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Vulnerability assessment of Ukrainian forests as the basis of nature-based solutions for mitigation and adaptation to climate change

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A wide range of climatic conditions in Ukraine causes significant regional differences in the vulnerability of forests to the current rapid climate change. The mitigation/adaptation strategy should be based on assessments of their vulnerability at the regional level.

Phytoindication model by Prof. Y. P. Didukh was used to assess forest vulnerability. The model provides a quantitative estimation of climate as one of the major environmental factors affecting the distribution, condition and productivity of vegetation on the base of climate-related indicators – continentality, humidity and frost. For these indicators climate suitability scales were calculated. The modeling was carried out for the main forest species: Pinus sylvestris L.*, Quercus robur* L.*, Fagus sylvatica* L.*, Picea abies* (L.) *H. Karst, Betula pendula Roth., Alnus glutinosa* (L.) *Gaertn. and Robinia pseudoacacia* L. *Climate projections based on the Euro CORDEX time series (up to 2100) and 2 scenarios of the Representative Concentration Pathways (RCP 4.5, RCP 8.5) were used. Using Q-GIS, the maps containing zones of suitability to climate for each of the studied species were created for current climate conditions and future time series.*

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The directions for strengthening the mitigation and adaptive capacity of forests are considered. The mainstream for nature-based solutions is adaptive sustainable forest management, which provides: 1) optimization of land use structure and increasing the forested area; 2) development and implementation of a national forestry program considering the priorities of climate change and low-carbon development; 3) using wood to substitute greenhouse gas intensive-materials and fossil fuels; 4) the best forestry practices through the introduction of modern Climate-Smart Forestry principles.

Key words: *RCP 4.5; RCP 8.5; Euro CORDEX; climate trends; adaptive forest management.*

Introduction. In Ukraine, the effects of climate change are already being observed and according to the projections of the Intergovernmental Panel on Climate Change (IPCC, 2014, 2022), further climate warming is expected soon. Forests are one of the main terrestrial carbon sinks, but in unfavorable conditions (forests decline, wildfires) they can become a carbon source, which will mitigate climate change.

The conditions of Ukraine's forests have deteriorated sharply since 2009. Over the last decade, the areas of Scots pine and Norway spruce damaged by bark-beetles significantly increased in Ukraine (Парпан та ін., 2014; Meshkova, 2021). Large forest areas have been damaged by wildfires. Such events are considered consequences of climate change (Zibtsev, Goldammer, Soshenskii, & Gumeniuk, 2022).

Previous studies (Shvidenko, Buksha, Krakovska, & Lakyda, 2017; I. Buksha, Pyvovar, M. Buksha, Pasternak, & T. Buksha, 2021) predicted significant deterioration of climatic conditions for forests in Ukraine, mainly associated with the lack of water, and showed shifting favorable conditions for forests to the north and northwest. According to the results of research by Boychenko (2008) the transformation of climatic fields in the territory of Ukraine will lead, in particular, to a shift in the boundaries of natural zones, and the appearance of a semi-desert zone in the south. In large areas of Ukraine, conditions for the growth of the main tree species will become unfavorable. The studies by Dyderski, Paź, Frelich, & Jagodziński (2018) showed similar results for forests in Europe. The study by Buras & Menzel (2019) predicted significant changes in the distribution of forest tree species in Europe in the current century. European beech and English oak can survive in quite large areas of Central Europe. Due to the increasing risk of drought-induced mortality, Scots pine and Norway spruce are likely to significantly decrease in abundance in Central European forests under the expected climate change (Buras & Menzel, 2019; Vacek et al., 2016). Scots pine is characterized by wide ecological plasticity and genetic variability within its natural range (Brichta et al., 2023).

A wide range of climatic conditions in Ukraine causes regional features of forest ecosystems, and their regional determinants – the specifics of vulnerability to climate change. Therefore, it is very important to assess the possible consequences for forests at the regional level to form an information base for developing strategies for adaptation and mitigation of consequences.

The purpose of the study is to evaluate climate suitability for the growth of the main forest tree species in Ukraine in the current climate and in the future under the most relevant scenarios RCP 4.5 and 8.5 scenarios as well as quantification of vulnerability. The results of the study are presented in this publication.

Material and methods. The phytoindication model by Didukh (1994, 2011) was used to assess forest vulnerability. The model provides a quantitative estimate of climatic conditions as one of the major environmental factors affecting the distribution, condition and productivity of forest vegetation on the base of indicators of climate continentality, humidity and frostiness.

A previous study (Швиденко, Букша, Краковська, 2018) showed that for the studied tree species the main limiting factor is climate humidity, so in this study the assessment was performed for this indicator. Climate humidity reflects the lack of moisture – as the difference between the annual amount of precipitation and potential evaporation. For 8 tree species (Scots pine (*Pinus sylvestris* L.), English oak (*Quercus robur* L.), European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abias* (L.) H. Karst), Silver birch (*Betula pendula* Roth.), Black alder (*Alnus glutinosa* (L.) Gaertn.) and Black locust (*Robinia pseudoacacia* L.) climate suitability scales were developed based on Didukh (2011) (Table 1).

Climate humidity index was calculated as the difference between the annual precipitation sum (W) and potential evaporation (E_0) by the method of Kolomyts (за Швиденком та ін., 2018):

$$Om = W - E_0, \text{ mm} \quad (1)$$

$$E_0 = 1384 - 161{,}6 \cdot t_{\max} + 6{,}245 \cdot t_{\max}^2, \quad (2)$$

where $t_{\max}$ is the mean temperature of the warmest month.

For the study, E-OBS climatic data (for the recent climate of the period 1991-2010) and regional climate model data from the international EURO-CORDEX initiative (Jacob et al., 2014; Krakovska et al., 2022) for scenarios RCP 4.5 and RCP 8.5 for the 21st century were used. Climate indices and forest areas were studied at the regional scale – within the forestry regions according to Gensiruk (2002), which are used for forest management in Ukraine and they almost coincide with natural zones: Forest region (Polissia), Forest-Steppe, Carpathian Mountains, Northern and Southern Steppe, Mountain Crimea. As a source of data on the area of forests by the main tree species, the database of the State Forest Register as of January 1, 2011, was used. Forest data were generalized at the forestry enterprise`s level. The effect of local site conditions such as soil humidity and fertility were not taken into account in the modeling.

Table 1. **Magnitude of the scales of tolerance and suitability for climate humidity for the main tree species (in absolute values of the indicator, mm)**

Species	Magnitude of tolerance	Optimum	Suboptimum	Satisfying	Subsatisfying
Pinus sylvestris	-500–1690	310–890	110–<310 & >890–1,090	-190–<110 & >1,090–1,390	-490–<-190 & >1390–1690
Quercus robur	-700–900	-100–300	-240 –<-100 & >300–440	-450–<-240 & >440–650	-690–<-450 & >650–890
Fagus sylvatica	-300–700	80–310	0–<80 & >310–390	-120–<0 & >390–520	-290– <-120 & >520–690
Picea abies	100–1,490	620–970	500–<620 & >970–1,090	320–<500 & >1,090–1,270	100–<320& >1,270–1,480
Betula pendula	-500–1,300	170–630	0–<170 & >630–790	-230–<0 & 790–1030	-490–<-230 & >1,030–1,290
Alnus glutinosa	-700–1,100	-30–430	-190–<-30 & >430–590	-430–<-190 & >590–830	-690–<-430 & >830–1,090
Carpinus betulus	-500–700	-40–240	-140–<-40 & >240–340	-290–<-140 & >340–490	-490–<-290 & >490–690
Robinia pseudoacacia	-900–700	-300–100	-440–<-300 & >100–240	-650–<-440 & >240–450	-890–<-650 & >450–690

By using Q-GIS, maps of dynamics of climate humidity index for the recent climate of the 1991-2010 period and projected climate scenarios RCP 4.5 and RCP 8.5 were elaborated. Modeling of the suitability of climate humidity conditions for studied tree species was performed on the base of determined scales (see Table 1) under different scenarios. For each forestry region and the total territory of Ukraine, the distribution of the current forest area of each species in different zones of climatic suitability conditions under the current climate and in the future under two scenarios was estimated. The vulnerability in this study was quantified as an area of a specific tree species and its share which in the future, according to the modeling, would be in unsuitable climate conditions compared to the current climate as well as areas, where favorable (optimum, suboptimum and satisfactory) conditions would become less favorable (unsatisfactory and extreme conditions). Such an approach allowed for the identification of forestry regions where the projected climate change will cause a more significant negative impact on specific forest stands of the main tree species.

Results. The values of the climate humidity are characterized by high variability within Ukraine: the highest values are observed in the Carpathian mountains, they are slightly lower in the Right-Bank Forest-Steppe and Mountain Crimea, which is related to the amount of precipitation and features of the terrain, while in the southern direction the moisture deficit increases: minimal values are in the Southern Steppe zone. In the future, a significant increase in potential evaporation is expected due to the increase in the temperature and, accordingly, a sharp increase in the humidity deficit of the climate starting from the south (Fig. 1). A significant decrease in climate humidity is predicted in the most forested regions: Forest-steppe and Forest zone.

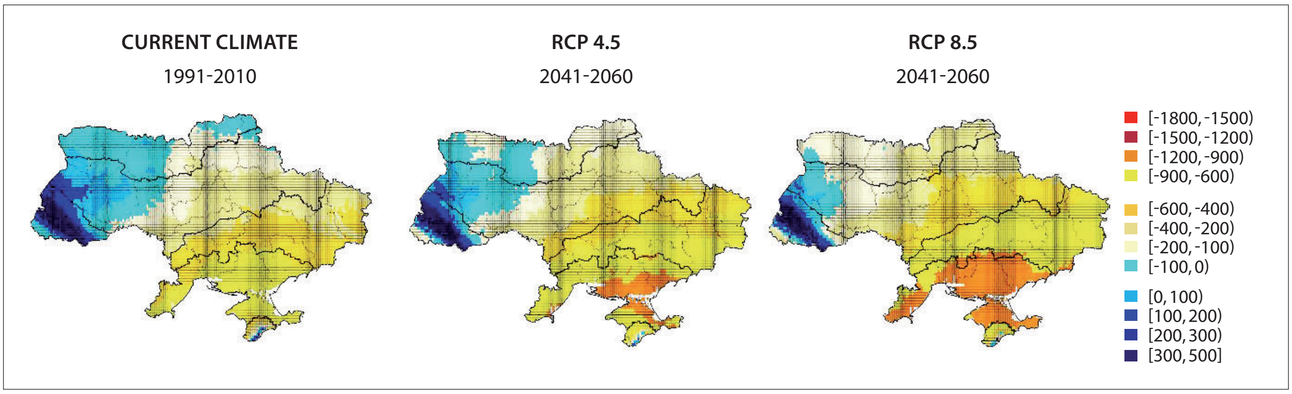

Fig. 1. Climate humidity in the 21st century under scenarios RCP 4.5 and RCP 8.5 and in the current climate

The climate scenario data show a long-term trend towards decreasing climate humidity in Ukraine. Less rapid climate change is expected in the case of the RCP 4.5 scenario, therefore, the consequences for forest stands in the case of realization of this scenario are expected to be less dramatic, than in the case of RCP 8.5.

The performed modelling (Fig. 2) showed that climate humidity conditions in Ukraine in the middle of the century will become less suitable for the studied species compared to the current climate. The predicted effect is different in different forestry regions and depends on the tolerance level of the species being studied and the actual areas of these species. For example, *Robinia pseudoacacia* can grow in a wide range of climate humidity, and in the middle of the century changes in the area of suitable conditions for this species were minimal. However, the forest areas of this species in Ukraine are rather small, and they are mainly located in the Steppe regions. The other species are characterized by a significant decrease in areas with suitable conditions. The lowest value of tolerance is characteristic of Norway spruce, which is a representative of boreal forests: in Ukraine, favorable climate conditions for this species are mainly in the Carpathian Mountains.

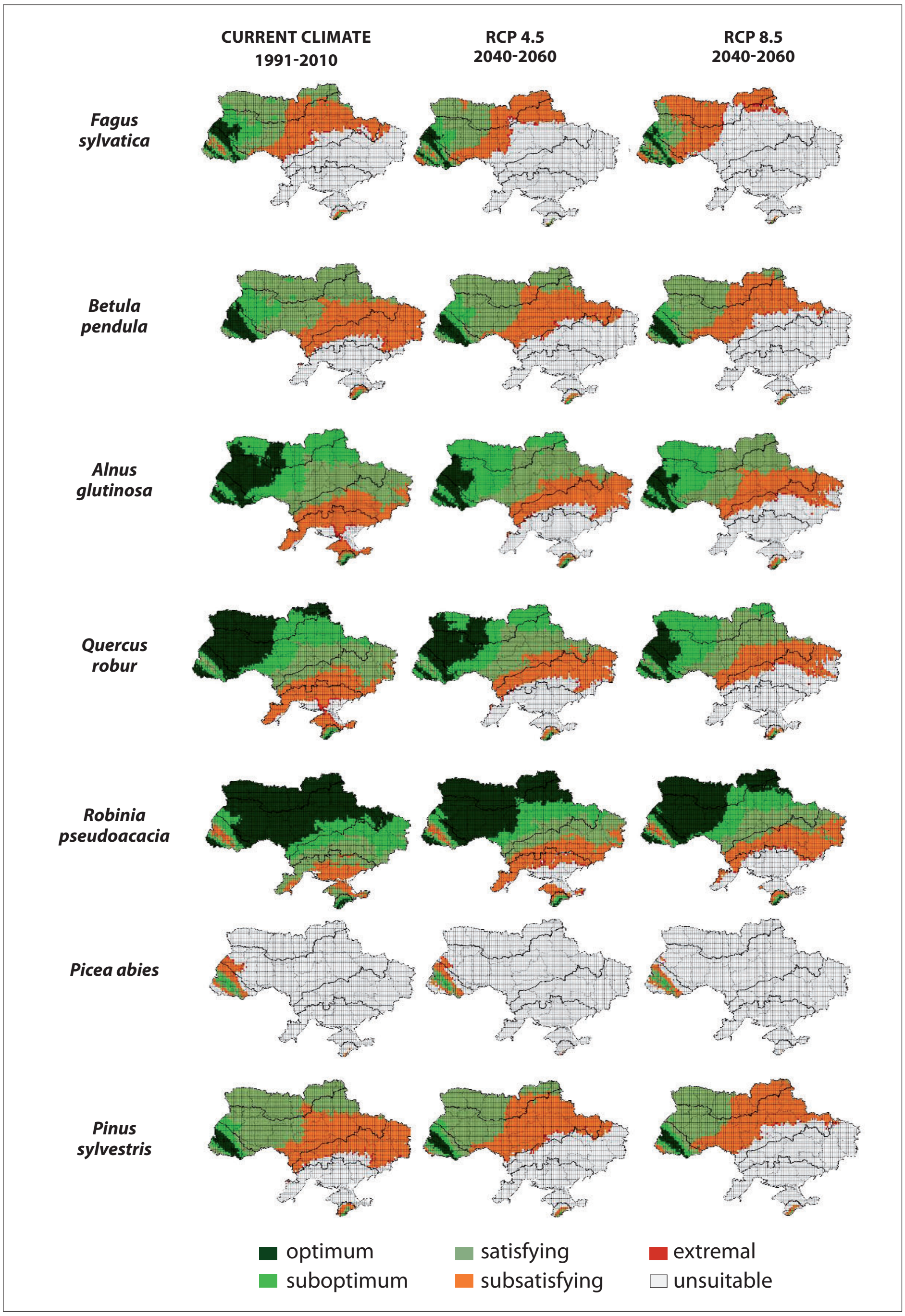

Fig. 2. Modelling of the suitability of climate humidity conditions in Ukraine for main tree species in the current climate and in the middle of the 21st century under scenarios RCP 4.5 and RCP 8.5

According to the climate classification, the most favorable conditions are currently in the Carpathian Mountains (Table 2), but pine in the region grows only in small areas due to the dominance of other tree species: European beech, Common hornbeam, Norway spruce, Silver fur, etc.

Table 2. **Changes in the area of Scots pine distribution according to suitability for climate humidity under different scenarios (in the current climate and the period 2041-2060 under RCP 4.5 and 8.5) in Ukraine (Standwise forest inventory database as of 1 January 2011)**

Natural zone	Total pine area, 10^3 ha, (%)*	Suitability of climate	Relative area of pine stands in the natural zone (%)			Pine area change in 2041-2060*** 10^3 ha, (%)	
			Current climate	2041-2060 RCP 4.5	2041-2060 RCP 8.5	RCP 4.5	RCP 8.5
Carpathian Mountains	16.8 (0.7%)	Favorable**	100	100	99.5	0	-0.05 ha (-0.5%)
		Unsuitable	0	0	0	0	0
Forest zone	1604.2 (66.7%)	Favorable**	97.7	84.8	64.9	-206.9 ha (12.9%)	-526.2 ha (32.8%)
		Unsuitable	0	0	0	0	0
Right bank Forest-steppe	314.4 (13.1%)	Favorable**	74.2	68.1	63.7	-19.2 ha (-6.1%)	-33.0 ha (-10.5%)
		Unsuitable	0	0	15.1	0	47.5 ha (15.1%)
Left bank Forest-steppe	309.7 (12.9%)	Favorable**	30.8	4	0	-83.0 ha (-26.8%)	-95.4 ha (-30.8%)
		Unsuitable	0	0	23.3	0	72.2 ha (23.3%)
Northern Steppe	124.7 (5.2%)	Favorable**	0	0	0	0	0
		Unsuitable	0.5	81.2	100	100.6 ha (80.7%)	124.1 ha (99.5%)
Southern Steppe	31 (1.3%)	Favorable**	0	0	0	0	0
		Unsuitable	99.9	100	100	0	0
Mountain Crimea	2.9 (0.1%)	Favorable**	83.1	44.1	44.1	-1.1 ha (-39%)	-1.1 ha (-39%)
		Unsuitable	0	0	0	0	0
Ukraine	2403.9 (100%)	Favorable**	79.7	66.8	52.4	-310.1 ha (-12.9%)	-656.3 ha (-27.3%)
		Unsuitable	1.3	5.5	11.4	100.7 ha (4.2%)	242.8 ha (10.2%)

* Share of Scots pine area in natural zone from the total Scots pine area in Ukraine.
** Favorable conditions include the sum of Scots pine areas in optimal, suboptimal, and satisfactory conditions.
*** Compared to the current climate.

The distribution of Scots pine stands by natural zones in Ukraine is not homogeneous due to differences in climate and soil conditions. The majority of pine forests (66.7% of total pine stands in Ukraine) are located in the Forest zone (northern part of the country), where the climate conditions currently are mainly favorable (97.7% of Scots pine forests in the region grow in a favorable climate). Among the forest-steppe regions, the Right Bank Forest Steppe is relatively more favorable for pine due to its more humid climate. While conditions of the Steppe zones are mostly unfavorable (subsatisfactory), extreme for the Northern Steppe, and unsuitable for the Southern Steppe.

The analysis of the distribution of existing Scots pine areas in Ukraine within the projected climate humidity suitability classes (see Table 2) and the study regions showed that in Ukraine as a whole in the middle of the century, 4.2 to 10.2% (depending on the scenario) of existing pine forests will be in unsuitable conditions (mainly in the Forest-Steppe and in the Northern Steppe zones), while in the Forest zone and the Forest-Steppe, conditions in large areas of Scots pine stands will vary from favorable to sub-satisfactory and extreme. In terms of area, the most significant changes are predicted in the Forest zone, where up to 32% of existing pine stands under RCP 8.5 might become vulnerable.

Thus, under the projected climate, pine stands become vulnerable over large areas in different regions. The estimated area of pine forests that may be affected will be about 411-899 thousand hectares (depending on the scenario). Our approach made it possible to identify regions, and forestry enterprises with the most unfavorable prognosis.

Discussion. Generally, the expected climate change will have negative consequences for the health condition, productivity and biodiversity of existing forest stands, as such rapid changes may disrupt the homeostasis of forest ecosystems. Taking into account the current age structure of Ukraine's forests, their adaptability to rapid climate change will be relatively weak, as adult plants are less able to adapt to changes in environmental conditions. At the same time, in Ukraine, there are large areas of pure even-aged pine stands that have the highest wildfire hazard.

The main consequences of climate change for forest ecosystems of Ukraine are manifested in the following areas: 1) geographical and landscape changes in areas suitable for growing certain tree species (shift of natural ranges, disappearance of some tree species or invasion of non-native species); 2) changes in the resilience, vitality and productivity of forest ecosystems; 3) the occurrence of water or heat stress, especially during extreme climate events; 4) changes in the ecosystem functions of forests (in particular – the impact on the quantity and quality of wood production, biogeochemical cycles, biodiversity loss, etc.); 5) changes in the content and circulation of plant nutrients; 6) changes in the reproductive cycle of species, patterns of succession dynamics, as well as changes in ecological and social services of forests; 7) changes in the hydrological regime, especially in arid areas.

The study results showed that changes in the climatic conditions will occur in all regions of Ukraine. In the Carpathians, the vegetation belts are expected to shift in altitude, for the plain part of Ukraine the impact of projected climate change will cause a shift of natural zones in the northern direction. Almost all of the studied tree species are sensitive to climate humidity, which is likely to decrease due to redistribution of precipitation, increase of air temperature and, as a consequence, increased evapotranspiration. Increasing climate aridity, variability and extremes of climatic phenomena will create stressful conditions for forest vegetation. The predicted changes will have a minimal effect on the black locust, so we can expect an increase in its expansion in forest stands, especially in the Forest-Steppe zone.

Forest vulnerability can be significantly reduced through the development and implementation of strategies (Bowditch et al., 2020; Temperli, Bugmann, & Elkin, 2012) and a system of actions aimed at adapting Ukraine's forests to climate change. On October 20, 2021, the Cabinet of Ministers of Ukraine adopted the Strategy for Environmental Safety and Adaptation to Climate Change until 2030. The document is aimed at fulfilling Ukraine's international obligations under the Paris Climate Agreement to reduce greenhouse gas emissions and adapt to the effects of global climate change. Bowditch et al. (2020) describe the process that developed a comprehensive definition of Climate-smart forestry, as well as the process for selecting indicators that assess the "climate-smartness" of forest management. The core focus of the Climate-smart forestry definition is integrating aspects of adaptation, mitigation and social dimensions.

Forest management strategy for adaptation to climate change should be developed on a regional basis, taking into account tree species composition and regional characteristics, in particular concerning modeled climate conditions; it should be based on the principles of Climate-smart forestry and in-depth study of bioecological characteristics of the major forest tree species (and potential prominent introduced species).

In regions with high vulnerability of tree species, it is necessary to carry out measures to increase forest resilience and adaptation to the expected climate. It is necessary to include in the list of planned activities not only the climate forecast for the territory but also the local characteristics of site conditions (soil fertility, soil water availability). It is recommended to transform the existing pure Scots pine stands into mixed forests (with an admixture of deciduous species). Use of provenances with high adaptability to dry conditions for reforestation. For detailed development of the list of measures at the level of forestry enterprises for pest and fire control, it is relevant to use the method of pests and wildfire prediction, developed by Meshkova & Borysenko (2021), based on scoring of soil fertility, soil water availability, species composition (share of Scots pine) and age. The basis for nature-based solutions is adaptive sustainable forest management, which provides: 1) optimization of land use structure, increasing the forested area; 2) introduction of close-to-nature forestry approaches.

Considering the diversity of natural conditions, adaptive measures in the forest sector should be localized (at the region level), species-specific and aimed at 1) maintenance of existing forest ecosystems and landscapes (implementation of sustainable forest management, fire control, forest protection from pests and diseases); 2) optimization of land use structure, increasing the forested area; 3) increasing the resilience of forest ecosystems (existing and newly created) – supporting of the best forest management practices through the introduction of Climate-smart Forestry principles: measures to control invasive species, selective felling system, regulation of species composition, adapted migration, controlled use of non-native species more adapted to new climatic conditions); 4) efficient use of natural resources, replacement of energy-intensive products (to reduce carbon footprint)) – using wood to substitute greenhouse gas-intensive materials and fossil fuels. To achieve the ambitious goals of the Paris Agreement in Ukraine, it is necessary to develop and implement a national forestry program considering the priorities of climate change, low-carbon development, and strengthening of intersectional cooperation (primarily for afforestation of the non-forest lands).

Conclusions. A change in climatic conditions will occur in all regions of Ukraine: in the Carpathians, a shift in vegetation zones is expected in altitude, for the plain part, the impact of the predicted climate changes will cause a shift in natural zones in the northern direction. Almost all studied tree species are sensitive to climate humidity, which is likely to decrease due to redistribution of precipitation, increased air temperature and, as a result, increased evaporation. Increasing aridity of the climate, variability and extremes of climatic phenomena will create stressful conditions for forest vegetation.

The proposed method can be used as the base for adaptation and mitigation measures development, and their correction. The developed approach makes it possible to identify and map the hot spots/regions as a priority for the preparation of the adaptation measures. Further studies with a comprehensive approach including national forest inventory data, climate and local site conditions are necessary.

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Оцінка уразливості лісів України як основа природо-орієнтованих рішень для запобігання та адаптації до зміни клімату

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Широкий діапазон кліматичних умов в Україні зумовлює значні регіональні відмінності в уразливості лісів до сучасної швидкої зміни клімату. Стратегія пом’якшення / адаптації має ґрунтуватися на оцінюванні їхньої вразливості на регіональному рівні. Для оцінювання уразливості лісів використано фітоіндикаційну модель проф. Я. П. Дідуха (1994). Модель забезпечує кількісну оцінку клімату як одного з основних екологічних чинників, що впливає на поширення, стан і продуктивність рослинності на основі кліматичних показників – континентальності, забезпечення вологою та морозостійкості. Для цих показників розраховано шкали кліматичної придатності. Моделювання здійснювали для основних деревних видів: *Pinus sylvestris* L., *Quercus robur* L., *Fagus sylvatica* L., *Picea abies* (L.) H. Karst, *Betula pendula* Roth., *Alnus glutinosa* (L.) Gaertn. і *Robinia pseudoacacia* L. Використовували прогнози клімату на основі часових рядів Euro CORDEX (до 2100 р.) та два сценарії репрезентативних шляхів концентрації (RCP 4.5, RCP 8.5). За допомогою Q-GIS створено карти, що містять зони придатності кліматичних умов для кожного з досліджуваних видів дерев за поточних і майбутніх кліматичних змін. Результати дослідження свідчать, що зміна кліматичних умов відбудеться в усіх регіонах України. У Карпатах очікується зміщення рослинних поясів за висотою, для рівнинної частини України – у північному напрямку. Майже всі досліджені деревні види чутливі до вологості клімату, яка має тенденцію до зменшення внаслідок перерозподілу опадів, підвищення температури повітря і, як наслідок, посилення випаровування. Підвищення посушливості клімату, мінливості та екстремальності кліматичних явищ створюватимуть стресові умови для лісової рослинності.

Розглянуто напрями посилення пом’якшувальної та адаптаційної здатності лісів. Основним напрямом природокористування є адаптивне стале лісове господарство, яке передбачає: 1) оптимізацію структури землекористування та збільшення лісистості; 2) розроблення та реалізацію національної програми лісового господарства з урахуванням пріоритетів зміни клімату та низьковуглецевого розвитку; 3) використання деревини для заміни матеріалів, що інтенсивно виділяють парникові гази, і викопного палива; 4) впровадження найкращих практик лісового господарства, що базуються на сучасних принципах кліматично орієнтованого лісівництва.

Стратегію управління лісами потрібно розробляти на регіональній основі з урахуванням змодельованого кліматичного стану та видового складу деревостанів, який має базуватися на принципах ведення кліматично обґрунтованого лісівництва та поглибленого вивчення біоекологічних характеристик основних лісотвірних видів. Для досягнення цілей Паризької угоди в Україні необхідно розробити та впровадити національну лісову програму з урахуванням пріоритетів зміни клімату, низьковуглецевого розвитку та посилення міжгалузевої співпраці.

Ключові слова: RCP 4.5; RCP 8.5; Euro CORDEX; кліматичні тренди; адаптивне лісове господарство.

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