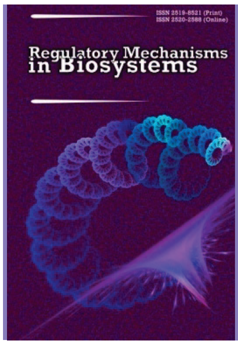

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Bioclimatic projection of the ecological niche of curly mallow (*Malva verticillata*) based on the forecast of the dynamics of the geographical range in the context of global climate change

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Curly mallow (*Malva verticillata* L.) is a promising species for cultivation to obtain valuable compounds for the application in medicine, and this species can be used in the bioenergy system to provide industry with alternative energy sources. For the highest economic efficiency, the practical use of this species requires the development of complex measures related to both agrotechnologies and selective breeding. Such measures require resources and there is an urgent problem of assessing the prospects of such investments taking into account the global climate change. Therefore, the problem that we aimed to solve was the assessment of how the global climate change would impact the curly mallow in general in the global context, as well as in the conditions of Ukraine in the next 50–70 years. The database of the Global Biodiversity Information Facility (GBIF) contains 2,104 records of curly-leaved mallow. This species is found on all the continents except Antarctica. Asia accounts for 39.1% of the species' range, Europe – 53.3%, Africa – 3.6%, North America – 3.2%, South America – 0.1%, Australia – 0.8%. The modelling of *M. verticillata* response to the climatic factors showed that the best response models were V (in 31.6% of cases) and VII (in 36.8% of cases). Model V characterizes unimodal bell-shaped asymmetric response, and model VII – bimodal asymmetric response. The species response to the mean annual temperature is asymmetric bell-shaped with a shift to the right. The optimal average annual temperature for this species is 9.1 °C. Comparing the distribution of available resources and their use is the basis for identifying the features of the ecological niche of the species. The MaxEnt approach indicates that Southeast Asia and Europe have the most favourable conditions for the existence of this species. Changes in the climatic conditions over the next 50–70 years will make the conditions for the life of *M. verticillata* in the southern hemisphere unfavourable, and the favourable conditions for it in the northern hemisphere will shift significantly to the north. At the same time, conditions in the autochthonous range of the species will become unfavourable. Obviously, if not for the significant potential of the species to disperse, it would have died out as a result of the significant climate change. The area where favourable conditions for the species will remain unchanged is Central Europe. Conditions in Eastern Europe, including Ukraine, will moderately improve. The results indicate the perspective of the cultivation of curly mallow in Ukraine in the future.

Keywords: spatial ecology; agriculture; global warming; biodiversity; extinction; species protection.

Introduction

Agriculture contributes significantly to the anthropogenic global warming and reducing agricultural emissions (mainly methane and nitrous oxide) can play an important role in mitigating the climate change (Lynch et al., 2021). The global climate change has affected agro-ecological conditions, affecting the growth of such an important agricultural indicator as the average temperature of the growing season (Arnell & Freeman, 2021). Hotter summers, changes in rainfall and increasingly frequent extreme weather events have led to significant losses in agriculture (Diffenbaugh et al., 2021). Moreover, due to the climate warming over the next decades, the risks for agriculture will increase (Fick & Hijmans, 2017). Those risks create an urgent need to model the state of agriculture in the future climate conditions (Fitzgibbon et al., 2022). The climate change is influenced by the natural factors and human activities (Pidlisnyuk et al., 2020). This clearly changes the biodiversity, agricultural production and food security. Mostly, the highly adapted and endemic species are under the threat of extinction (Zhukov et al., 2022). Accordingly, the concern about species extinction is real, since plants provide food for all forms of life and primary health care for more than 60–80% of people worldwide (Muluneh, 2021). Climatic factors significantly shape the distribution of many species, and the dynamics of climatic conditions prmote changes in their ranges (Avtaeva et al., 2021). The identification of climate projection of the ecological niche of species is an important aspect of agroecological, biogeographical and ecological research (Brandmayr, 2016). The study of climatic factors is especially important regarding the current global changes in the climate system and there organization of biosphere processes (Zymaroieva et al., 2022). The methods of environmental analysis based on the spatial ecology (Neuhauser, 2001) allow modelling species distribution not only for the current period, but also for the future, taking into account climate change forecasts (Moullec et al., 2022).

The *Malva* genus is a widespread group of plants of tropical and temperate latitudes, belonging to the Malvaceae family (Sharifi-Rad et al., 2020). This genus includes at least 25–30 different species, which are distributed in temperate, subtropical and tropical regions of Africa, Asia and Europe, as well as in China, India, Central Asia, the Mediterranean, South America, America and Mexico (Ray, 1998). Those plants are fast growing and used as garden flowers, while some grow as invasive weeds, especially in the United States where they are not native. The curly mallow (*Malva verticillata* L.), the natural range of which is Southeast Asia, has a potential for agricultural use. This plant has long been in cultivation in China, where several vegetable varieties of it with purple and white stems and large and small leaves have been cultivated since about 500 AD. During the 7–10th centuries, the cultivation of this crop in China declined. In 1848, it was observed only in remote areas. The species was introduced to Japan, where it is now a weed. Now, the species is widespread in western Asia and Europe. In Europe, it is cultivated as a medicinal crop (Zeven & de Wet, 1982). This plant is grown from seeds in early spring (Vogl et al., 2013). In the West, young leaves of the plant are processed as greens similar to lettuce and used as a filling for rice (Veshkurova et al., 2006). Mallow species have been used in medicine since ancient times. In Catalonia (Spain), the leaves are used to treat urticaria or hives (*Urtica dioica* L.) (Vogl et al., 2013), and in Austria it is used in the form of tea for the treatment of skin diseases and infections of the respiratory tract and gastrointestinal tract (Vogl et al., 2013). In traditional Iranian medicine, the leaves are used to treat cuts, eczema, infected skin wounds, bronchitis, digestive problems and inflammatory disorders, as indicated in the Unani medical literature (Henry & Piperno, 2008). The research of *Malva* plants has shown important therapeutic properties such as anti-ulcerogenic, antioxidant, anticancer, preservation of skin tissue integrity and anti-inflammatory (Quave et al., 2008; Barros et al., 2010). Many species of this genus have been shown to be effective for coughs, bladder ulcers, intestinal infections, colitis, tonsillitis, gastroenteritis, as a means to lower cholesterol and lipids, as an antihypertensive, antioxidant, analgesic, emollient, for the chest girdle, as well as in the treatment of arteriosclerosis (Abdel-Ghani et al., 2013).

Among 4,200 species belonging to the Malvaceae family, mallows belong to the group of economically important species (Sharifi-Rad et al., 2020). In addition, in their natural habitats, mallows grow as weeds of many agricultural plants or are cultivated in gardens and fields. The name comes from the Greek word "malasso", which indicates their emollient properties, mainly related to the mucous canals, cavities and epidermal cells located both in the roots and in the aerial parts of the plants. Mallow species are annual, biennial or perennial terrestrial herbs spread almost throughout the world, however, mainly in Europe, Asia, North Africa and America. Those that are found in Australia (*M. rotundifolia* L., *M. parviflora* L., *M. verticillata* L. and *M. sylvestris* L.) are mostly considered naturalized weeds. There is no certainty on where the mallow species have originated from, but the Mediterranean and Southwest Asian regions are indicated as probable centers of diversity. The vegetative parts are usually covered with hairs; the stipule apparatus is variable. The leaves are simple, alternate, more or less palmately dissected, with stipules. The flowers are actinomorphic, hermaphroditic, with five sepals and five petals. The bracts form an epicarp, the fruit is a schizocarp with numerous single-seeded mericarpies. Depending on the classification, there are up to 40 species within the genus (Ray, 1995). Most mallow species are nitrophilous plants that require nitrogen-rich soils for normal growth. Their habitats are usually warm and brightly lit, located mainly in temperate zones. The plants thrive on moderately dry soils that have a normal variation of moisture content, neutral or alkaline chemical reaction and are somewhat aerated. Mallow species are commonly found in ruderal habitats and grasslands (Landolt, 2010). In the monograph by Tarasov (2012) for the flora of Dnipropetrovsk and Zaporizhia Oblasts, there are data for 4 species of the *Malva* genus: *M. mauritiana* L., *M. neglecta* Wallr., *M. pusilla* Smith, and *M. sylvestris* L. Species *M. mauritiana* L. is synonymous with *M. sylvestris* L.

Malva verticillata (Chinese mallow, or curly mallow) is a popular leafy plant in East Asia, used as herbal tea and as a medicine (Odontuya, 2012). Over the past few decades, the use of *M. verticillata* as a food product has spread from East Asia and consumers can easily find it on markets around the world. The seeds of *M. verticillata* are also used in traditional Chinese medicinal formulas as a diuretic, laxative and galactopoietic agent (Gonda et al., 1990). Despite its use in medicine, the chemical composition and biological activity of the aerial parts of *M. verticillata* are not well understood. It is known that crude vegetable oils contain large amounts of partial acylglycerides, such as diacylglycerols or monoacylglycerols (Franke et al., 2009). Lipid droplets (LDs) such as acylglycerides are dynamic organelles that regulate lipid storage and trafficking (Farese & Walther, 2009), and they play an important role in membrane and lipid transport, protein storage, protein degradation and replication of hepatitis C and dengue viruses (Martin & Parton, 2006). In addition, acylglycerides have been reported to have anticancer (Abdel-Hamid et al., 2012), anti-neuroinflammatory (Wu et al., 2016) and anti-tumour (Ramos-Bueno et al., 2016) activities. Mature seeds of *M. verticillata* have been used for centuries as a diuretic and laxative medicinal product (Azab, 2017). Recently, an aqueous extract of *M. verticillata* seeds was reported to inhibit osteoclastogenesis and bone resorption by inhibiting receptor activator of NF-κB ligand signaling pathway (RANKL), without affecting osteoblast differentiation (Shim et al., 2016). Ethanolic extracts from *M. verticillata* seeds increased the concentration-dependent activity of the Wingless-related integration site (Wnt) and led to an increase in the level of β-catenin in cultured human dermal papillae cells (DPC) (Lee et al., 2016). Gas chromatography and mass spectrometry (GC-MS) revealed that *M. verticillata* contains the following chemical compounds: 1,3-dihydroxyacetone dimer, D-alanine, 5-hydroxymethylfurfural, 2-hydroxygamma-butyrolactone, palmitic acid, oleamide and β-sitosterol (Shim et al., 2016). Moreover, myristolic acid, a compound found in the seeds, stimulates the proliferation of DPCs in a dose-dependent manner and increases the transcriptional levels of downstream targets such as insulin-like growth factor 1, vascular endothelial growth factor and hepatocyte growth factor (Lee et al., 2016). The leaves, stems and seeds of *M. verticillata* have been shown to be a rich source of phenolic compounds. In particular, the leaves contain a variety of flavonoids and their derivatives, which are ideal for scavenging free radicals 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) and have a ferric reducing antioxidant power (Bao et al., 2018).

Curly mallow is a promising species for cultivation for obtaining valuable medicinal compounds, and this species can be used in the bioenergy system to provide industry with alternative energy sources. A complex of measures related to both agrotechnologies and selective breeding should be designed for the greatest economic benefit of using the plant. Such measures require resources and there is an urgent problem of assessing the prospects of such investments taking into account the global climate change. Therefore, the objective of the study was assessment of the impact the global climate change would make on the curly mallow around the world in general and in Ukraine in the perspective of the next 50–70 years.

Materials and methods

Ecological niche factor analysis. Hutchinson (1957) defined the ecological niche as a hypervolume in a multidimensional space determined by the environmental variables where a species can potentially maintain viable populations. The Ecological Niche Factor Analysis (ENFA) procedure is based on this concept. The habitat is characterized by the availability of resources and conditions for a given species in a certain area, which makes it possible for the species to inhabit this area, including its survival and reproduction (Hall et al., 1997). The purpose of studying habitat selection by species is to identify environmental characteristics that make a place suitable for a species (Calenge et al., 2008). Theoretically, the distinction between habitat and non-habitat becomes apparent by comparing the composition of environmental properties of areas where the species occurs and areas where the species is absent. However, areas where the species is absent are difficult to identify. The species may have not been discovered in an area due to imperfect survey methods. A species may be absent from a site for historical reasons. Not only environmental properties can determine habitat. Therefore, habitat selection analysis often consists of comparing sites where the species occurs and all available sites. The study area can be represented as a collection of discrete resource units (RUs), which can correspond to pixels on a raster map or a locus on a vector map. Each RU is characterized by a list of environmental variables (elevation, slope, biomass, etc.). The use of available RUs can be measured. For example, the number of plants found in each pixel of a raster map can be estimated. Factor analysis of ecological niches is based on the assumption that species are distributed non-randomly with respect to ecogeographic variables (Hirzel et al., 2002). The ecological niche of a particular species may be characterized by some marginality (expressed as the difference between the species mean and the global mean of an ecogeographic variable) and some specialization (expressed as the species variance being smaller than the global variance). The ecological niche is a useful model for describing habitat selection by a species.

A raster map consisting of N isometric cells covering the entire study area was used to conduct an ecological niche factor analysis. Each raster cell contains the value of one variable. The ecogeographic map contains continuous values measured for each of the descriptive variables. The species map contains Boolean values (0 or 1). A value of 1 means that the presence of the species of interest in the given cell has been confirmed. The value 0 means that there is no evidence of the species presence. Thus, each cell in the image is associated with a data vector the components of which represent the values of ecogeographic variables within the space bounded by that cell and can be represented as a point in a multidimensional space of ecogeographic variables. If the distribution of the variables is multivariate normal, then the scatter plot of these points will have the shape of a hyper-ellipsoid. The cells where the species of interest has been detected represent a subset of the global distribution that is shaped like a smaller ellipsoid within a larger ellipsoid. The first factor, or marginality, is a straight line that passes through the centroids of the two ellipsoids. The marginality of a species is the distance between these centroids. In order to obtain the specialization factors, the original system is transformed so that the species ellipsoids become spheroids, the variation of which is equal to one in all directions. The first specialization factor maximizes the variation of the global distribution, being orthogonal to the marginality factor. The next specialization factor to be extracted describes the maximum remaining part of the variation, and it must be orthogonal to the previously extracted ones. All specialization factors are orthogonal in the sense that the distribution of a subset of a species by these factors is independent of each other. Among the specialization factors, ranked by decreasing importance, the first few will contain the bulk of the essential information. Their smaller number and independence will make their use more appropriate than data on the original ecogeographic variables. The coefficients mi of the marginality factor expresses the marginality of the species of interest for each ecogeographic variable, which is represented in units of the standard deviation of the global distribution. The higher the absolute value of the coefficient mi, the further the species optimum is from the mean value of the corresponding variable within the study area. A negative value of the coefficient indicates that the species prefers values of the ecogeographical variable lower than its global average, while a positive value indicates a preference for variable levels higher than the average in the area under study. The coefficients of other factors (specialization factors) can be interpreted as follows: the higher the absolute value of the coefficient, the more restricted range of the variable can be inhabited by the species of interest. Ecological-niche factor analysis calculations were performed using the adehabitatHSlibrary (Calenge, 2011).

Gradient analysis. Species respond to environmental gradients. Describing their distribution along those gradients is important agroecological knowledge. The distribution of a species along a gradient is called the species response curve. Many species exhibit unimodal response curves and this curve is often symmetrical. Such a response curve can be easily modelled using a normal distribution model, which can be specified by three parameters: optimum, tolerance and maximum response. The optimum characterizes the place where the species is most likely to be found, i.e. the peak of the distribution. For any distribution, the optimum is equivalent to the mode of the distribution. For a symmetric distribution, the optimum is also equivalent to the mean of the distribution. Tolerance measures the ability of a species to live in a suboptimal environment, i.e. describes the spread or width of the distribution. For a symmetric distribution, it is equivalent to the standard deviation of the distribution. Maximum measures the abundance of a species at its optimum, i.e. the height of the response curve at the optimum. The maximum can be described in terms of abundance, but most often it is described as a probability, e.g. the probability of encountering a species at its optimum. The method of weighted averaging is used to calculate the species optimum. The number-weighted average of the gradient position of each sample containing a given species. By weighting this abundance-weighted average, a sample containing many individuals of a species and therefore likely to be close to the optimum is counted proportionally more than a sample containing only one individual of the species, which is likely to be far from the optimum. In ordination methods such as correspondence analysis and non-metric multivariate scaling, species scores are calculated as abundance-weighted averages. If response curves are calculated using these ordination methods and no additional calculations are required to obtain optimum values – they are simply species scores. Tolerance is calculated by calculating the standard deviation of the gradient position of all samples containing a given taxon. For ordination-based methods, the tolerance is the standard deviation of the estimates of the samples containing the taxon. If a species occurs over a limited set of gradient positions, the standard deviation will be small, and if the species occurs over a wide range of gradient positions, the standard deviation will reflect a large tolerance.

The use of symmetric Gaussian response functions in gradient analysis is not a universal approach due to the systematic deviation of real data from the symmetric response (Austin, 1976, 1999, 2013). The hierarchical models of Huisman, Olf and Fresco (Huisman et al., 1993) include asymmetric response along with symmetric response. In addition to the five HOF models, two bimodal (asymmetric and symmetric) response forms were included in the list to account for species that are limited to extreme gradient values due to competition (Jansen & Oksanen, 2013; Michaelis & Diekmann, 2017), and are ranked according to the increasing complexity of the biological information they contain.

Model I: represents the absence of a significant trend in space and time:

$$y = M\frac{1}{1+e^{a}}.$$

Model II: shows a rising or falling trend, where the maximum is equal to the upper limit M:

$$y = M\frac{1}{1+e^{a+bx}}.$$

Model III: indicates a rising or falling trend, where the maximum is below the upper limit M:

$$y = M\frac{1}{1+e^{a+bx}}\frac{1}{1+e^{c}}.$$

Model IV: indicates increase and decrease at the same rate (symmetrical response curve):

$$y = M\frac{1}{1+e^{a+bx}}\frac{1}{1+e^{c-bx}}.$$

Model V: shows increase and decrease at different rates (asymmetric response curve):

$$y = M\frac{1}{1+e^{a+bx}}\frac{1}{1+e^{c+dx}}.$$

Model VI: indicates bimodal symmetric responses:

$$y = M\frac{1}{1+e^{a+bx}}\frac{1}{1+e^{c+b(x-d)}}+\frac{1}{1+e^{a+b(x-d)}}\frac{1}{1+e^{c-b(x-d)}}.$$

Model VII: indicates bimodal asymmetric responses:

$$y = M\frac{1}{1+e^{a+bx}}\frac{1}{1+e^{c+b(x-d)}}+L\frac{1}{1+e^{a+b(x-d)}}\frac{1}{1+e^{c-b(x-d)}},$$

where *y* and *x* are, respectively, the response and explanatory variables, *a*, *b*, *c* and *d* are the estimated parameters (*b* and *d* have opposite signs), *M* is a constant equal to the maximum value that can be achieved (for relative frequencies $M = 1$, for percentages $M = 100$), *L* is a constant equal to the maximum value that can be achieved for a small extreme value (Jansen & Oksanen, 2013; Michaelis & Diekmann, 2017).

The index of qualitative variation (IQV) was calculated as an assessment of the stability of the model shape. This index equals zero if all repeated runs lead to the same model shape, while it equals one if all model types are selected equally often (Mueller & Schuessler, 1962). The index was calculated by the formula:

$$IQV = \frac{1-\sum_{i=n} p_i^2}{\frac{1}{n}\times(n-1)},$$

where *n* is the number of model types, *p* is the share for each model (Michaelis & Diekmann, 2017). The parameters of the species response models to the influence of bioclimatic factors were calculated using the *eHOF*-library (Jansen & Oksanen, 2013).

MaxEnt model of spatial range and its modelling in the future. Species Distribution Models (SDMs) are widely used to predict the geographic range of a species, given data on the presence and environmental variables that affect its distribution (Wilson et al., 2011). The MaxEnt method (Phillips et al., 2004) has proved to be the most effective of the many algorithms for modelling species distribution and for predicting range dynamics under the global climate change (Marcer et al., 2013). The maximum entropy model (MaxEnt) was used in this study (www.cs.princeton.edu/wschapire/MaxEnt), because it has been shown to perform better for modelling the spatial distribution of species in the present and for predicting future changes under the influence of the global climate change (Chen et al., 2022). MaxEnt (Phillips et al., 2004) and uses presence-only data to predict species distributions based on maximum entropy theory. The program attempts to estimate the probability distribution of species occurrence that is closest to uniform, but still subject to ecological constraints (Elith et al., 2011). In our models, we selected 75% of the data to train the model and 25% to test the model (Phillips, 2008), leaving the other values as defaults. We used the area under the receiver operator curve (AUC) to evaluate the model performance. The AUC value ranges from 0 to 1 (Fielding & Bell, 1997). An AUC value of 0.50 indicates that the model performs no better than by chance, while a value of 1.0 indicates perfect discrimination (Swets, 1988). The model with the highest AUC value was considered the best. To determine the first score, at each iteration of the learning algorithm, the increment of the regularized gain is added to the contribution of the corresponding variable, or subtracted from it if the change in the absolute value of the lambda is negative. For the second estimation, for each environmental variable, the values of this variable are randomly permuted in turn in the presence of training and background data. The model is re-estimated on the permuted data and the resulting drop in training AUC is shown in the table, normalized as a percentage. As with the leverage variable, the contributions of the variables should be interpreted with caution when the predictor variables are correlated.

Bioclimatic variables. For bioclimatic modelling, 19 bioclimatic variables with 2.5 min spatial resolution of from the global climate database WorldClim (www.worldclim.org, accessed December 15, 2022) were used. Bioclimatic variables are derived from monthly temperature and precipitation values in order to obtain more biologically relevant variables. They are often used in species distribution modelling and related ecological modelling techniques. Bioclimatic variables represent annual trends (e.g., mean annual temperature, annual precipitation), seasonality (e.g., annual range of temperature and precipitation), and environmental extremes or limiting factors (e.g., temperature of the coldest and warmest month, precipitation in wet and dry quarters). A quarter is a period of three months (1/4 year).

BIO1 – an average annual temperature in degrees Celsius (approximates the total energy input to the ecosystem).

BIO2 – an average of monthly temperature ranges in degrees Celsius (mean monthly tempmax – tempmin) (this index can help provide information on the significance of temperature fluctuations for different species).

BIO3 – isothermicity in % quantifies how large the day-night temperature variations are relative to the summer-winter (annual) variations (BIO2/BIO7) (×100); Isothermicity is generally useful for tropical, island and marine environments (Nix, 1986). Isothermicity quantifies how large the day-night temperature fluctuations are compared to the summer-winter (annual) fluctuations. An isotherm value of 100 indicates that the diurnal temperature range is equivalent to the annual temperature range, while anything less than 100 indicates a lower level of temperature variability during an average month compared to a year. The distribution of a species may be influenced by greater or lesser temperature variability within a month compared to a year, and this predictor is useful for elucidating such information.

BIO4 – a seasonality of temperature (standard deviation of monthly mean temperature ×100) indicates the variability of temperature throughout the year.

BIO5 – a maximum temperature of the warmest month in degrees Celsius is useful when studying whether species distributions are affected by warm temperature anomalies during the year.

BIO6 – a minimum temperature of the coldest month in degrees Celsius is useful when studying whether species distributions are affected by low temperature anomalies during the year.

BIO7 – an annual temperature range (BIO5-BIO6) in degrees Celsius is useful when examining whether species distributions are affected by ranges of temperature extremes.

BIO8 – an average temperature of the wettest quarter in degrees Celsius provides average temperatures during the wettest three months of the year, which can be useful in examining how such environmental factors may influence the seasonal distribution of species.

BIO9 – an average temperature of the driest quarter in degrees Celsius provides average temperatures during the driest three months of the year, which may be useful for studying how such environmental factors may influence the seasonal distribution of species.

BIO10 – an average temperature of the warmest quarter in degrees Celsius provides average temperatures during the warmest three months of the year, which can be useful for studying how such environmental factors may influence the seasonal distribution of species.

BIO11 – an average temperature of the coldest quarter in degrees Celsius provides average temperatures during the coldest three months of the year, which can be useful for studying how such environmental factors may influence the seasonal distribution of species.

BIO12 – an annual precipitation in millimeters of water column approximates total water supply and is therefore useful in determining the importance of water availability for species distribution.

BIO13 – a precipitation of the wettest month in millimeters of water column is useful if extreme precipitation conditions during the year affect the potential range of species.

BIO14 – a precipitation of the driest month in millimeters of water column is useful if extreme precipitation conditions during the year affect the potential range of the species.

BIO15 – a seasonality of precipitation (coefficient of variation) indicates the unevenness of precipitation throughout the year.

BIO16 – a precipitation for the wettest quarter in millimeters of water column, which can be useful for studying how such environmental factors may affect the seasonal distribution of species.

BIO17 – a precipitation of the driest quarter in millimeters of water column, which may be useful for studying how such environmental factors may influence the seasonal distribution of species.

BIO18 – a precipitation of the warmest quarter in millimeters of water column, which can be useful for studying how such environmental factors can influence the seasonal distribution of species.

BIO19 – a precipitation of the coldest quarter in millimeters of water column, which may be useful for studying how such environmental factors may influence the seasonal distribution of species.

The information on bioclimatic variables was downloaded using the getDatafunction of the raster package (Hijmans, 2022).

Results

The database of the Global Biodiversity Information Facility (GBIF) contains 2,104 records of the curly mallow (*Malva verticillata* L.). This species is found on all the continents except Antarctica (Fig. 1). Asia accounts for 39.1% of the species, Europe – 53.3%, Africa – 3.6%, North America – 3.2%, South America – 0.1%, Australia – 0.8%.

Modelling of *M. verticillata* response to the impact of climatic factors showed that the best response models were V (in 31.6% of cases) and VII (in 36.8% of cases, Table 1). Model V characterizes a unimodal bell-shaped asymmetric response, and model VII represents a bimodal asymmetric response. The species response to mean annual temperature is asymmetric bell-shaped with a shift to the right (Fig. 2). The optimal mean annual temperature for this species is 9.1 °C. For Ukraine, this value is 8.3 °C, indicating that the most favourable temperature regime is now in the central and southern regions of the country. Mallow is able to survive in the temperature conditions with an average annual temperature in the range from 0.2 (conditions close to Norway) to 16.1 °C (conditions close to Greece). The response to the mean daily temperature range is bimodal with a tendency for lower values to prevail. This species prefers lower isothermal values than those observed on land in general. Moderate and insignificant conditions of temperature fluctuations during the year are favourable for *M. verticillata*. The pattern of species response to the temperature seasonality factor is unimodal with a shift to the right. The response to the factor of average temperature of the warmest month is unimodal symmetric with a preference of 23.0 °C in the range from 17.3 to 28.6 °C. The species response to the temperature of the coldest month is asymmetric unimodal with a shift in the distribution towards higher values. This indicates that winter conditions may be of great importance in determining the species distribution.

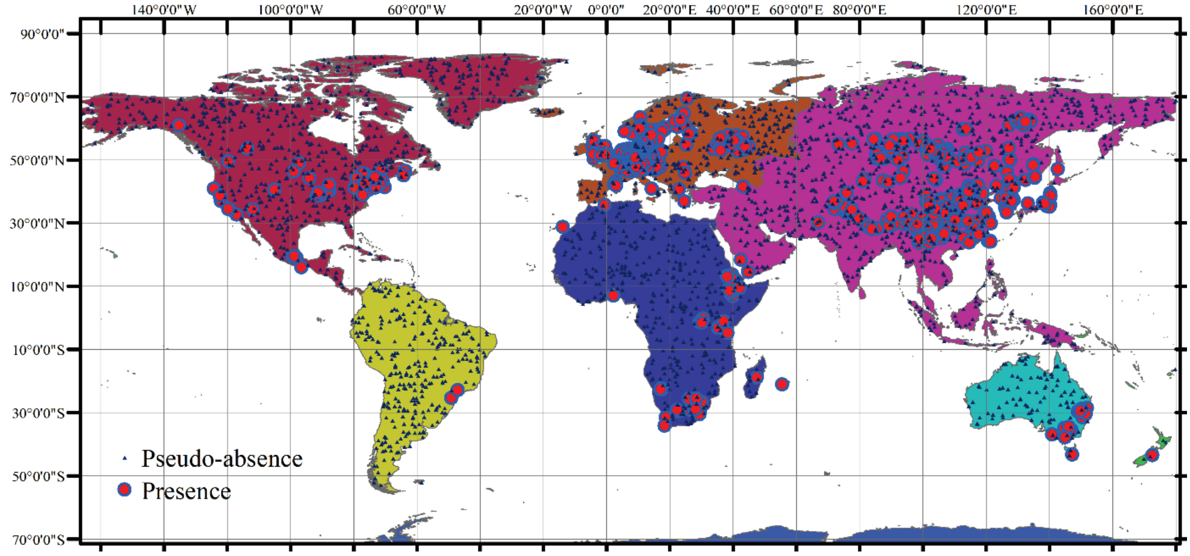

Fig. 1. Locations of recording of curly mallow (*Malva verticillata* L.) according to the Global Biodiversity Information Facility (GBIF)

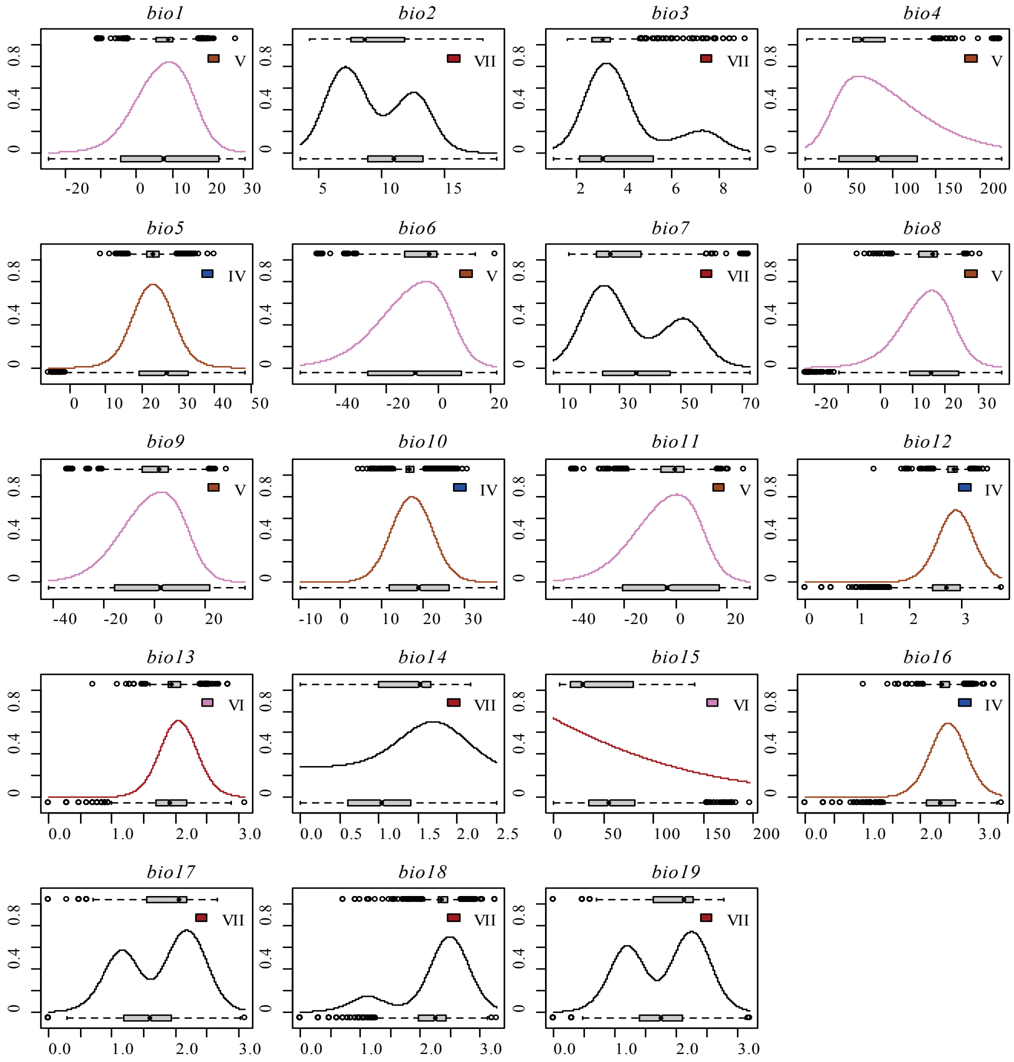

Fig. 2. Response of curly mallow (*Malva verticillata* L.) to the influence of climatic factors within the entire range: the axis is the value of bioclimatic variables 1–19, the ordinate axis is the species response (presence/absence); pseudo–absence points are generated by random placement within all continents where the species occurs; bioclimatic variables: bio1 – mean annual temperature, bio2 – mean of monthly temperature ranges, bio3 – isothermicity, bio4 – seasonality of temperature, bio5 – maximum temperature of the warmest month, bio6 – minimum temperature of the coldest month, bio7 – annual temperature range, bio8 – mean temperature of the wettest quarter, bio9 – mean 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 of the driest month, bio15 – seasonality of precipitation, bio16 – precipitation of the wettest quarter, bio17 – precipitation of the driest quarter, bio18 – precipitation of the warmest quarter, bio19 – precipitation of the coldest quarter

The response to annual temperature fluctuations has a bimodal distribution with a preference for a more stable temperature regime. These plants prefer warmer conditions during the period of greater moisture supply, as evidenced by the distribution of bioclimatic variable 8. The response of the species to the temperature of the driest period has a unimodal asymmetric pattern, but more favourable regimes for this species are formed under conditions of higher temperature in the driest period of the year. The average temperature of the warmest period of the year should be moderate for optimal conditions for this species, while the temperature for the coldest period of the year should be higher. The species is not significantly demanding of rainfall and can exist in the range of 452–1304 mm per year. It prefers relatively lower precipitation in both the wettest and driest months or quarters of the year. As indicated by the IQV, the most stationary species responses are bio2, bio3, bio5, bio7, bio12. The models in the list under consideration cannot provide a good enough description of the response to bio16, bio15, bio13. The comparison of the distribution of available resources and their use is the basis for the identification of features of the species ecological niche (Fig. 3). As revealed by the ENFA approach, positive values of the species ecological niche marginality are marked with bioclimatic variables bio14 and bio17, and negative values are marked with bioclimatic variables bio2 and bio15. The axis of specialties is marked with bioclimatic variables bio1 and bio11. Also, the ENFA approach made it possible to estimate the habitat preference index (HSI) (Fig. 4). The climatic conditions currently prevailing on the globe's landmasses are favourable for the species' to spread in Southeast Asia, North and South America, Australia and Europe. The potentially favourable conditions are much larger than the realized range of the species, which indicates a significant potential for its dispersal.

Table 1

Parameters of ecological niche of curly mallow (*Malva verticillata* L.): species optimum, central limits and outer limits

Bio*	Model	Optimum		Central border 1		Central border 2		Outer border 1		Outer border 1		IQV**
		min	max	low	high	low	high	low	high	low	high	
bio1	V	9.12	–	0.22	16.14	–	–	–8.44	21.96	–	–	0.21
bio2	VII	7.16	12.58	5.50	8.99	10.15	14.07	3.88	10.15	10.15	15.31	0.00
bio3	VII	3.25	7.31	2.31	4.21	5.99	8.15	1.44	5.66	5.66	8.23	0.00
bio4	V	62.26	–	32.51	120.68	–	–	8.76	200.74	–	–	0.49
bio5	IV	23.00	–	17.38	28.61	–	–	11.84	34.16	–	–	0.00
bio6	V	–4.87	–	–21.03	5.22	–	–	–39.24	13.32	–	–	0.21
bio7	VII	24.63	50.71	17.25	32.52	40.16	57.44	9.83	39.26	39.26	62.50	0.00
bio8	V	15.85	–	7.36	22.43	–	–	–2.60	28.59	–	–	0.49
bio9	V	2.80	–	–12.10	13.25	–	–	–27.19	21.58	–	–	0.37
bio10	IV	17.27	–	12.22	22.31	–	–	7.35	27.18	–	–	0.21
bio11	V	0.47	–	–14.73	10.51	–	–	–31.10	18.58	–	–	0.49
bio12	IV	2.88	–	2.54	3.23	–	–	2.17	3.60	–	–	0.00
bio13	VI	0.00	2.04	–0.08	0.00	1.75	2.34	0.00	0.00	1.44	5.57	0.77
bio14	VII	0.00	1.69	0.00	0.14	1.05	2.29	0.00	0.14	0.14	5.05	0.37
bio15	VI	0.00	196.0	0.0	67.9	196.0	246.9	0.0	196.0	196.0	231.6	0.58
bio16	IV	2.47	–	2.16	2.79	–	–	1.82	3.13	–	–	0.56
bio17	VII	1.16	2.18	0.87	1.48	1.83	2.50	0.58	1.61	1.61	2.82	0.21
bio18	VII	1.12	2.49	0.82	1.44	2.17	2.82	0.84	1.42	1.80	3.16	0.21
bio19	VII	1.21	2.24	0.91	1.52	1.91	2.56	0.61	1.68	1.68	2.89	0.40

Notes: species optimum describes the highest probability of species existence along the environmental gradient; the outer and central limits are determined by the distance from the optimum, which is necessary for the response curve to decrease by a certain amount, i.e. these parameters reflect the rate of response decrease in both directions from the optimum, independently of each other; the central limits are calculated as the gradient values at which the response reaches exp(-1/2) = 0.61 from the peak; the outer borders of the species niche are calculated as the gradient values where the response reaches exp(-2) = 0.14 from the top (Heegaard, 2002); * – bioclimatic variables: bio1 – mean annual temperature, bio2 – mean of monthly temperature ranges, bio3 – isotherm, Bio* – bioclimatic variables: bio4 – seasonality of temperature, bio5 – maximum temperature of the warmest month, bio6 – minimum temperature of the coldest month, bio7 – annual temperature range, bio8 – average temperature of the wettest quarter, bio9 – 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 of the driest month, bio15 – seasonality of precipitation, bio16 – precipitation for the wettest quarter, bio17 – precipitation of the driest quarter, bio18 – precipitation of the warmest quarter, bio19 – precipitation of the coldest quarter; IQV** – index of qualitative variation.

The MaxEnt approach showed that bioclimatic variables bio1, bio9 and bio7 have the highest information value for explaining the species response to climatic conditions (Fig. 5). The MaxEnt approach indicates that Southeast Asia and Europe have the most favourable conditions for the existence of this species (Fig. 6). The changes in climatic conditions in the next 50–70 years will make the conditions for the life of *M. verticillata* in the southern hemisphere unfavourable, and in the northern hemisphere the favourable conditions will shift significantly to the north. At the same time, conditions in the autochthonous range of the species will become unfavourable (Fig. 7). Obviously, if not for the significant potential of the species to disperse, it would have died out as a result of the significant climate change. Central Europe will be the area where favourable conditions for the species will remain unchanged. Conditions in Eastern Europe, including Ukraine, will moderately improve. Conditions in Northern Europe will improve significantly.

Discussion

The data obtained indicate that climatic conditions largely determine the features of the ecological niche of *M. verticillata* and are sources of information that can explain the spatial distribution of this species. Obviously, the relationship of the species to the environmental conditions has developed as a result of a long evolutionary process, making an ecological standard for the species (Khomyak et al., 2017). Any species has to be adapted to a complex of biotic and abiotic conditions. The temperature of the environment is only one of many conditions for the existence of a species. However, the spatial distribution of many plant species is limited by the frosty climate regime, and many natural history data suggest that temperature and precipitation are key determinants of species ranges (Pimm, 2008). Temperature has been proven to be a factor that directly or indirectly affects many species over large areas (Root et al., 2003). Based on the information on the impact of climatic factors of the environment at present and forecast estimates of climatic conditions, it is possible to estimate trends in the distribution of the species in the near future (Fu et al., 2021).

The natural range of *M. verticillata* is Southeast Asia (Rakhmetov, 1999). Crops originating from seasonally arid regions have been found to have the greatest agricultural value. Ancient crops have a global importance and are grown over larger geographical areas than crops of recent origin (Milla & Osborne, 2021). The precipitation level during the driest period of the year (month or quarter) is the limiting factor that determines the spatial distribution of *M. verticillata*. This result is in line with findings that indicate that the response of vegetation to increasing temperature may depend on soil moisture, as the climate warming increases the abundance of functional groups of vegetation in wetter, but not in drier areas (Elmendorf et al., 2012).

Also *M. verticillata* avoids conditions with a high level of average monthly temperature ranges. Obviously, the most important driver of changes in the spatial distribution of the species in the context of global climate change is the increased probability of drought. The global climate change in the long term leads to both an increase in average annual temperature and changes in precipitation dynamics (Tabari, 2020). The frequency of extreme climate events changes in response to changes in both climate averages and climate variability (Clarke et al., 2022).

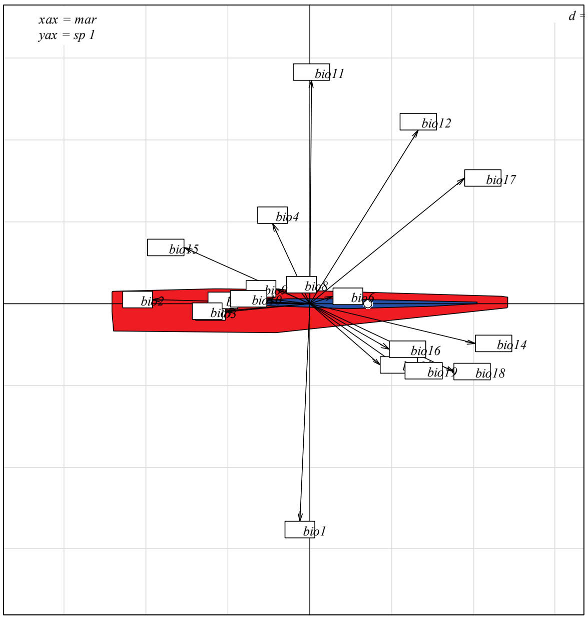

Fig. 3. Results of the ENFA analysis: abscissa is marginality (Mar = 2.042), ordinate is specialization (Sp = 28.73); red area represents the available resources, blue area represents the used resources; the arrows indicate correlations of bioclimatic variables 1–19 with marginality and specialization axes; bioclimatic variables: bio1 – average annual temperature, bio2 – average of monthly temperature ranges, bio3 – isothermality, bio4 – seasonality of temperature, bio5 – maximum temperature of the warmest month, bio6 – minimum temperature of the coldest month, bio7 – annual temperature range, bio8 – average temperature of the wettest quarter, bio9 – 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 of the driest month, bio15 – seasonality of precipitation, bio16 – precipitation of the wettest quarter, bio17 – precipitation of the driest quarter, bio18 – precipitation of the warmest quarter, bio19 – precipitation of the coldest quarter

The increase in the frequency of monthly high-temperature events is determined by the warming of the average climate(Soltani et al., 2016).

By contrast, the future changes in monthly precipitation are largely dependent on trends in climate variability(Tofu & Mengistu, 2023). The spatial variations of climate regimes are significant, emphasizing the importance of regional processes(Engeland et al., 2017). The contributions of mean and variability to the likelihood ratio are largely independent of the event threshold, the magnitude of warming, and the climate model (Zymaroieva et al., 2019). The projections of extreme temperatures are more reliable than projections of extreme precipitation because the mean climate is better understood than climate variability (van der Wiel & Bintanja, 2021). In the dynamics of precipitation in the context of the global climate change, the most important trend is the change in their rhythmicity during the year, and the annual amount of precipitation may not change or even increase (Koshelev et al., 2020). The global climate change induces a significant redistribution of precipitation during the year, causing increase in the amount of extremely intense precipitation increases and prolongation of periods with no precipitation (Sarkar & Maity, 2021). Obviously, drought is the most important factor determining the potential spatial range of *M. verticillata*.

The climatic forecasts suggest that the biggest trend in the future will be the expansion of the territory of regular droughts towards the poles in both hemispheres. In the southern hemisphere, we can expect a total spread of arid conditions under which the duration of the period with moisture deficit will be so long that the probability of survival of *M. verticillata* in the future 50–70 years will be close to zero. In the northern hemisphere, the area favourable for this species will shift to the north. As a result, currently marginal territories will turn into the center of the species distribution. The results of our modelling indicate that as a result of global climate change in the near future, the natural range of the species will lose its importance for maintaining the existence of the species, as the climatic conditions in it will become very unfavourable for *M. verticillata*. Our results are in line with the findings that the climate change in recent years has led to numerous changes in the distribution and abundance of species, as well as to the extinction of some species (Zymaroieva et al., 2021). Based on mid-range climate warming scenarios, 15–37% of species are projected to be "comitted to extinction" by 2050 (Thomas et al., 2004).

Numerous studies show that the climate change is decreasing species ranges (Thomas et al., 2006). Forecasting the prospects of the range dynamics of *Thuja sutchuenensis* Franch., the natural range of which is also located within Southeast Asia, indicates that the optimal area of its range in the near future will be outside the current territory (Qin et al., 2017).

There is a growing global awareness of the need for renewable energy and energy efficiency to create new economic opportunities and curb environmental pollution. Anaerobic digestion technology is a biochemical biogas production process that can convert complex organic matter into a clean and renewable energy source in the form of biogas (Hagos et al., 2017). The growing number of biogas plants creates pressure on the production of appropriate feedstock.

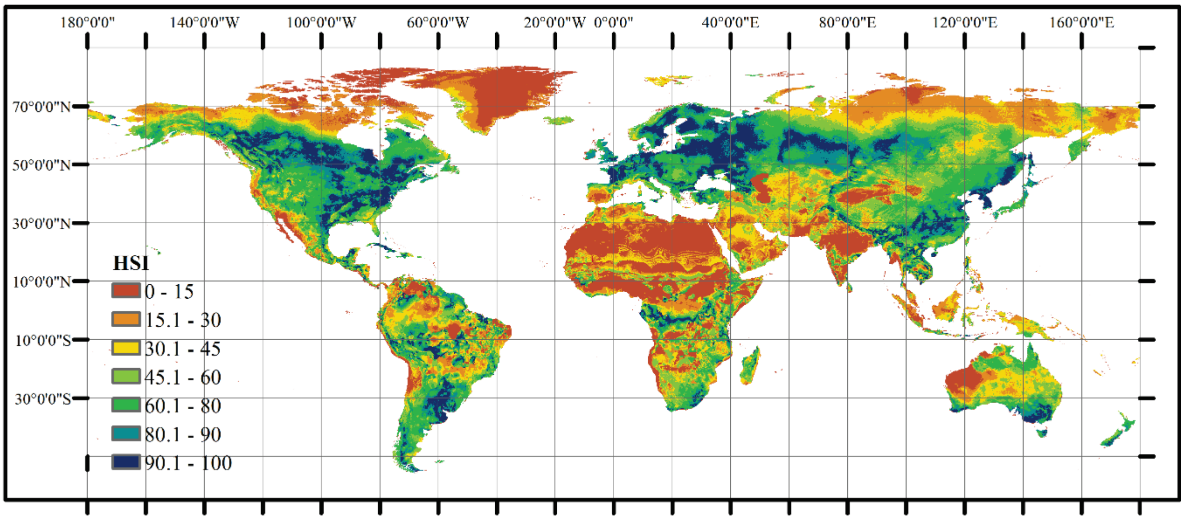

Fig. 4. Spatial variation of the habitat suitability index (HSI, %) within the Earth's landmass based on the ENFA approach under current climatic conditions

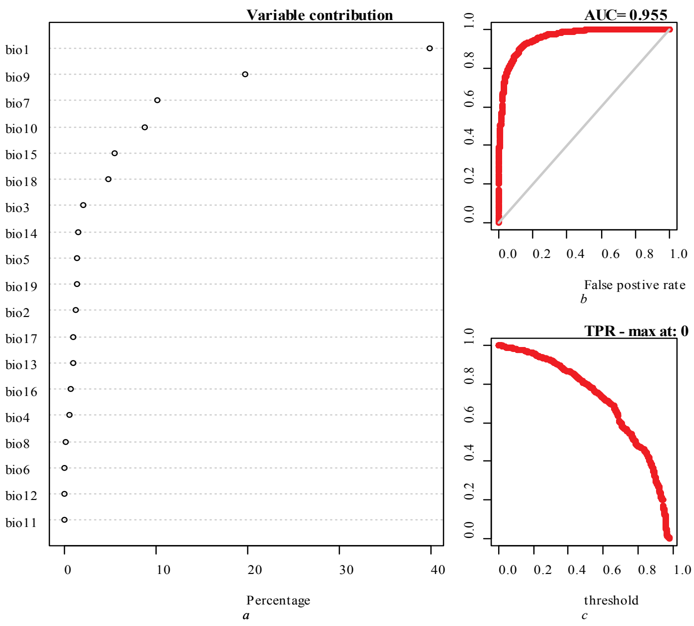

Fig. 5. Analysis of predictor contributions to the MaxEnt model (*a*), receiver operating characteristic (ROC) curve (*b*) and true positive rate (TPR) (*c*): bioclimatic variables: bio1 – annual mean temperature, bio2 – average of monthly temperature ranges, bio3 – isothermality, bio4 – seasonality of temperature, bio5 – maximum temperature of the warmest month, bio6 – minimum temperature of the coldest month, bio7 – annual temperature range, bio8 – average temperature of the wettest quarter, bio9 – 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 of the driest month, bio15 – seasonality of precipitation, bio16 – precipitation of the wettest quarter, bio17 – precipitation of the driest quarter, bio18 – precipitation of the warmest quarter, bio19 – precipitation of the coldest quarter

The digesters where the anaerobic digestion process takes place can be compared to the digestive tract of ruminants where the congested substrates are gradually processed by microorganisms into the final product – biogas, the main energy component of which is methane. This biological process is sensitive to the conditions under which it occurs, namely temperature and pH (Cioabla et al., 2012). Therefore, unsuitable feedstock and inappropriate fermentation conditions can lead to a decrease in biogas production or even to the termination of fermentation processes (Rabii et al., 2019). The analysis of the composition of input raw materials in biogas plants showed that the current dominant plant material is corn silage (Cuetos et al., 2017). The silage can make up more than three quarters of raw materials for biogas plants (Einarsson & Persson, 2017). Corn silage is considered the most suitable for biogas production. Intensive cultivation of maize as an energy crop in monoculture creates environmental risks, such as erosion of arable land and increased use of mineral fertilizers and pesticides. Therefore, it is necessary to search for new crops to use as biogas plants, which would potentially have less negative impact on the environment (Meyer et al., 2018). If good agricultural practices are not followed, intensive maize cultivation can lead to a number of negative environmental impacts, such as loss of biodiversity, soil erosion and leaching of reactive nitrogen into water sources (Svoboda et al., 2013). Biogas production opens new opportunities for the use of legumes (Fabaceae). This can be an impetus for more frequent inclusion of legumes in crop rotation. Requirements to the quality of legumes for biogas production are not as high as for other types of their use. The positive impact of legumes on the soil and on subsequent crops is well known. Therefore, they should be included in crop rotations to improve soil fertility and sustainability of agricultural systems (Brooker et al., 2015). Higher nitrogen content in legume biomass can be a limitation as it can cause inhibition of the anaerobic process (Wahid et al., 2018). The anaerobic digestion process is unstable when the nitrogen content of corn silage is low and they recommend adding a substrate with a higher nitrogen content to stabilize it. This is exactly the requirement that can be met by adding legumes. Mixed cropping of maize and legumes is one of the most common and effective combinations for the use of natural resources (Ofori & Stern, 1987). The maize-legume intercropping system is seen as an alternative to legume-free systems, saving nitrogen, increasing maize biomass production and achieving higher productivity per unit of time and space (Seran & Brintha, 2010).

One of the alternative legume crops for biogas production is white sweet clover, which is mainly used as a fodder crop, soil improvement crop on less fertile soils and green manure crop (Turkington et al., 1978). Although originally a biennial plant, some annual varieties have also been developed. It also grows on soils poor in organic matter, is drought tolerant and prefers sunny areas. The plant contains a large amount of coumarin, which smells of its crushed stems, leaves and especially flowers (Nair et al., 2010). The coumarin content in white sweet clover can be an important factor when used for biogas production. Coumarin has a negative effect on the microbial activity in the fermenter of the biogas plant. Inhibition of the anaerobic process has been reported when using feedstocks with high coumarin content (Popp et al., 2017). Coumarin concentrations between 0.25 and 1 g/L were reported to inhibit methanogens as well as synthetic propionate and butyrate degrading cultures. The appropriate dosage of silage of white sweet clover can promote biogas production (Kintl et al., 2020). Another energy crop is fodder mallow. The origin of the plant is East Asia. It used to be grown in China and Egypt, and now it is grown in Germany and Ukraine. It is a tall, highly branched, squat plant, which due to its tall stature is used as an energy crop. Growing fodder mallow for energy production does not require special technology or mechanization (Kintl et al., 2022). The study of anaerobic digestion (AcoD) process has received much attention in the field of biogas production and is used broadly. A reliable alternative is AcoD, which overcomes the disadvantages of mono-substrate digestion related to substrate characteristics and system optimization (Hagos et al., 2017). The technology of mixed cultivation of crops and substrates is an ecological alternative to the monoculture substrates that are predominantly used. It can also contribute to increasing the diversity of crop rotations and the development of alternative technologies for maize cultivation, for example, in mixed culture (Kintl et al., 2020). The course of the anaerobic digestion process depends on many parameters related to the composition and mutual ratio of fermentable substrates. For biogas production, it is possible to use such feedstocks as alternative crops (fodder mallow and white sweet clover) and their mixed crops. The yields of biogas and methane from silage of these crops and their mixtures are fully comparable with the yields achieved in the production of biogas and methane from corn silage. Fodder mallow and white sweet clover could be potentially used as intercrops or co-fermentation crops with maize, where relatively good biogas production can be achieved (Kintl et al., 2022).

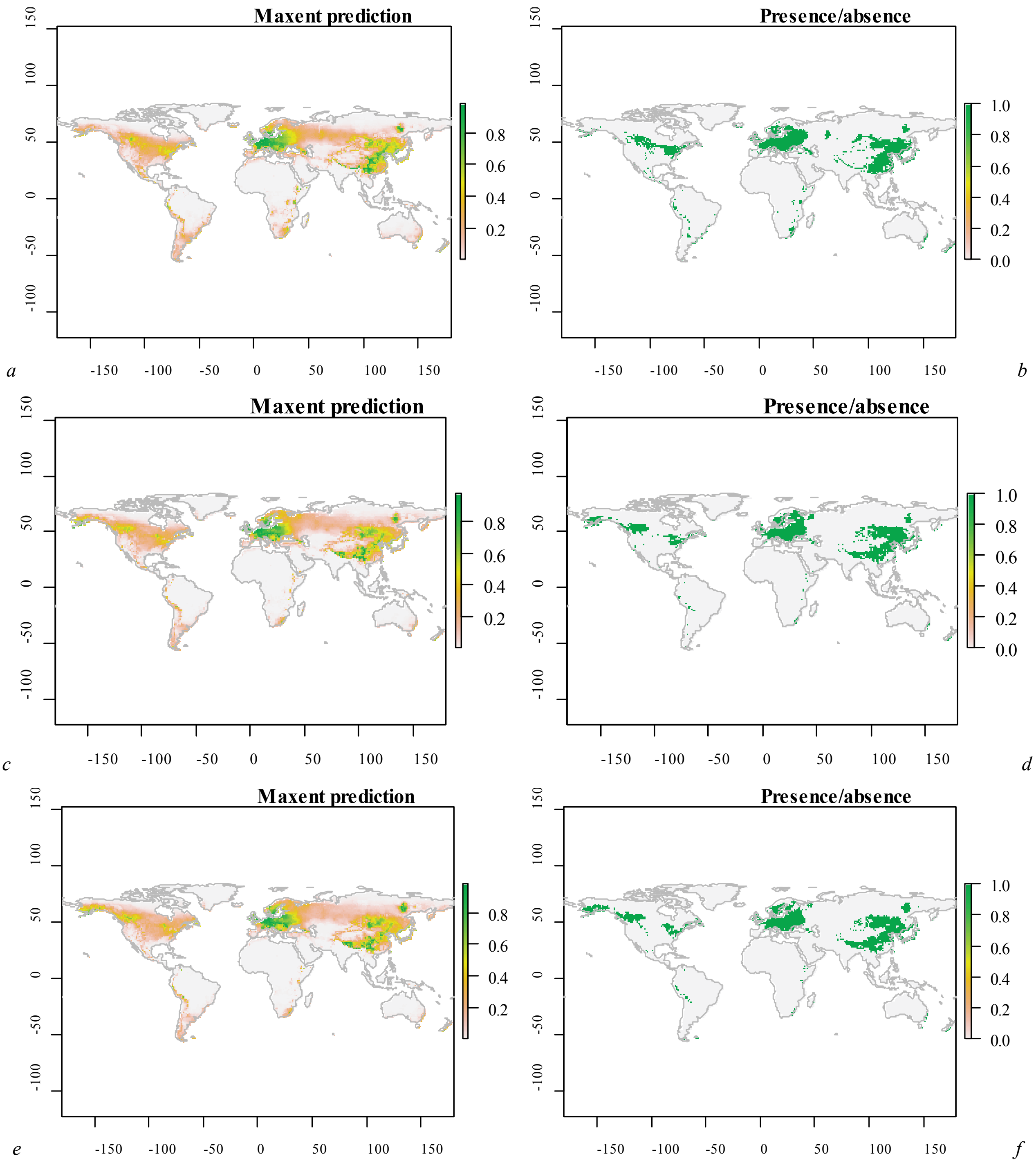

Fig. 6. Range model of *M. verticillata* developed using the MaxEnt approach based on current climatic conditions (*a*, *b*) and the projected state of the range based on the projected climate model for 50 years (*c*, *d*) and 70 years (*e*,*f*): predicted probabilities of species occurrence in geographic space (*a*, *c*, *e*) and presence/absence of the species as an assessment of the probability of occurrence which exceeds the threshold of 0.31 (*b*, *d*,*f*)

It should be noted that in addition to climatic factors, soil factors are also important for the life and geographical distribution of plants (Salisbury, 1926). The transformation of the species range will also depend on how soil regimes will change. The response of plant communities to the global climate change was confirmed to depend on soil moisture regime (Peng et al., 2020). Plants that grow in wet conditions are more resource-intensive, while plants that grow in drier conditions are resource-saving, which leads to a smaller growth of the latter group in a warming climate (Bjorkman et al., 2018). A dominant joint effect of climate and soil regimes on the variation of plant traits was found (Alasmary et al., 2020). Additional independent effects of climate are also observed for most traits, while independent effects of soil are observed almost exclusively for plant efficiency traits (Zymaroieva et al., 2019). The variation of size traits correlates well with the latitudinal gradient, which is associated with water or energy limitation. In contrast, variation in performance traits is better explained by the interaction of climate with soil fertility (Joswig et al., 2021). This is very important, because northern soils that had long been experiencing heat deficit have developed specific features that are not favourable for the growth of highly productive plants. Soils will also change along with global climate change (Pareek, 2017) and the actual range of the species will depend on the coincidence of favourable climatic and soil conditions. In this context, the territory of Eastern Europe and Ukraine is of great importance. The climatic conditions in Ukraine will change, but these changes will not significantly affect the level of favourable conditions where *M. verticillata* currently grows. Soil conditions in the forest-steppe zone are generally favourable for the life of *M. verticillata*, so they will not be a limiting factor for the spread of the species in case of a favourable climate change.

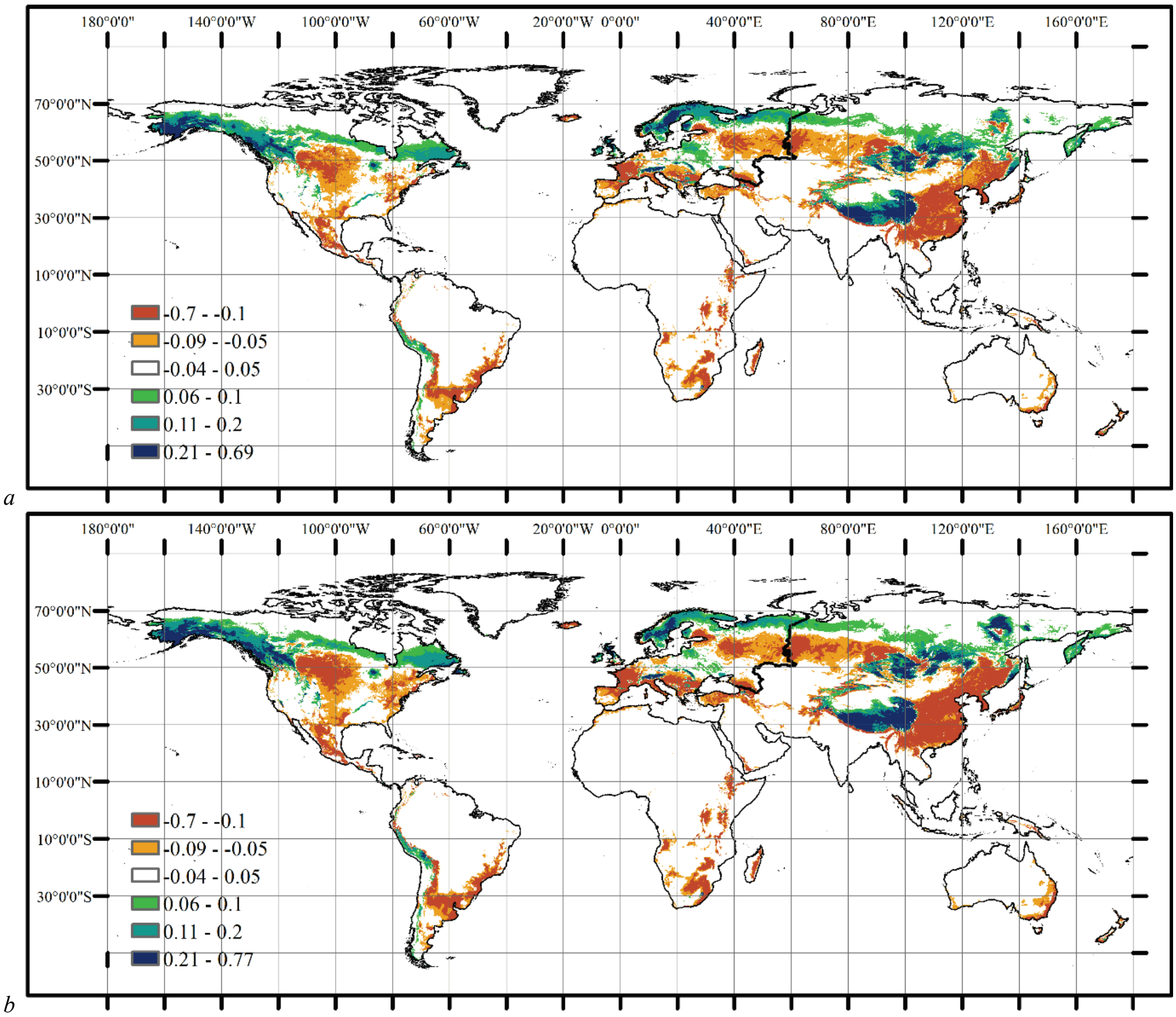

Fig. 7. Climate-induced changes in the probability of occurrence of *M. verticillata* compared to the present in 50 (*a*) and 70 (*a*) years

Conclusion

The natural range of the curly mallow (*Malva verticillata* L.) is located in Southeast Asia, but now the species occurs on all continents, except Antarctica. As a result of the global climate change, in the near future, the natural range of the species will lose its importance for maintaining its existence. In Europe, the number of species occurrences is currently the highest. The species response to the environmental factors, which are indicated by the bioclimatic variables, is mainly unimodal bell-shaped asymmetric or bimodal asymmetric. The level of precipitation in the driest period of the year and the high level of average monthly temperature ranges are the limiting factors that largely determine the spatial distribution of *M. verticillata*. Changes in drought probability in the context of the global climate change are the most important driver of changes in the spatial distribution of the species. In the northern hemisphere, the area favourable for this species will shift northward. The climatic conditions in Ukraine will change, but these changes will not significantly affect the level of favourable conditions where *M. verticillata* currently grows. This forecast substantiates the significant importance of curly mallow as a promising crop in Ukraine for obtaining the necessary raw materials for medical purposes and as an element of bioenergy technologies.

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