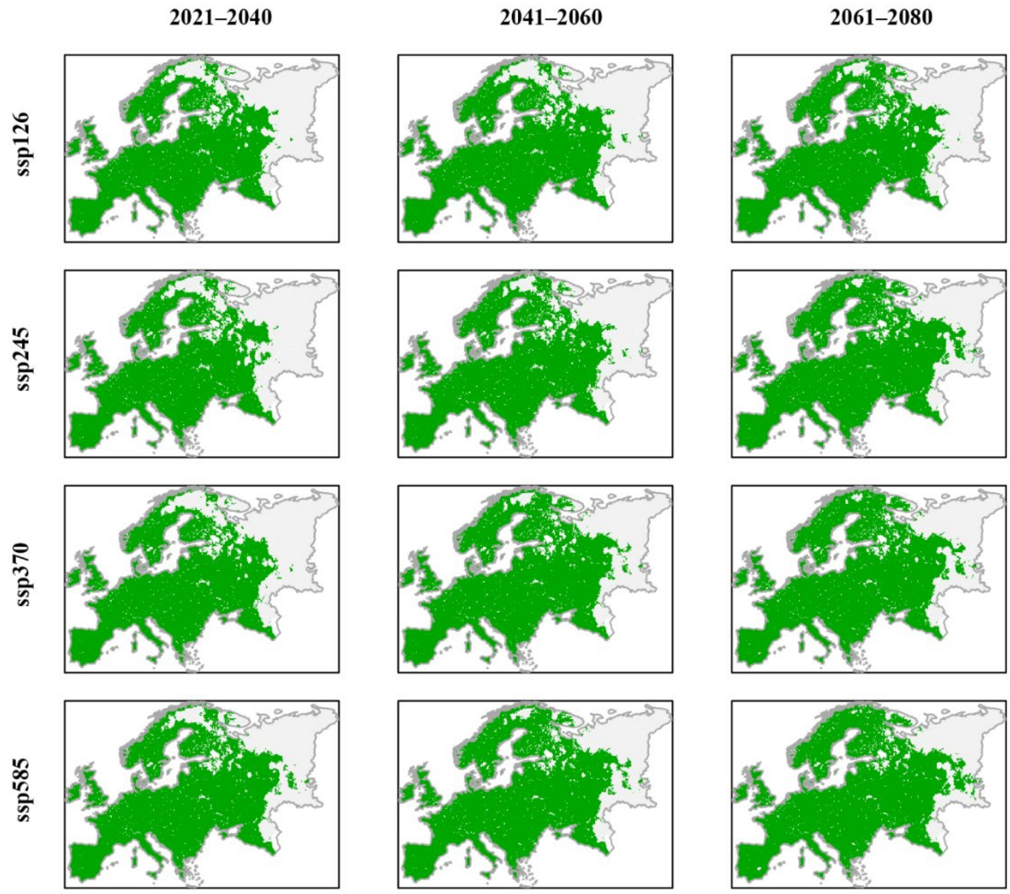

Fig. 4. Forecast of changes in the range of *Vanessa cardui* over time depending on different climate change scenarios

Table 1
Forecast of the habitat preference index for *Vanessa cardui* over time depending on different climate change scenarios

Region	Physical-geographical zone	Current	2021				2041				2061			
			ssp1 26	ssp2 45	ssp3 70	ssp5 85	ssp1 26	ssp2 45	ssp3 70	ssp5 85	ssp1 26	ssp2 45	ssp3 70	ssp58 5
Cherkasy	Forest-Steppe	0.57	0.57	0.56	0.56	0.58	0.57	0.56	0.57	0.57	0.57	0.57	0.55	0.53
Kharkiv	Forest-Steppe (south-east – transition to steppe)	0.52	0.51	0.49	0.5	0.5	0.51	0.49	0.51	0.49	0.50	0.51	0.48	0.47
Kyiv	Polissya – Forest-Steppe (transitional)	0.54	0.54	0.53	0.54	0.55	0.54	0.54	0.55	0.55	0.54	0.55	0.54	0.54
Kyiv	Polissya – Forest-Steppe (transitional)	0.48	0.48	0.47	0.48	0.49	0.48	0.47	0.48	0.48	0.48	0.49	0.47	0.47
Kirovograd	Forest-Steppe (south – transition to steppe)	0.54	0.53	0.5	0.53	0.54	0.53	0.52	0.54	0.51	0.53	0.52	0.48	0.46
Poltava	Forest- steppe	0.53	0.53	0.51	0.52	0.53	0.52	0.51	0.53	0.51	0.52	0.53	0.49	0.47
Sumy	Forest-Steppe – Polissya (transitional; forest-steppe often dominates)	0.48	0.49	0.47	0.48	0.49	0.48	0.48	0.49	0.49	0.48	0.49	0.48	0.47

In this context, the Poltava region appears to be a «middle» forest-steppe region with moderately high suitability in the current climate (0.53) and maintaining this level in the coming decades under low and very high scenarios in 2021–2040 (SSP1-2. 6 = 0.53; SSP5-8.5 = 0.53), while under SSP2-4.5 and SSP3-7.0 there is a slight decrease to 0.51–0.52. In 2041–2060, Poltava region continues to demonstrate stability without a directed trend: values fluctuate between 0.51–0.53 (SSP1-2.6 = 0.52; SSP2-4.5 = 0.51; SSP3-7.0 = 0.53; SSP5-8.5 = 0.51), i.e. the model does not indicate a systematic "erosion" of suitable conditions in the medium term. The most significant changes for the region appear in 2061–2080 and are clearly scenario-driven: under

SSP1-2.6 and SSP2-4.5, the index remains close to the current level (0.52–0.53), but under SSP3-7.0 it drops to 0.49, and under SSP5-8.5 to 0.47, i.e. the relative decline compared to the current state is approximately 0.04–0.06. In terms of population interpretation, this means that for the Poltava region, under low and moderate climate change trajectories, conditions sufficient for the regular presence of the species are expected to be maintained, while under high scenarios in the long term, there is an increased likelihood of reduced stability of presence, greater interannual variability in abundance, and increased dependence on migration inflows and the local mosaic of food resources and microclimatic «refugia» in the forest-steppe landscape.

The results of the modelling are consistent with current understanding of the influence of climatic factors on the spatial dynamics of migratory Lepidoptera. Previous studies have shown that the distribution of *Vanessa cardui* is largely determined by environmental temperature parameters, in particular seasonal temperature and temperature conditions during the cold season, which affect the success of overwintering, phenology and migration processes of the species [1–5, 19]. The results obtained in our study confirm the dominant role of temperature variables in the formation of the ecological niche of *V. cardui*, which is consistent with the conclusions of other authors regarding the climatic determination of the migrations of this species.

The use of the MaxEnt algorithm for modelling environmental suitability is also consistent with

current practice in species distribution research. As noted by Elith J. and Merow C. et al., this approach is one of the most effective tools for analysing the potential distribution of organisms based on presence-only data and is widely used to assess the impact of climate change on biodiversity and pest distribution [8–10]. The AUC values obtained in our model correspond to typical indicators for species distribution studies with a broad ecological niche and high migratory activity.

The predicted changes in the spatial structure of suitable habitats for *V. cardui* are consistent with the results of other studies, which show that climate change more often leads not to a sharp expansion or contraction of the range, but to an increase in spatial mosaicism and fragmentation of suitable territories [20–22]. Similar trends may manifest themselves in the form of increased interannual variability in population size and instability of local species populations.

From a practical point of view, this means that in soybean agroecosystems, spatial and temporal variability of phytophagous pressure may increase. This situation requires the improvement of pest monitoring and forecasting systems using climate-oriented models, which will allow for the timely assessment of phytosanitary risks and the planning of adaptive agroecosystem management measures in the context of climate change [23–25].

Conclusions

The study proved that the state and spatio-temporal dynamics of biota determine the ability of agrocenosis to maintain productivity and ecological stability without excessive dependence on external resources. To analyse the main ecosystem services, indicator groups representing different functional blocks of the agroecosystem were used. Entomophages (beneficial insects) were considered as indicators of regulatory services. Pedobionts are considered as indicators of supporting services: soil formation, structure formation, organic matter transformation, and element cycling. Pests are considered as agents of ecosystem disservices: risks that reduce crop yields and system stability, and as indicators of the potential intensification of harmful effects under climate instability.

The dominant factors in the dynamics of indicator groups in the context of climate change differ, but they share a common climatic context. For entomophages, temperature indicators (especially seasonality and cold period parameters) dominate, determining overwintering, phenology and synchronisation with the food base; the hydrothermal regime of the growing season is also significant. At the same time, the actual level of services will be determined both by the climate and by the quality of agroecological management, which can compensate for some of the negative trends by supporting biodiversity and the functional integrity of the agricultural landscape.

The practical value of the information obtained lies in the formation of a decision support system for the adaptation of soybean production. The results can be used for territorial risk differentiation (identification of areas where the likelihood of weakening biocontrol or deterioration of soil functions will increase); prioritisation of adaptation measures (integrated plant protection with a focus on preserving beneficial biota; soil conservation technologies; maintaining organic matter and minimising compaction; landscape elements that serve as refuges for entomophages and pedobionts); optimisation of monitoring (transition to monitoring indicator groups as proxy indicators of services, enabling early warning of service degradation); justification of regional recommendations for agricultural policy and advisory services to improve the resilience of soybean agrocenoses in conditions of climate uncertainty.

DECLARATIONS

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Conflict of interest
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Declaration of AI and AI-assisted technologies
The authors declare that no artificial intelligence or AI-assisted technologies were used in the preparation of this manuscript.

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ORCID

V. Lohvynenko https://orcid.org/0009-0006-8299-6148