FORESTRY IDEAS, 2021, vol. 27, No 2 (62): 470–482

MODELLING AND FORECASTING THE IMPACT OF CLIMATE CHANGE ON FORESTS OF UKRAINE FOR 21ST CENTURY TIME HORIZON

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Received: 05 October 2021 Accepted: 29 November 2021

Abstract

In Ukraine and elsewhere on the planet, study of climate change effects on forests is of great public interest. The study aimed to evaluate climate humidity dynamics in the 21st century according to Vorobiev indicator under RCP 4.5 and RCP 8.5 scenarios. E-OBS and EURO-CORDEX project climate data were used. Climate humidity indicator by Vorobiev was used to assess the suitability of climatic conditions for forests (suitable conditions are from fresh to wet forest types). In the current climate condition in Ukraine the climate humidity varies from very dry in the south to very wet in the Carpathians. Dry (30 %) and fresh (40.1 %) types dominate. Comparing to 1961–1990, aridity has increased, boundaries of climatic zones shifted by 1 class to the north for the plains of Ukraine and to higher elevation for the Carpathians. In the Forest and the Forest-Steppe zones the fresh climate prevails, wet climate becomes less represented. Climate condition suitable for forests covers about 50 % of the country area. Both scenarios show a further aridity increase and climate zones shift to the north. Under the RCP 4.5, the areas of wet and fresh climate are expected to decrease with substitution by dry climate. In 2040–2060 the area of conditions suitable for forests will decrease to 37 % of the country area, and to 30 % in 2080–2100. Favourable conditions for the forest will remain only in the Carpathians, the western Forest-Steppe and partly in Forest zones. Under the RCP 8.5 scenario, the process of climate aridization will accelerate: dry climate types are expected to dominate. The area suitable for forest conditions will decrease significantly to 30 % in the middle and to 10 % at the end of the century.

Key words: climate zones, main trees species, RCP 4.5, RCP 8.5 scenarios, soil humidity index, Vorobiev climate indices.

Introduction

Climate change is a real threat to forest ecosystems in the temperate climate. Many climate-related studies (Dyderski et al. 2018, Buras and Menzel 2019) predicted shifting of natural ranges of main forest forming species in Europe due to unfavourable future climate conditions. In such conditions forests become vulnerable to biotic damage and fires.

The earlier study in Ukraine (Shvidenko et al. 2017) predicted deterioration of climate conditions (under scenario A1B)

(IPCC 2000) for forest vegetation due to climate aridization in the 21st century. Water stress is the major limiting factor for forest distribution in Ukraine. Within scenario A1B, the area with unsuitable growth conditions for major forest forming species will substantially increase by the end of the century, occupying a major part of Ukraine. It is expected that the boundary of conditions that are favourable for forests will shift to north and northwest, and forests of the xeric belt will be the most vulnerable.

In this study we used the climate scenarios of The Intergovernmental Panel on Climate Change (IPCC AR5 2014), focusing on average values of climate indices, which gradually change within decades. The study aimed to evaluate climate humidity dynamics in the 21st century according to Vorobiev indicator in Ukraine under RCP 4.5 and RCP 8.5 scenarios.

Our tasks were to reveal temperature trends, create maps of climate humidity and its zoning, evaluate total forest area and distribution of main tree species forest stands distribution by climate zones, and perform correlation analysis of local soil humidity of forest stands with climate humidity indices.

Materials and Methods

The area of study was the whole territory of Ukraine. For the classification of the territory we used forestry zones of Ukraine according to Gensiruk et al. (1981) (Fig. 1).

Forests in Ukraine totally cover about

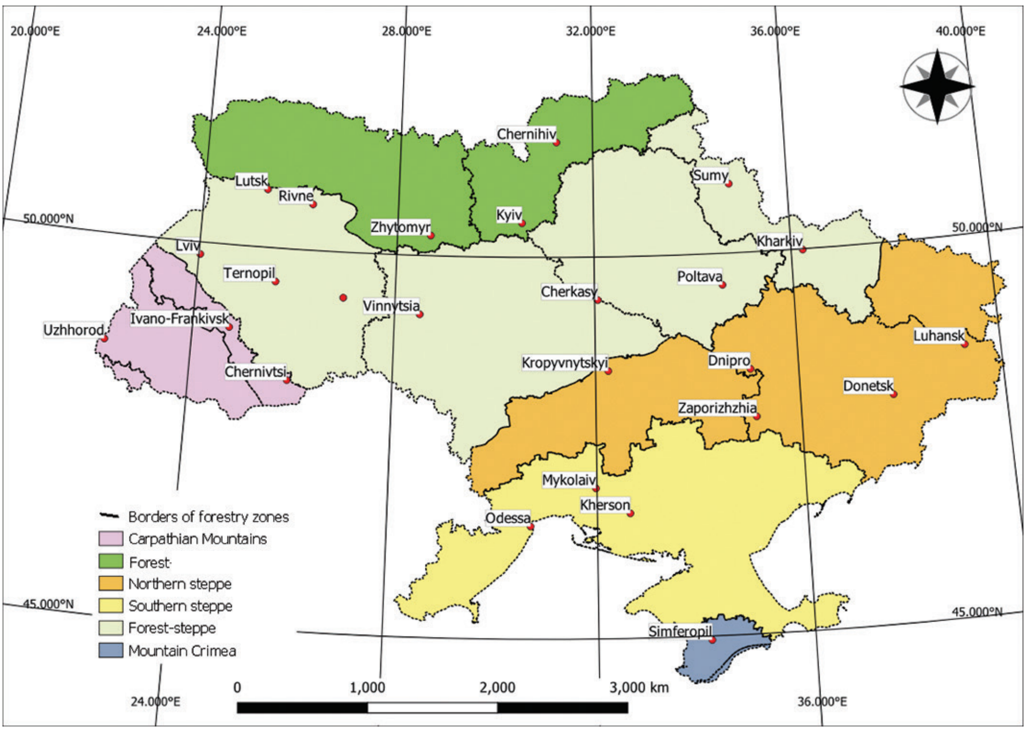

Fig. 1. Forestry zones of Ukraine (Gensiruk et al. 1981).

9.7 mill hectares, which makes 15.9 % of the total country area (Forest … 2012). Forests are mainly located in three zones: Forest zone, Forest-Steppe and Carpathian Mountains. Each zone is characterized by specific climate and soil conditions, which influence to forest structure and composition.

According to the Forest stand-wise inventory database (2011) in highlands of the Carpathian Mountains, the main forest forming tree species is Norway spruce (*Picea abies* (L.) Karst.), lower in Carpathians and in the western part of Forest-Steppe grow mainly European beech (*Fagus sylvatica* L.) and Common hornbeam (*Carpinus betulus* L.), in the Forest zone the most widespread tree species are Scots pine (*Pinus sylvestris* L.) and silver birch (*Betula pendula* L.), in the Forest-Steppe zone deciduous stands prevail, with predominance of English oak (*Quercus robur* L.), on sandy soils in this zone grow Scots pine stands, in wet site conditions all over the country grow black alder (*Alnus glutinosa* (L.) Gaertn.) forests (Table 1). The lowest area of forests is in the Steppe zone, and they are mainly artificial with English oak, Scots pine, Crimean pine (*Pinus nigra* subsp. *palassiana* (Lamb)) and black locust (*Robinia pseudoacacia* L.).

Table 1. Distribution of forests of the main trees species within forestry zones of Ukraine, in %.

Forestry zone	*F. sylvatica*	*Q. robur*	*P. sylvestris*	*P. abies*	All forests
Carpathian Mountains	82.7	6.3	0.7	93.8	22.1
Forest zone	0	13.8	66.7	2.8	31.6
Forest-steppe zone	12.7	66.9	26	3.4	33
Crimean Mountains	4.6	0	0.1	0	3.3
Steppe zone	0	13	6.5	0	9.9
Ukraine (whole territory)	100	100	100	100	100
Share of species areas at country level	9	28	35	7	100
Areas*, mill ha	0.86	1.81	2.40	0.63	7.58

Note: * Data on forest areas subordinated to SFRAU from forest inventory database as of 01.01.2011.

In this study, only forest areas that subordinate to State Forest Resources Agency of Ukraine (SFRAU) (Forest … 2012) available at the forest inventory database were included in calculations. Distribution of four main forest-forming species in Ukraine of the area covered with forest vegetation, respectively (Forest … 2012) within climate zones under different time periods and climate scenarios, was evaluated.

Average monthly precipitation and air temperature at 7371 points of climate grids in Ukraine for the past climate (baseline period) 1961–1990, recent climate 1991–2010 (E-Obs data), and projected climate under scenarios RCP 4.5 and RCP 8.5 for 2021–2040, 2041–2060 and 2081–2100 (EURO-CORDEX Data 2021) were used as primary climate data for further calculations. We compared distributions with those at the baseline period (1961–1990).

Forest management in Ukraine is based traditionally on forest typological basis, which among other includes climate characteristics according to Vorobiev (1961). The climate classification was developed by Vorobiev (1961) for forest areas of USSR, and detailed for Ukraine, as a component of forest typology classification of forest stands and classification of edaphic conditions. This index is easy to calculate on the basis of monthly average climate data, and results can be compared with data obtained for 1960, when boundaries of climate zones under Vororbiev humidity index were similar to natural climatic zones. The limitations of the method are that decreasing of index values is observed both in case of decreasing precipitation and temperature growth, and in case of decreasing of winter period the index will include data of the annual temperature and precipitations. In this study these limitations were not considered.

So climate change evaluation using Vorobiev humidity index can be the basis for substantiation of changes in traditional silvicultural practice in Ukraine: as different silviculture measures, rotation period, tree species for reforestation.

Climate humidity was modelled using Vorobiev's method (Vorobiev 1961), according to which the climate type is a function of heat and moisture availability on the territory. Heat availability (T) and moisture availability (W) were evaluated using the formula (1):

$$W = \frac{\sum R_{Tmon>0}}{\sum T_{mon} > 0} - 0.0286 \sum T_{mon} > 0\,, \quad (1)$$

where: $\sum T_{mon} > 0$ is the sum of average monthly air temperatures for the months with above-zero temperatures; and $R_{Tmon>0}$ is the amount of precipitation for the months with above-zero temperatures.

Climate humidity index W was used to assess the suitability of climatic conditions for forests, suitable conditions ranged 2–6 (fresh climate and above) (Table 2), below this range only intrazonal forest vegetation can grow.

Table 2. Climate humidity zones by Vorobiev and main climate indicators.

Climate zone name	Class W	Climate index W range	Colour	Conditions for forest	Average* $\sum R_{Tmon>0}$	Average* $\sum T_{mon>0}$
Extremely dry	-1	≤-2.2		Unsuitable	415.3±11	177.9±2
Very dry	0	-2.2 – -0.8			392.9±7.3	142.8±1.2
Dry	1	-0.8 – 0.6			472.8±6.8	129.1±0.9
Fresh	2	0.6 – 2.0		Suitable	531±5.2	115.7±0.7
Humid	3	2.0 – 3.4			619±13.3	109.8±1.4
Moist	4	3.4 – 4.8			732.6±19	104.4±2
Wet	5	4.8 – 6.2			728.7±11.6	91.4±1.3
Very wet	6	>6.2			772.3±22.6	78.3±2

Note: * average values of indicators used for calculations of W index ± confidence interval.

For description of forest site conditions in Ukraine the classification of Alekseev-Pogrebniak is used (Ostapenko and Tkach 2002), which includes a combination of soil fertility and humidity. In this study we used only soil humidity index (hygrotop) (classes have the same numbers and names as climate humidity classes (Table 2), and ranged from 0 to 5).

Forest stand-wise inventory database (18,649 forest compartments of 297 forestry enterprises) as of 01.01.2011 was used as a source of forest data and data on soil humidity. GIS of forestry enterprises boundaries, and forestry zones (Gensiruk et al. 1981) were used for mapping and evaluation of forest and climate variables.

QGIS and R were used to create maps, classify data, and calculate areas distribution. Statistical analysis of data was performed using SPSS program.

Results and Discussion

In the recent climate (1991–2010), the average annual air temperature in Ukraine has increased by 0.8 °C compared to the baseline climate (1961–1990). At the same time, the average temperature of the coldest winter month and the warmest summer month has increased significantly (by 2 °C and 1.5 °C, respectively). The RCP 4.5 scenario predicts a steady rise in temperature: compared to the basic climate by 1.2–1.8 °C in 2021–2040, by 1.8–2.3 °C in the middle of the century, and by 2.3–3.0 °C at the end of the century. For the RCP 8.5 scenario the warming rate will accelerate – in the middle of the century expected temperature values will be the same as predicted under the RCP 4.5 at the end of the century, and by 2081–2100 the temperature may increase by 5.1 °C.

At the territory of Ukraine in 1961–1990, climate humidity varied (Fig. 2) from very wet (6) in the Carpathians to very dry (0) in the Southern Steppe, with dry (1) and fresh (2) types predominating. Very dry type prevailed in the Southern Steppe region, dry climate was represented in the Northern Steppe, and partially at the Forest-steppe, fresh type of climate dominated in the Forest-steppe and Forest zones, wet climate was represented in the Western Forest-Steppe, partly in Forest zone; in the Carpathian Mountains the conditions were the wettest: here climate varied from fresh to very wet.

In the recent climate (1991–2010), compared to the past, an increase in climate aridity in all regions was observed. The zone of very dry climate spread to the south of the Northern Steppe region, and the fresh climate (2) covered almost the whole territory of the Forest zone, while the area of moist climate (3) significantly decreased, and it remained in the Lviv region and in the Carpathians, where the area of very wet (6) climate decreased. In fact, the climate conditions in the Forest zone have become similar to those in the Forest-Steppe (Fig. 2).

Both scenarios of future climate showed further increase in climate aridity and shifts of class boundaries in the northern direction. An extremely dry climate is expected to appear in the south. Under the RCP 4.5 scenario, the areas of wet and fresh types of climates are expected to decrease while dry climate types are expected to grow. In the middle of the century, the total area with dry climate conditions (sum of classes -1, 0 and 1) will occupy 63.2 % of the country's area, and by the end of the century – 70.5 % (Table 3). Climate conditions suitable for forest (fresh type of climate) will remain only at the Carpathians, western part of the Forest-Steppe and the western and northern part of the Forest zone.

If the RCP 8.5 scenario is implemented, the process of climate aridization will accelerate: in the middle of the century it is expected that dry climate types will occupy about 69.6 %, and at the end of the century – 89.7 % of the territory of Ukraine (Table 3). Accordingly, the area of climate conditions suitable for forest (classes 2–6) will decrease significantly: up to 30.4 % in the middle of the century, and up to 10.3 % at the end of the century. If the pessimistic scenario is implemented at the end of the

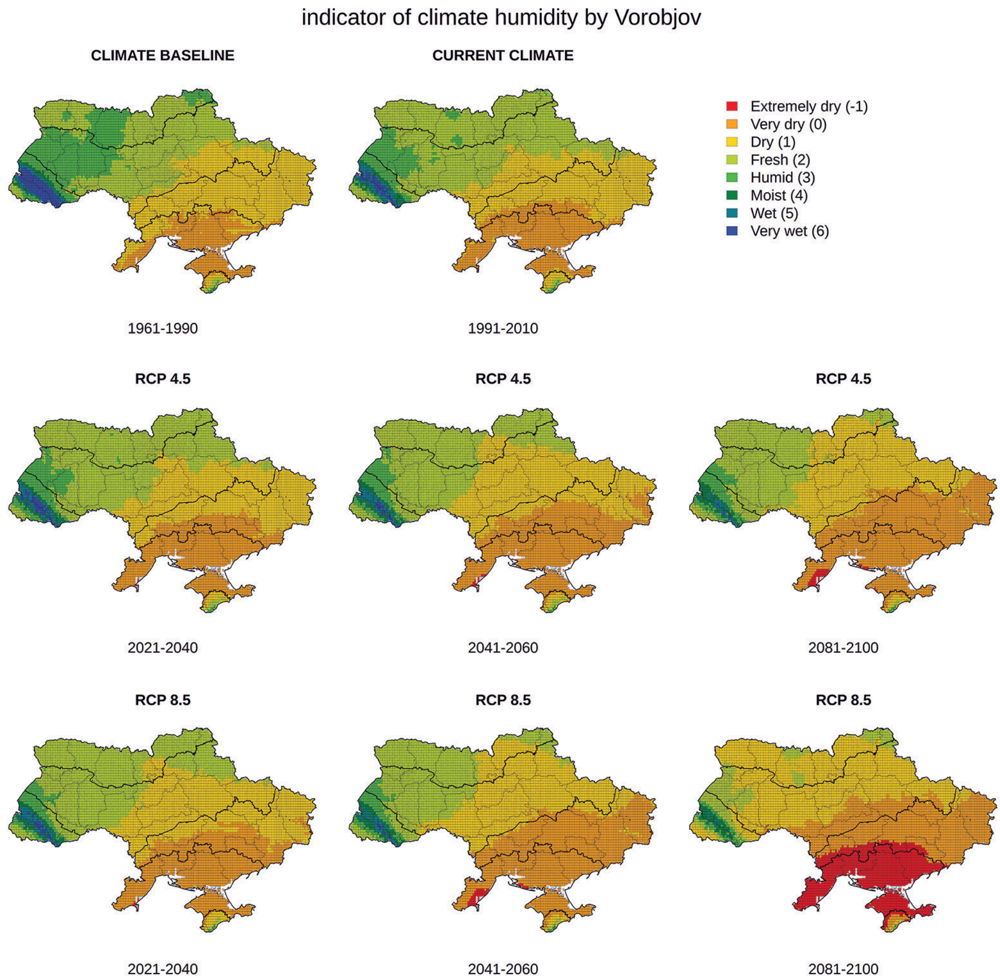

Fig. 2. Climate humidity W zones in past climate, recent climate, projected climate under RCP 4.5 and RCP 8.5 scenarios.

century, favourable conditions for forests will remain in the Carpathians, and in the western Forest-Steppe (Lviv region) and partly in the Forest zone, while in the rest of the territory more arid conditions typical of the Steppe zone will be formed. Boundaries of climate types will shift to the northwest: in the middle of the century the significant changes are expected in the Forest-Steppe zone (except its western part), as well as in the central part of the Forest zone. Conditions in the Northern steppe will be similar to the Southern steppe.

Analysis of forested area distribution by climate humidity zones (Table 4) showed, that in the past and in recent climates the majority of forests (about 80 %) were located in climate zones from fresh to very wet. Tree species are well adapted to such conditions, because the majority of Ukrainian forests were planted mostly after II World War.

Table 3. Total area of Ukraine distribution by climate humidity zones, in %.

Class W	1961–1990	1991–2010	RCP 4.5			RCP 8.5		
			2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100
Extr. dry (-1)	0	0	0	0.2	0.7	0.1	0.7	18.7
Very dry (0)	12.4	18.6	21.9	28.7	36.1	25.4	35.6	28.7
Dry (1)	35.8	31.0	32.4	34.4	33.7	34.8	33.3	42.3
Fresh (2)	31.0	40.1	37.3	30.4	24.0	34.1	25.1	7.8
Humid (3)3	17.2	7.3	5.6	3.9	3.5	3.1	3.0	1.2
Moist (4)	0.8	1.0	1.0	1.1	1.4	1.1	1.3	1.2
Wet (5)	0.7	1.1	1.0	0.9	0.5	1.0	0.8	0.1
Very wet (6)	2.2	0.9	0.8	0.4	0.1	0.5	0.2	0
Total	100	100	100	100	100	100	100	100

Table 4. Forest area of Ukraine distribution by climate humidity zones, in %.

Class W	1961–1990	1991–2010	RCP 4.5			RCP 8.5		
			2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100
Extr. dry (-1)	0	0	0	0	0	0	0	3.0
Very dry (0)	2.0	2.6	3.3	6.1	10.2	4.2	9.0	16.2
Dry (1)	18.1	17.8	22.9	26.1	29.7	27.0	30.3	52.3
Fresh (2)	34.3	51.2	48.8	45.5	39.3	47.1	40.6	14.0
Humid (3)3	26.9	12.5	9.7	7.8	8.7	7.2	5.5	9.3
Moist (4)	2.2	4.9	5.2	5.8	11.0	5.8	7.6	5.2
Wet (5)	4.6	5.1	7.9	8.7	1.1	8.7	6.9	0.0
Very wet (6)	11.9	5.9	2.3	0	0	0	0	0
Total	100	100	100	100	100	100	100	100

Projected climate will change the distribution of forested areas within climate zones: by the middle of the century the share of forests in suitable climate condition will amount to 67.8 % in RCP 4.5, and 60.7 % in RCP 8.5. By the end of the century these values will decrease to 60.1 % in RCP 4.5, and only 28.5 % in RCP 8.5.

By the average values soil humidity index in forests, zones can be arranged in descending order: Carpathians (2.9); Forest zone (2.7), Forest-steppe (2.2), Steppe (1.4) and Crimea Mountains (1.3) (Table 5). This ranking generally corresponds to regions ranked by climate humidity (except Steppe and Crimean Mountains). Climate humidity in the Carpathians is much higher than the weighted average soil humidity index, which is explained by the high amount of precipitations and mountain relief and low thickness of mountain soils. The opposite figure is in Forest zone: the average soil humidity index is significantly higher than the average W index, which is explained by the low relief and the ability of soils of the region to retain moisture. In the Steppe zone, the average value of soil humidity is higher than the climatic index, which is due to the fact that in this region the forests are intrazonal vegetation and confined to wetter habitats.

Table 5. Average values of soil humidity index (2011), climate humidity index (W) and class (Class W) for 1961–1990.

Zone	Soil humidity index	Climate humidity index W*	Climate humidity class W**
Ukraine	2.2±0.04	1.8±0.1	2.3±0.07
Carpathians	2.9±0.03	6.3±0.2	4.9±0.2
Forest zone	2.7±0.05	1.9±0.04	2.4±0.02
Forest-steppe	2.2±0.04	1.3±0.07	2.1±0.8
Steppe	1.4±0.05	-0.5±0.07	0.7±0.06
Crimean mountains	1.3±0.1	0.7±0.3	1.5±0.2

Note: * Climate humidity index W – absolute values of Vorobiev index, ** climate humidity class W – classified data.

In order to check the relationship, found by Vorobiev (1961), we carried out correlation analysis between the humidity of the modern climate in Ukraine according to the W index, Class W (for the period 1961–1990) and local soil humidity as the weighted average indices for each forestry enterprise (Table 6). It showed a significant positive correlation between the studied indicators for Ukraine as a whole and its forest regions: Carpathians, Forest, and Forest-Steppe zones. For the Steppe correlation is significant at $p<0.01$.

Table 6. Results of correlation analysis of average values of soil humidity index with climate humidity index (W) and class (Class W).

Correlation index	Climate index	Ukraine	Forested area	Carpathians	Forest zone	Forest steppe	Steppe
Kendall tau	Class W	0.602**	0.485**	0.275**	0.112**	0.380**	0.076*
	W	0.582**	0.471**	0.260**	0.153**	0.379**	0.065*
Spearman's Rho	Class W	0.746**	0.612**	0.355**	0.140**	0.478**	0.093*
	W	0.773**	0.652**	0.367**	0.229**	0.539**	0.093*
Number of forest sites		2336	1704	344	504	856	560

Note: * Correlation is significant at the level of 0.05; ** Correlation is significant at the level of 0.01.

Climatic conditions according to the humidity index cause the formation of zonal hydrological conditions, respectively, the increase in climate aridity causes changes in humidity: hydrological regime and groundwater levels. In recent years, a decrease in the groundwater level in the Forest zone was observed (State … 2021) and an increase in the frequency of wildfires in forests and peatlands (Soshenskyi et al. 2021), which indicates that soils become dryer, and, accordingly, the soil humidity index decreases. On the other hand, local intrazonal conditions formed under certain relief and water availability that may significantly differ from the zonal ones. Some of such places can remain favourable for forests.

Tree species can grow in a certain range of environmental conditions. European beech stands in the current climate grow in a narrow range of soil humidity (2 and 3). Comparison of the distribution of forest areas of the studied species with the data of climate humidity W (Table 7) showed that in the Western part of the Forest-Steppe zone, conditions for beech will become drier, which will negatively affect their health condition. Norway spruce stands grow in a wide range of soil humidity from 1 to 5, (the weighted average index is 3.0). Stands in more dry conditions will be potentially most vulnerable to increasing climate aridity. Among the studied species, oak is less demanding of soil humidity: it grows in the range of soil humidity from 0 to 4 (average index – 2.1); Scots pine grows in the range from 0 to 5, (average index – 2.3).

Table 7. Main tree species area distribution by humidity climate zones (Class W), in %.

Class W	1961–1990	1991–2010	RCP 4.5			RCP 8.5		
			2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100
Scots pine								
Extr. dry (-1)	0	0	0	0	0	0	0	1.4
Very dry (0)	1.4	1.4	1.5	3.5	7.1	2.3	5.6	10.3
Dry (1)	13	11.9	16.2	22.2	32.1	22.4	30.6	73.4
Fresh (2)	48.9	77.1	78.5	71.5	58.7	73.2	61.8	14.5
Humid (3)3	36.2	9	3.2	2.4	1.7	1.6	1.5	0.4
Moist (4)	0.3	0.4	0.4	0.3	0.4	0.3	0.3	0.1
Wet (5)	0.1	0.1	0.1	0.1	0	0.1	0.1	0
Very wet (6)	0.2	0.1	0	0	0	0	0	0
Total	100	100	100	100	100	100	100	100
English oak								
Extr. dry (-1)	0	0	0	0	0	0	0	1.3
Very dry (0)	0.3	1.0	1.5	6.1	13.0	2.7	11.6	27.5
Dry (1)	27.9	29.6	41.4	46.7	46.4	48.1	49.6	59.1
Fresh (2)	42.4	56.1	47.2	40.2	34.0	42.8	33.8	11.1
Humid (3)3	27.0	11.4	8.7	6.0	5.8	5.4	4.0	0.9
Moist (4)	1.0	1.5	0.8	0.9	0.7	0.9	0.9	0.0
Wet (5)	0.8	0.4	0.3	0.0	0.0	0.0	0.0	0.0
Very wet (6)	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100	100	100	100	100	100	100	100
Norway spruce								
Extr. dry (-1)	0	0	0	0	0	0	0	0
Very dry (0)	0	0	0	0	0	0	0	0.1
Dry (1)	0	0.1	0.2	0.5	1.7	0.5	1.6	12.6
Fresh (2)	3.4	7.9	8.5	10.3	13.7	10.4	14.7	9.9
Humid (3)3	9.4	10	9.5	11.7	16.1	11.6	6.3	46.9

Class W	1961–1990	1991–2010	RCP 4.5			RCP 8.5		
			2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100
Moist (4)	5.3	17.1	22.8	21.9	60.9	21.9	29.3	30.6
Wet (5)	9.1	24.5	43.1	55.5	7.6	55.5	48.2	0
Very wet (6)	72.7	40.4	16	0	0	0	0	0
Total	100	100	100	100	100	100	100	100
European beech								
Extr. dry (-1)	0	0	0	0	0	0	0	0
Very dry (0)	0	0	0	0	0	0	0	2.2
Dry (1)	2.2	2.2	2.2	2.2	2.2	2.2	3	19.4
Fresh (2)	5.3	9.8	9.3	19.6	25.2	20.9	24.4	28.6
Humid (3)3	22.2	34	35.5	28.5	35.5	27.2	22.9	31.3
Moist (4)	7.4	19.7	20.8	26.9	32.8	26.9	35.7	18.4
Wet (5)	26.4	21.6	25.5	22.9	4.4	22.9	14	0
Very wet (6)	36.5	12.7	6.7	0	0	0	0	0
Total	100	100	100	100	100	100	100	100

So taking into account the correlation analysis (Table 6) the indirect impacts of projected climate change at the site level are likely to occur: as lowering groundwater levels, drying of small rivers and other water bodies etc. Such a phenomenon has already been observed in many regions of Ukraine. Consequences of climate change are observed now: forest stands become more susceptible to damaging agents, including biotic (pests and diseases) and abiotic (fires) damage. During last decade massive Scots pine (Tkach and Meshkova 2019, Meshkova 2021) and Norway spruce decline caused by bark-beetles (Parpan et al. 2014), diseases of Norway maple (Meshkova and Davydenko 2016) and common ash (Davydenko and Meshkova 2017) were reported in different regions of Ukraine. According to statistical data of the State Agency of Forest Resources of Ukraine (Bondar 2019) for the period 2009 – 2018 the trend to increasing of forest dieback area (from 176,000 ha in 2009 to 413,000 ha in 2018) was revealed. In 2019 the total area of declined Scots pine (*Pinus sylvestris*) forests was 222,000 ha, Norway spruce (*Picea abies*) – 27,000 ha, English oak (*Quercus robur*) – 100,000 ha and at stands of other species – 64,000 ha (Bondar 2019). In 2018, catastrophic mortality of pine forests caused by bark beetle *Ips acuminatus* outbreaks mainly in Forest zone was observed.

For recent decades the frequency of large wildfires in Ukraine significantly increased, especially in 2020 when the catastrophic fires took place: 74,600 ha of forests were damaged (Soshenskyi et al. 2021), this figure is 4.9 times higher than the previous fire maximum (15,300 ha) registered in 2014 (year of war conflict in the Eastern Ukraine). Large fires took place in pine forests in Forest zone, as well as in Northern Steppe zone. The incidence of forest fires depends species composition of forests and correlates with precipitation amounts during warm period (Zibtsev et al. 2019).

According to the latest data (Shparyk et al. 2020), climatic changes in the Carpathians have already occurred and led to a shift in the altitude boundaries of vegetation zones, changes in trees species composition, Norway spruce decline, and reduction of soil humidity by 1–2 classes. The area of Norway spruce decreases, while the area of beech stands increases. Projected climate change will lead to further changes in the altitudinal zonation of the Carpathians. Unfortunately, the latest data on the soil humidity indices in forests and their dynamics in other regions of Ukraine are not available today, reduction of soil humidity in other regions should be expected.

Projected climate changes are very rapid, so tree species and forest ecosystems cannot adapt to them, so in the business as usual case, decreasing of forest area is expected. The probability of natural zones shifting to the north is very high, even under the optimistic scenario. The extension of the steppe ecoregion is forecasted. Under new climate conditions shifting of natural ranges of the main tree species, e.g. *Pinus sylvestris*, *Quercus robur*, *Fagus sylvatica* to the north is probable (Shvidenko et al. 2017, Dyderski et al. 2018, Buras and Menzel 2019). Conditions favourable for *Picea abies* stands will remain at higher altitudes in the Carpathian Mountains, while at lower elevations they will be replaced by *Fagus sylvatica*.

Measures for adaptation of forests in Ukraine to projected climate change should be developed. It is very important is to maintain existing forests, and gradually replace coppice oak stands with seed, the pure pine stands with mixed one, improvement of species composition, taking into account species adaptive capacity, conservation of the gene pool of native tree and shrub species, improve the technology of creating forest culture and growing of drought-resistant seedlings. In the steppe zone, special attention should be paid to protection against forest fires.

Conclusions

Our study showed that projected climate conditions in Ukraine in the 21st century due to climate warming and aridization will become unfavourable for forest vegetation across large areas all over the country. Projected climate change negative effect in terms of forest areas is expected to be the biggest in Forest-Steppe and Forest zones. Under new climate conditions by the middle of the century, the share of forests in suitable climate conditions will amount to 67.8 % or 60.7 % of the current forested area, depending on scenario, by the end of the century these figures may amount to 60.1 % or 28.5 % depending on scenario.

Significant deterioration of forest health condition is expected all over the country. There is a big risk of forest decline over large territories, partly caused by outbreaks of pests and diseases outbreaks and forest fires. With unfavourable climate conditions forests may remain only locally, as intrazonal vegetation in wet sites.

To reduce the negative consequences of climate change on forests, it is necessary to develop and implement multiple adaptation measures, taking into account local site conditions and tree species composition.

Acknowledgments

This work was performed within a research plan of URIFFM (2020–2024). Climate data for our study was provided from the study 'Assessment of the Impact, Opportunities and Priorities of Climate Change in Ukraine', supported by The World Bank. We would like to thank S. V. Krakovska, PhD, Head of the Laboratory of Applied Climatology of the Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine for consulting and assistance in processing and analyzing climate data.

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