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Vulnerability of Ukrainian Forests to Climate Change

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Abstract: Ukraine is a country of the Mid-Latitude ecotone—a transition zone between forest zone and forestless dry lands. Availability of water defines distribution of the country's forests and decreases their productivity towards the south. Climate change generates a particular threat for Ukrainian forests and stability of agroforestry landscapes. This paper considers the impacts of expected climate change on vulnerability of Ukrainian forests using ensembles of global and regional climatic models (RCM) based on Scenarios B1, A2, A1B of the Intergovernmental Panel for Climate Change, and a "dry and warm" scenario A1B+T−P (increasing temperature and decreasing precipitation). The spatially explicit assessment was provided by RCM for the WMO standard period (1961–1990), "recent" (1991–2010) and three future periods: 2011–2030, 2031–2050 and 2081–2100. Forest-climate model by Vorobjov and model of amplitude of flora's tolerance to climate change by Didukh, as well as a number of specialized climatic indicators, were used in the assessment. Different approaches lead to rather consistent conclusions. Water stress is the major limitation factor of distribution and resilience of flatland Ukrainian forests. Within Scenario A1B, the area with unsuitable growth conditions for major forest forming species will substantially increase by end of the century occupying major part of Ukraine. Scenario A1B+T−P projects even a more dramatic decline of the country's forests. It is expected that the boundary of conditions that are favorable for forests will shift to north and northwest, and forests of the xeric belt will be the most vulnerable. Consistent policies of adaptation and mitigation might reduce climate-induced risks for Ukrainian forests.

Keywords: Ukrainian forests; climate change; xeric belt; predictions of state and distribution of forests over 21st century; Mid-Latitude ecotone

1. Introduction

During last centuries, temperate forests of the Northern Hemisphere faced grave threats [1]. In Eastern Europe, initially it was tied with the human-induced land use-land cover change following deforestation for increasing areas for agriculture and overexploitation [2]. However, starting from the second half of the 20th century, climate change has brought new threats caused by hotter droughts of historically unprecedented severity, acceleration of natural disturbances, and worsening environment conditions due to air pollution, soil and water contamination [1]. This has led to widespread increasing mortality over the extra-tropical zones of the Northern Hemisphere [3], basically as a result of weather extremes and combination of direct and indirect impacts of disturbances [4,5]. The biggest threat for temperate forests is observed in the Mid-Latitude ecotone—a transition xeric belt between the forest zone and southern forestless territories where climate aridity is the major driver, which restricts distribution, growth and resilience of forests. Typical features of the Mid-latitude ecotone include: (1) extremely high vulnerability of forests, particularly due to differences in the magnitude of latitudinal and altitudinal lapse rates: along the latitudinal temperature gradient the temperature change amounts to 6.9 °C/1000 km (and for flatland of Ukraine, 1.0 °C/160 km [6]) while the vertical gradient is 5.0–6.5 °C/1000 m above sea level, and minor changes of temperature over flatland affect disproportionally large tracts as compared to mountain regions [7]; (2) high probability of ecologically harmful processes (degradation of forest ecosystems, oxidation of soil carbon, etc.); (3) unsatisfactory state and structure of landscapes (a large share of degraded land, lack of stabilized landscape components, e.g., forests); and (4) high uncertainty of climatic predictions [8,9]. The threat of new forest types formation, or transition to open woodland and non-forest vegetation is particularly acute over the ecotone.

The study region, Ukraine, one of the biggest countries by area in Europe (6% area of the European subcontinent) is a typical region of Mid-latitude ecotone's environment and vegetation. Overall, Ukraine is a forest-poor country with an average forest cover percentage of 16.5% to the land area (15.9% to the total area of the country) and a very uneven distribution of forests over the territory due to climate conditions and anthropogenic impacts [10]. The forests grow in different bioclimatic zones. The flat part of the country's territory includes the forest zone (Polissja, with forest cover percentage 37%), forest steppe (29%) and steppe (11%). The steppe zone is usually divided into northern steppe, with forest plots distributed mostly in hilly elements of the relief, and practically forestless southern steppe. Forest forms the major land cover type in two mountain systems where forest covers up to 50%, i.e., Carpathian and Crimea Mountains [11]. Over the above regions, forests differ by dominant species, forest type, composition, age, origin and productivity. The xeric belt covers about one-third of the total country's area occupying southern forest steppe and steppe.

Coniferous forests cover 42% of the total forest area, including 32% dominated by pine (*Pinus silvestris*), distributed across major part of the country's flat land, and 10% spruce (*Picea abies*) and fir (*Abies alba Mill.*) together, basically in the Carpathians. Hard deciduous species cover 43%, of which oak (*Quercus robur*) and beech (*Fagus sylvatica*) dominate in 32% of the total forest area. The remaining forest areas are mostly dominated by soft wood deciduous birch (*Betula pendula* and *B. pubescens*), aspen (*Populus tremula*) and alder (basically *Alnus glutinosa*). About 32% of forests are represented by young stands, 44% middle-aged, 13% immature, and 11% mature and overmature. On average, the forests are of a high productivity, e.g., the average growing stock over the country is 200 m^3 ha^{-1} [12]. More than 50% of forested areas are presented by planted forests. As a whole, the country provides a contrasting set of zones with different land cover structures which covers a substantial portion of the Eastern-European diversity of natural landscapes.

Forests, particularly in major agricultural regions, play an extremely important protective role in agroforestry systems. The country has the highest share of ploughed land in Europe, which comprises 53.8% of the total land area and about 76% of all agricultural land. The total area of agricultural land affected by water erosion is estimated at 13.4 mln ha (above one third of the total area of agricultural land) and by wind erosion—54.2% [8]. Official statistics report dramatic developments of the continuing processes of soil degradation. Estimates report that only 11% of the entire Ukrainian territory have favorable ecological conditions, with 18%—satisfactory, 22%—conflict, 25%—before crisis, and 24%—crisis conditions [13].

The country has an impressive experience of optimization of agroforestry landscapes. Intensive reforestation and afforestation programs were realized during the period from 1950s to 1990s resulted in increasing the forest area in Ukraine by ~50%. About 150×10^3 ha of river shelter belts and 440×10^3 ha field protective shelter belts that protect 13×10^6 ha of arable land were established during that time. However, the essential political, social and economic change in the country after 1990s and military operation in the southeast of the country have led to the decline of governance of agroforestry landscapes, and current state of the protective forests over the xeric belt is not known.

The extent and severity of natural disturbances in Ukrainian forests have been growing during the last decades. The area of wildfire doubled during several last years. The area of forests affected by pests and diseases did not exceed 4% at end of the 20th century, was 5–6% during 2001–2010, and reached 8% after 2011. The area of dead forests increased from ~4.0×10^3 ha year^{-1} in the 1990s to above 20×10^3 ha year^{-1} in 2015, basically due to unfavorable weather conditions, insects, pathogens and fire [8].

Impoverishment and death of forests in southern part of Ukraine are reported in number of publications [14]. A recent map of Ukrainian forests [15] that was developed using multi-sensor remote sensing concept, geographically weighted regression and Geo-wiki validation at spatial resolution of 60 m (accuracy—91.8%, CI 0.95) estimated the forest area at 8.71 mln ha, which is ~10% less than the official data of forest inventory (9.57×10^6 ha), with major differences in steppe and southern steppe where the regional differences reach 30% and more.

Earlier studies on the impacts of climate change on forests in Ukraine were few. The projections basically used global climatic models of the previous generation [16]. One of the first studies was provided within the framework of US Country Studies Program—an international initiative on climate change in countries in transition at end of the 1990s [17]. The forest climate indicators were modeled using Holdridge life zones classification [18] and Vorobjov's model [19]. These studies reported that the expected changes in temperature, humidity and climate continentality will shift the borders of the bioclimatic zones (and, consequently, borders of forest-growing regions) and areas of major forest forming species [20]. It was shown that climate change will contribute to the extension of species with a large ecological amplitude, while species with limited adapted capacity will diminish and possibly become extinct. The changes in the forest-growing regions will determine the regional character of the changes in forest ecosystem structures and their biological productivity, growth dynamics and health of forests [21,22]. Several publications of the last decades reported a number of partial results [12,16], but did not present any detailed spatially distributed estimates.

The paper considers impacts of ongoing and expected climate change on vulnerability (or its antithesis-resilience) of Ukrainian forests. IPCC defined vulnerability as "the degree to which a system is susceptible to, or unable to couple with, adverse effects of climate change, including climate variability and extremes" [23]. An important socio-economic feature of adaptive capacity has been added to the definition later, interpreted vulnerability as "the degree to which an ecosystem service is sensitive to global change + the degree to which the sector that relies on this service is unable to adapt to the changes" [24].

The assessment was provided basically using models of reaction of forest ecosystems to climate change that were developed in Ukraine. These models are based on climate-ecological "portraits" of the major forest forming species of the country's forests. The climate change projections for 21st century were provided based on ensembles of global and regional climate models, which have been used under Scenarios B1, A1B and A2 of the Intergovernmental Panel on Climate Change (IPCC). Considering Scenario A1B as the most probable way of future developments, we also applied additional Scenarios A1B±T±P, which describe different combinations of temperature and precipitation within Scenario A1B.

2. Materials and Methods

Assessment of the impacts of climate change on Ukraine's forests has been provided for 5 periods—WMO climatic norm or "standard period" (1961–1990), "recent period" (1991–2010)—and three projections—"near future" (2011–2030), "intermediate future" (2031–2050) and "remote future" (2081–2100). IPCC SRES scenarios B1, A2 and A1B [25] have been selected for assessing projections of change of basic and some of specialized climatic indicators. The "balanced" Scenario A1B, which is close to (and somewhat more tough than) RCP6.5, was considered as the most probable trajectory of future development. To assess major climatic factors impacted vulnerability of forests, a number of Scenarios A1B±T±P were used for considering different combinations of extreme changes of temperature (T) and precipitation (P) in A1B by using 10% and 90% percentiles of the RCM ensembles for changing temperature and precipitation instead of means. Taking into account that major risks for

Ukrainian forests are generated by the insufficient water supply, "warm and dry" scenario A1B+T–P (increasing temperature and decreasing precipitation) was considered as a critical one for assessment of future vulnerability of Ukrainian forests.

Calculations were provided by ensembles of both global and regional climatic models. Diversity of climatic conditions and complexity of topography over the country do not allow recognizing some important signals at a fine resolution by global models, particularly the precipitation change signal that necessitates the use of regional models [26,27].

With respect to the global models, the results of Project CMIP3 (Coupled Model Intercomparison Project, phase 3) have been used. Of 23 Atmosphere-Ocean Global Circulation Models (AOGCMs), which were used in the project, 10 models were selected. Based on a comprehensive analysis, these models have been defined as the most suitable for modeling future climates across the Ukrainian territory. Among the criteria, used under selection, the following ones were taken into account: appropriate horizontal spatial resolution (<2.8°), and number of vertical layers (>20); values of temperature and precipitation change in selected for an ensemble models represented full projected range of both parameters by all AOGCMs, meaning discriminated models just repeated results of selected ones and the defined ensemble covered all possible future projections. Totally, 84 computations of climatic parameters (means, averaged maximal and minimal air temperature, amount of precipitation, etc.) were provided to estimate projected climate change for Ukraine. Regional Climate Models (RCM) were derived from European project ENSEMBLES [28] (ensembles-eu.metoffice.com). The spatial resolution of RCMs was 25 km. The ensembles of this study were formed from 10 RCMs for estimation of temperature indicators and 4 RCMs for precipitation based on comprehensive statistical analysis of climate models errors over territory of Ukraine in past periods [29].

Major forest forming tree species of Ukrainian forests include above 30 tree species, among which the most important from economic and ecological points of view are Scotch pine (*Pinus sylvestris*), Oak (*Quercus robur*), European beech (*Fagus silvatica*), Norway spruce (*Picea abies*), birch (mostly *Betula pendula*), alder (mostly *Alnus glutinosa*), and hornbeam (*Carpinus betulus*) [30]. Vulnerability of the forests with dominance of the above species that cover about 95% of forested areas of Ukraine was a major object of this study.

The territory of the country has been divided in 5 regions: Northern, Southern, Western, Eastern and Central (Figure 1, Table 1). The regions are similar by physical and geographical conditions, consistent with major current and projected climatic factors (temperature and precipitation) and take into account administrative division of the territory that gives a possibility to use different statistical information and to work out future adaptation and mitigation strategy plans on regional level.

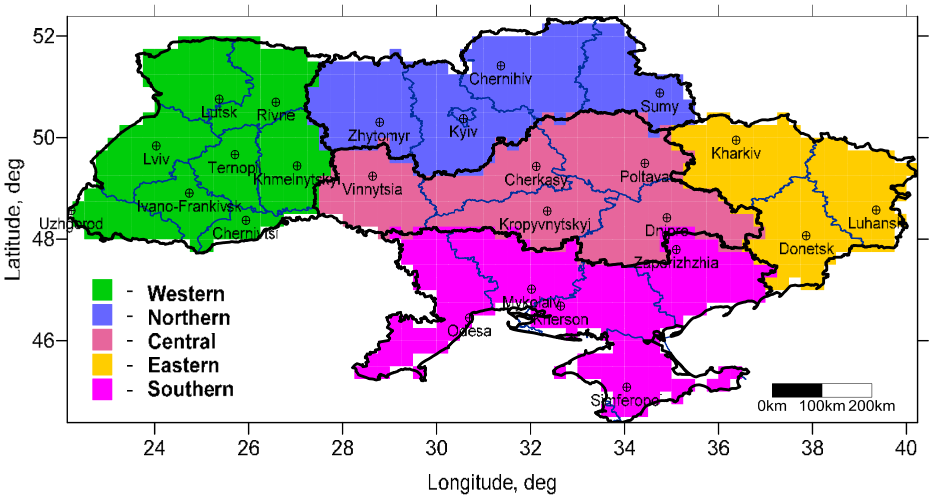


Figure 1. Five bioclimatic regions of Ukraine: Western, Northern, Central, Eastern and Southern. Boundaries of administrative units (*oblasts*) are shown within the regions.

Table 1. Forested area and forest cover percentage by region (data of Sate Forest Account by state on 1 January 2011).

Region	Total Area of Land, km^2	Including Forested Area, Thousand ha	Forest Cover Percentage, %
Northern	11,125	2747.7	24.7
Western total	12,876.6	3887.8	30.2
Including Western flat land	10,250.2	2660.1	26.0
Including Carpathians	2626.4	1227.7	46.7
Central	12,707.2	1252.7	9.9
Eastern	8338.4	854.8	10.3
Southern total	12,881.9	830.9	6.5
Including Southern flat land	12,381.9	705.5	6.8
Including Crimea mountains	500.0	244.5	50.5
Ukraine total	57,929.1	9573.9	16.5

Selection of methods, approaches and models for assessment of climate changet impacts on Ukraine's forests was provided based on trade-offs between different limiting factors: available national and international findings on the topic; expediency and possibility of using climate indices and process-based vegetation models; and necessity to obtain the meaningful results which would accumulate the current level of knowledge. Numerous climate indices (means and variability of temperature and precipitation, various measures of climate extremes) that were developed for assessing the impacts of changing environment on forest ecosystems are often used as an initial step in transition to more complex relations climate change—forest ecosystems. Although these relations are multifaceted, water availability is the most important for the Mid-Latitude ecotone forests. Many indices of climate aridity were investigated to assess impacts of drought on temperate forests, e.g., De Martonne Aridity Index (1920) [31,32] and Palmers Drought Severity Index (1965) [33] as well as, particularly during several last decades, the Pinna Combinative Index [34], UNEP Aridity Index [35], Budyko Aridity Index [36], Standardized Precipitation Evapotranspiration Index (SPEI) [37], relative extractable soil water (REW) [38], and many others. Practically, all indices are based on the use of ratio between the amount of incoming water (precipitation) to evaporation, presented in different form and for different periods of time, e.g., for growth period or for the driest month(s) of the growth period. As a rule, individual climate indices are not able to define all diversity of such basic drought parameters like intensity, duration, severity and spatial extent [39]. This problem can be mitigated by use of specialized bioclimatic indices which take into account either combinations of the drivers (like hydrothermal coefficients) or ensembles of different indices (e.g., [40,41]).

In this study, we used a number of climate indices including two hydrothermal coefficients and two models of interrelation of forest ecosystems with climate change, namely a forest-climatic model developed by Vorobjov (1961) [19] and model of environment amplitudes of flora's tolerance by Didukh [42,43]. In essence, these models are "semi-empirical" because they are based on "ecological portraits" (i.e., requirements to environmental conditions) either dominant tree species or specific forest types. They provide a reliable links between combinations of climatic indicators, on the one side, and distribution, resilience, and, to some extent, productivity of regional forest ecosystems of the country on the other side. These models have been verified for the country's forests [19,22,43].

Vorobjov's model is based on close connections between forest typological classification units that are used in Ukraine and climate [19]: (1) under homogeneous parent material and land form, forest plot (forest stand) type is formed by impacts of humidity and heat; (2) within an individual type of forest plot, the forest type depends on climate continentality; and (3) forest productivity directly depends on the amount of heat. Based on analysis of these dependences, a classification of climate was developed as part of forest-typological classification of tree species together with classification of edaphic conditions. In such an approach, analysis of impacts of the most important climatic indicators—heat and humidity—on diversity and ordination of forests simultaneously relates to soil fertility (formation of forest plot types), potential productivity (forest type) and species composition (type of forest stands) (Ukrainian forest typology classification has three basic hierarchical levels: type of forest growing conditions represented by the edaphic net of availability of nutrients and humidity; forest type (edatop); and type of stand (forest plots) that is homogeneous by species composition and morphological structure of stands). As a result, each type of forest plot of the edaphic net receives the quantitative estimates: T, indicator of heat (sum of positive monthly temperature); A, indicator of climate continentality (difference between temperature of the warmest and the coldest months of a year); and W, indicator of climate humidity, which in essence is a hydrothermal coefficient and is defined as:

$$W = \frac{P}{T} - 0.0286 \times T$$

where P denotes amount of precipitation during the warm period (mm) when $T > 0$.

The ranges of grades for division of climates by moisture availability were settled at 20 °C for T and 1.4 for W. For current Ukrainian climate conditions, this resulted in 6 climate types by moisture availability (including very dry climate with $-2.2 \leq W < -0.8$; dry; fresh; humid; moist; and wet climate with $4.8 \leq W < 6.2$) and 7 climate types by heat availability (including very cold climate, $T < 24$ °C; cold; relatively cold; relatively temperate; temperate; relatively warm; and warm climate, for the latter $124 \leq T < 144$ °C). Forest typology classification of climate allows predicting formation of most probable types of forests (or their absence under critically harsh conditions) and their productivity under climate change [19,44].

The model of amplitudes of flora tolerance to environmental conditions is based on a seminal paper by Didukh and Plyuta [42] who summarized the ecological scales for vegetation of Ukraine and its regions for the major forest forming species in terms of changing major environmental factors (including radiation balance, aridity–humidity, continentality and cryoclimate). The coefficient of satisfyability (CS) of environmental conditions for tree species, developed by Tsyganov [45], was used in the form modified by Bondaruk and Telishev [46]

$$CS_{avr} = 10^{-2}\,(2d - 1)\,a^{-1},$$

where CS_{avr} is the average value of the coefficient of satisfyability of environment conditions to an environment factor (measured in percent); d is the distance (scores) between the value of a factor's regime, for which CS is calculated, to the nearest boundary of tolerance type's amplitude; and a is the number of the elementary regimes of a given ecological factor which is covered by the amplitude of the tolerance type.

Thresholds of certain factors, above and below which the organisms are not able to live, are called critical limits [47]. Interval between lower critical limit (minimum) and upper critical limit (maximum) forms a zone of ecological tolerance or climatogenic amplitude of tolerance. Within this zone, the behavior of biological systems varies depending on intensity of exposure to environmental factors. Directly to the critical limits adjoin the zones of pessimums (approximately 7–8% of the length of the amplitude's tolerance on both sides), in which activity of species is limited. Further, towards growing activity, are suboptimal zones (approximately 27–28% of the length amplitude's tolerance between the zones of optimum and pessimum). The average part forms the ecological optimum (30% of the length of the amplitude's tolerance) [47].

Degrees of satisfyability of climate environment for tree species by individual ecological factors was based on the scale by Tsyganov [45]: the conditions are optimal for a species if CS is in range 91–100%; suboptimal—71–90%; satisfactory—51–70%; 21–50%—heavy; and ≤20%—for extreme (unsatisfactory) conditions. Using the cross-platform geographic information system QGIS, spatial modeling of dynamics of areas with different satisfyability by climatic conditions was provided for the major forest forming species by two scenarios—A1B (balanced) and A1B±T±P (basically "warm-dry" scenario A1B+T−P) for five time periods, 1961–1990, 1991–2010, 2011–2030, 2031–2050, and 2081–2100, by thermoregime, continentality index by Ivanov, index of aridity–humidity by Vysotsky–Ivanov, and indicators of cryoclimate (winter severity, defined as average temperature of the coldest month of the year). The expected tendencies of development and growth of forest vegetation were assessed by bioclimatic zone, region and the entire country.

In this approach, *thermoregime* is calculated based on radiation balance of the underlying surface R as

$$R = Q\,(1 - \alpha) - \text{Eef},$$

where Q is the incoming radiation, α is the albedo, and Eef is the effective radiation. The scale of thermoregime for plants has 17 grades with the interval of 5 kcal cm^{-2} year^{-1} from <10 kcal cm^{-2} for gekistoterms to $\geq$85 kcal cm^{-2} for megatherms [43]. The highest value of thermoclimate in Ukrainian territory is 63 kcal cm^{-2} year^{-1} (west coast of Crimea), and the minimal (in northeastern part of the country) is 42 kcal cm^{-2} year^{-1}.

Didukh's model uses index of *continentality* by Ivanov [48], which is calculated as

$$K_{\text{Iv}} = \frac{\text{Ayear} + \text{Aday} + 0.25\,\text{DH}}{0.34\varphi + 14} \times 100\%,$$

where Ayear and Aday are yearly and daily amplitude of temperature, respectively; DH is moisture deficit of the driest month of the year; and φ is latitude of the area. The phyto-indication scale of climate continentality includes 17 gradations, from extra-oceanic ($K_{\text{Iv}} < 61\%$) to ultra-continental (>210%) [49]. For comparison, we also calculated index of climate continentality by Khromov [50], which characterizes the relative contribution of continents' impacts on the amplitude of annual temperature Ayear.

$$K_{\text{Khr}} = (\text{Ayear} - 5.4 \sin \varphi)/\text{Ayear} \times 100\%.$$

Aridity–humidity index by Vysotsky–Ivanov *CWD* (Climatic Water Deficit) integrates effect of precipitation and thermal resources of the area defined as difference between precipitation and evapotranspiration Eo, where the latter is defined as

$$\text{CWD} = P - \text{Eo} = P - 0.018\,(t + 25)^2 \times (100 - \text{RH}),\ \text{mm},$$

where t and RH are, respectively, average monthly temperature (°C) and relative air humidity (%).

Based on extensive databases, the boundaries of amplitudes of tolerance to environmental conditions for major forest forming species and their division by grades of satisfyability (pessimum; extreme conditions; subsatisfying; satisfying; suboptimum; and optimum) were assessed by Didukh (2011). As an example, Table 2 contains a shortened version of these data for common oak in Ukrainian conditions [43].

The hydrothermal coefficient by G. Selyaninov (HTCS) [51] is used in Ukraine as the main meteorological indicator of aridity in agriculture and forestry. HTCS is calculated as

$$\text{HTCS} = 10\frac{\sum P_{T>10}}{\sum T_{>10}},$$

where $\Sigma P_{T>10}$ is the sum of precipitation (mm) for days with average temperature exceeded 10 °C and $\Sigma T_{>10}$ is the sum of temperature (degrees) for the same days. HTCS allows joint consideration of most important resources (heat and moisture) for growth and development of plants. It has been shown that the HTCS isoline equal 1.0 well coincides with northern boundary of the steppe zone in Ukraine, and HTCS < 1 means insufficient water availability during the vegetation period; where 0.5 indicates the northern boundary of semi-desert, and 0.3 indicates desert. Two latter zones are unsuitable for growth of forests.

Table 2. Boundary of amplitudes of tolerance to environmental conditions and its division in zones of satisfyability for common oak (*Quercus robur*). Modified from Didukh (2011) [43].

Tree Species	**Ecological Factors**				
	Ecological Group by Didukh	**Tolerance Amplitude**	**Zone of Ecological Optimum**	**Sub-OPTIMUM Zones**	**Pessimum Zones**
Common oak (*Quercus robur*)	**Thermoregime (Radiation Balance)—Tm**				
	Sub-mesoterm	In scores on scales by Didukh (2011)			
		6–12	8.1–9.9	6.5–8.0 10.0–11.5	6.0–6.4 11.6–12.0
		In absolute values: kcal/cm^2 per year			
		30–60	41–49	33–40 50–57	30–32 58–60
		In absolute values: MJ/m^2 per year			
		1256–2512	1675–2093	1350–1675 2093–2418	1256–1350 2418–2512
	Humidity or aridity of climate (ombroregime)—Om				
	Sub-aridophyte	In scores on scales by Didukh (2011)			
		10–16	12.1–13.9	10.5–12.0 14.0–15.5	10.0–10.4 15.6–16.0
		In absolute values: mm			
		−600–800	−100–300	−400–−100 300–600	−600–−400 600–800
	Cryo-climate—Cr				
	Hemi-cryophyte	In scores on scales by Didukh (2011)			
		5–12	7.5–9.5	5.6–7.4 9.6–11.4	5.0–5.5 11.5–12.0
		In absolute values: °C			
		−22–10	−10–−2	−18–−10 −2–6	−22–−18 6–10
	Continentality of climate—Kn				
	Hemi-continental	In scores on scales by Didukh (2011)			
		2–16	6.9–11.1	3.1–6.8 11.2–14.9	2.0–3.0 15.0–16.0
		In absolute values: %			
		61–210	111–160	76–110 161–195	61–75 196–210

3. Results

3.1. Climate Change in Ukrainian Territory

3.1.1. Projections by Global Models

All the global models that were included in the analysis predict stable increase of air temperature during 21st century for all scenarios (Figure 2a). The ensemble coefficients of the linear trend of annual temperature for Scenario B1 is 0.023 °C year^{-1}, for A1B is 0.037 °C year^{-1} and for A2 is 0.044 °C year^{-1}. In addition, for all scenarios, the rate of growing of minimal temperature in Ukraine is higher than this for average and maximal temperature (corresponding coefficients of the linear trend for Scenario B1 is 0.021 °C year^{-1}, for A1B is 0.035 °C year^{-1} and for A2 is 0.040 °C year^{-1}). The maximal predicted rate of increasing average minimal temperature was defined for Scenario A2 (the trend is estimated at 0.048 °C year^{-1}). For other scenarios, such a coefficient is also bigger than for average and maximal temperature (for B1 is 0.025 °C year^{-1}, and for A1B is 0.040 °C year^{-1}) [52].

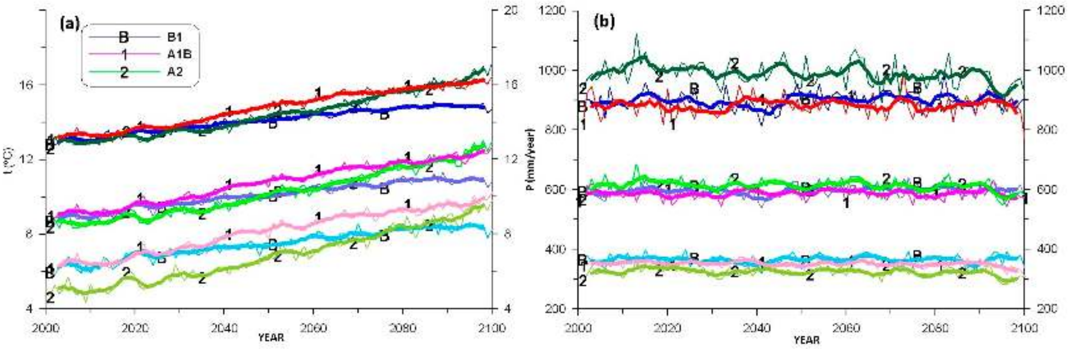


Figure 2. Projections of minimal, average and maximal annual temperature (**a**); and amount of precipitation (**b**) in Ukraine for 21st century estimated by 10 GCMs for the three IPCC SRES Scenarios B1, A2 and A1B (bold lines are moving five-year averages).

The increase of air temperature in 21st century in Ukraine is expected due to much warmer winter temperature. For all considered scenarios, coefficients of linear trend for winter minimums are higher than for summer maximums. Therefore the total increase of temperature is expected due to decreasing frequency of extreme cold days in winter, and, to a lesser extent, due to increasing the frequency of extreme hot days in summer. The least but increase of air temperature is projected for spring and fall [53].

The annual amount of precipitation (Figure 2b) has a larger variance than the temperature, even for five-year moving averages. However, this indicator remains, on average, practically without any marked changes during the 21st century for all scenarios. Comparisons of all three scenarios show that the biggest differences are in forecast of average maximal amounts of precipitation: they are expected to be substantially larger in Scenario A2 (almost at 100 mm), but their amount decreases by end of 21st century with the coefficient of linear trend at -0.44 mm year^{-1}, and the average minimal amounts of precipitation also are smaller than in other scenarios. Overall, Scenario A2 for Ukraine is the most extreme by amount of precipitation, both maximal and minimal.

The expected increase for precipitation is likely to be caused by high repeatability of events with heavy precipitation during this period. Average data for the ensemble of models show that precipitation will decrease in summer and autumn periods in all the scenarios used, and the largest negative linear trend coefficient values are obtained for A2. Note that for scenarios A2 and A1B the rate of decrease in precipitation in summer also exceeds the rate of their increase during winter.

Overall, based on the ensemble of 10 AOGCMs, the increase of the annual air temperature by end of the 321st century compared to 2001–2010, averaged for the entire Ukrainian territory is expected: for Scenario B1 from 0.7 to 3.0 °C with the average 2.0 ± 0.8 °C, for A1B from 2.4 to 4.2 °C (average 3.1 ± 0.7 °C) and for A2 from 2.6 to 4.6 °C (average 3.8 ± 0.8 °C). The forecast of annual amount of precipitation in Ukraine, according to the selected AOGCMs during 21st century, compared to 2001–2010, differs between models substantially and have a large range of changes to current values: from −23.4% to 11.6%. The highest rates of temperature change and the amount of precipitation were obtained for Scenario A2, the least—for B1 [52].

3.1.2. Projections by Regional Climate Models

The projected changes of average temperature compared to 1991–2010 and their confidential intervals were calculated based on 10 RCM [54] for three periods and five regions (Figure 3). For 2011–2030, the projected changes of the thermal regime show tendencies to both warming and cooling. The cooling is most probably in March (up to −0.3 ± 0.3 °C in the east), while the noticeable warming is from June to end of the year with maximum in December at 0.8–1.3 °C ± 0.4–0.6 °C. On average, the projected range of the temperature change in Ukraine during 2011–2030 varies from −0.1 °C to 0.8 °C with the maximal values in north of the Eastern region.

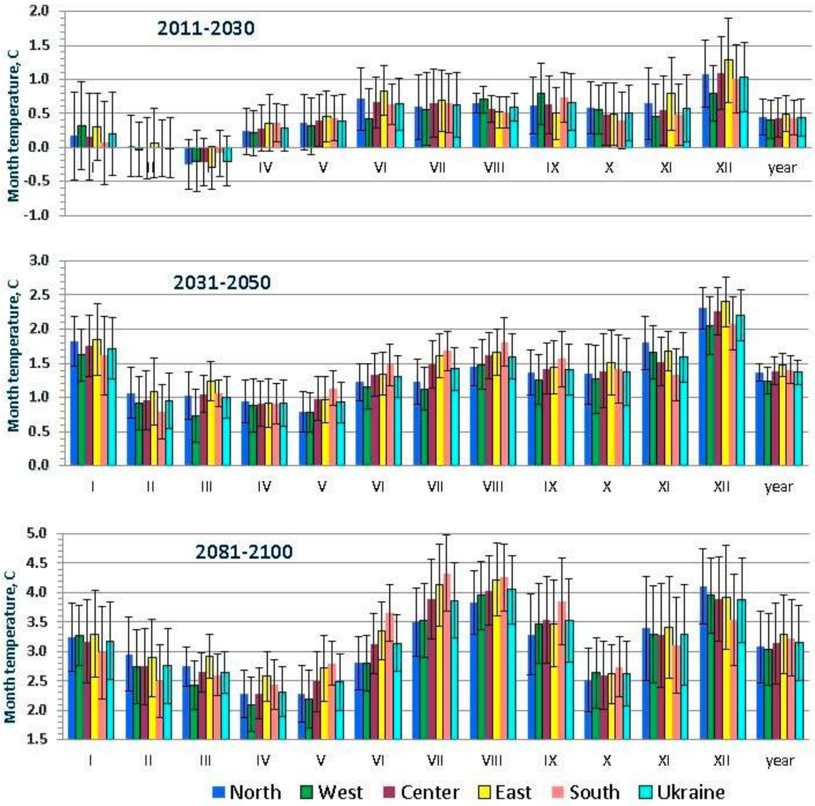


Figure 3. Change of mean monthly temperature with CI (95%) for three projection periods (2011–2030, 2031–2050, and 2081–2100), compared to the recent period (1991–2010) based on the ensemble of 10 RCMs.

All projections of change of temperature by middle of 21st century (2031–2050 compared to 1991–2010) show a warming for all months. On average for the entire territory, the temperature will increase at 1.2–1.5 °C, from 0.7 °C in west in spring to 1.9 °C in northeast in winter. The maximal warming is expected for December (+2.2 °C ± 0.4 °C for the entire country), and a little bit less for January (+1.7 °C ± 0.5 °C). The smallest changes are expected in spring. Summer and fall warming will be approximately the same, with the maximum in August. Warming during the cold period will be more intensive in Northern and Eastern regions, and during the warm period over the country's south and east. The largest confidential intervals (±0.5 °C) was obtained for January and October, the least (±0.2 °C)–for yearly values.

The increase of *the annual temperature* in Ukraine by end of the century (2081–2100) is expected on average to be +3.2 °C ± 0.6 °C. The largest warming is expected in the Southern region in summer (at +4.3 °C ± 0.6 °C in July when the average month's temperature will reach 27.4 °C) and in the Northern region in winter (+4.1 °C ± 0.6 °C in December), and the minimal warming in April and October (Figure 3). Confidential intervals for this period are the largest, with the maximum for November for all regions and December for the Eastern region (±0.9 °C). Figure 4 shows temperatures in Ukraine of the coldest (January) and the warmest (July) months for standard period (1961–1990), by middle (2031–2050) and the end of the century (2081–2100). Significant warming is remarkable by both parameters: (1) the coldest month is an indicator of cryoclimate and it is obvious from Figure 4 that, by end of the century, the winter climatic season will disappear in Southern and some oblasts of Western and even Northern regions, because monthly averages will be higher than 0 °C; and (2) the warmest month as an indicator of potential evaporation shows the same significant increase over the entire territory and projected to be higher than 25 °C for more than half-country with maximum over 27 °C in Southern region.

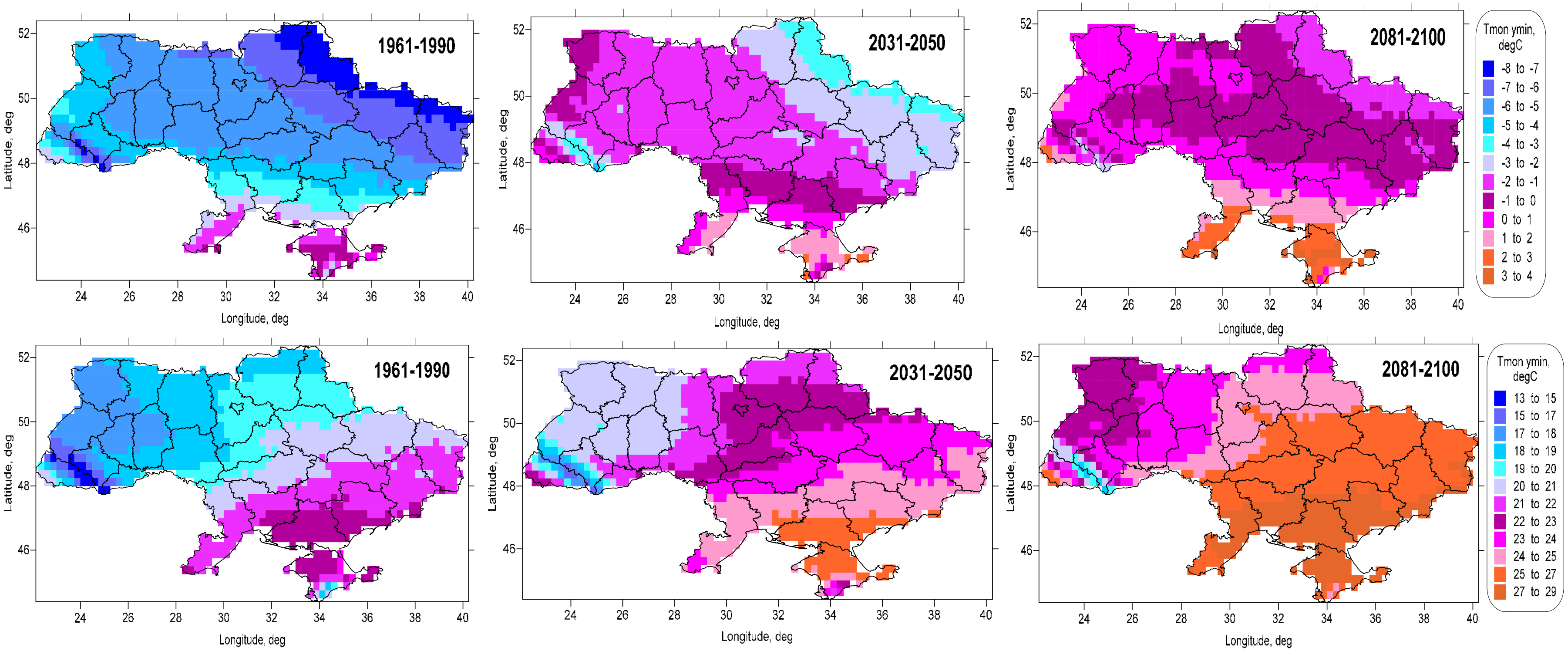


Figure 4. Temperature of: the coldest (**upper**); and the warmest (**lower**) months in year as indicators of cryoclimate for 1961–1990, 2031–2050, and 2081–2100.

During the near future period (2011–2030), both an increase and decrease of *the amount of precipitation* is expected compared to 1991–2010 (Figure 3). Overall, annual sums of precipitation will grow for all regions (+7% average over the entire country) although these changes are in limits of confidential intervals with a tendency of increasing in winter and decreasing during summer. At the same time, precipitation decreases up to 20% in Central, Northern and Southern regions in summer and increases up to 42% in Western, Northern and Eastern regions in winter and spring. It is expected that, during 2031–2050, an increase of precipitation is expected in spring and fall, except a small reduction in the Central and Southern regions. For major part of the country, reduction of precipitation is expected in August (the biggest reduction is in the Eastern region (18%)). Overall, the expected range of change of precipitation for the country is +8%, but the cold season becomes wetter, while the warm period drier.

By end of the century, the abovementioned tendency of increasing precipitation in the cold period (particularly, in winter) and increasing the dryness over the warm period (particularly in summer) becomes stronger. The amplitude of predicted changes becomes larger: from −40% to +48%. Another tendency that remains from the previous period is that the largest increase in precipitation is again expected in the Western region, up to +21% of annual increase. In addition, the tendency of the overall increase of precipitation remains in the Northern region (to +15% for annual values), while, in the summer months, unlike the previous period, the decrease in precipitation is predicted, with the largest (−20%) in August. Changes for some months exceed the confidence intervals, i.e., they are statistically significant.

For all the regions, except the western one, the "wavy" yearly distributions of precipitation becomes widespread that provides a rather evenly distribution of precipitation over a year, with little or no clearly identified maximums and minimums (Figure 5). The maximal values at end of the century are in the Western and Northern regions in summer (105 and 71 mm in July, respectively), and the minimal in the Eastern and Southern regions, also in summer—21 mm in August. The confidence intervals are low, which indicates the high consistency of the models. Over all forecast periods, the precipitation will increase in winter and spring, mostly in the Western, Northern and Eastern regions. Precipitation in these regions will also increase as opposed to central and southern parts for the middle of the 21st century when a slight decrease in precipitation is projected. In summer, across almost the entire country (except the Western region), the amount of summer precipitation will decrease.

For entire Ukraine (except western areas in all periods and in the east in the near future period), precipitation decreases, and this trend will increase during the century. At the end of the century, summer decrease of precipitation envelopes almost the entire country (about 80% of its territory), except for the Western region. The center of maximal decrease of precipitation remains the same, but quantitatively these values will likely exceed 30% (about 10% of the country's area). For another 20%, the projected decrease in precipitation is from −20 to −30% and, for 30%, from −10 to −20%. This projected reduction in summer precipitation is statistically significant.

Dynamics of temperature and precipitation defines the change of such important indicators as relative air humidity and potential evaporation. Relative air humidity (RH) might limit distribution and/or productivity of some species. In this study we also used RH for calculation of special climatic indicators, particularly connected to continentality of climate. The calculations showed that, for the first three periods considered in this study (e.g., WMO norm, recent and near future), monthly RH averaged for a number of years did not change substantially. However, by mid-century, and especially during 2081–2100, the RH will decrease throughout almost the entire country, apparently due to both the increase in temperature and decease in precipitation in the driest summer months (Figures 5 and 6), i.e., August, for all regions except the Western region.

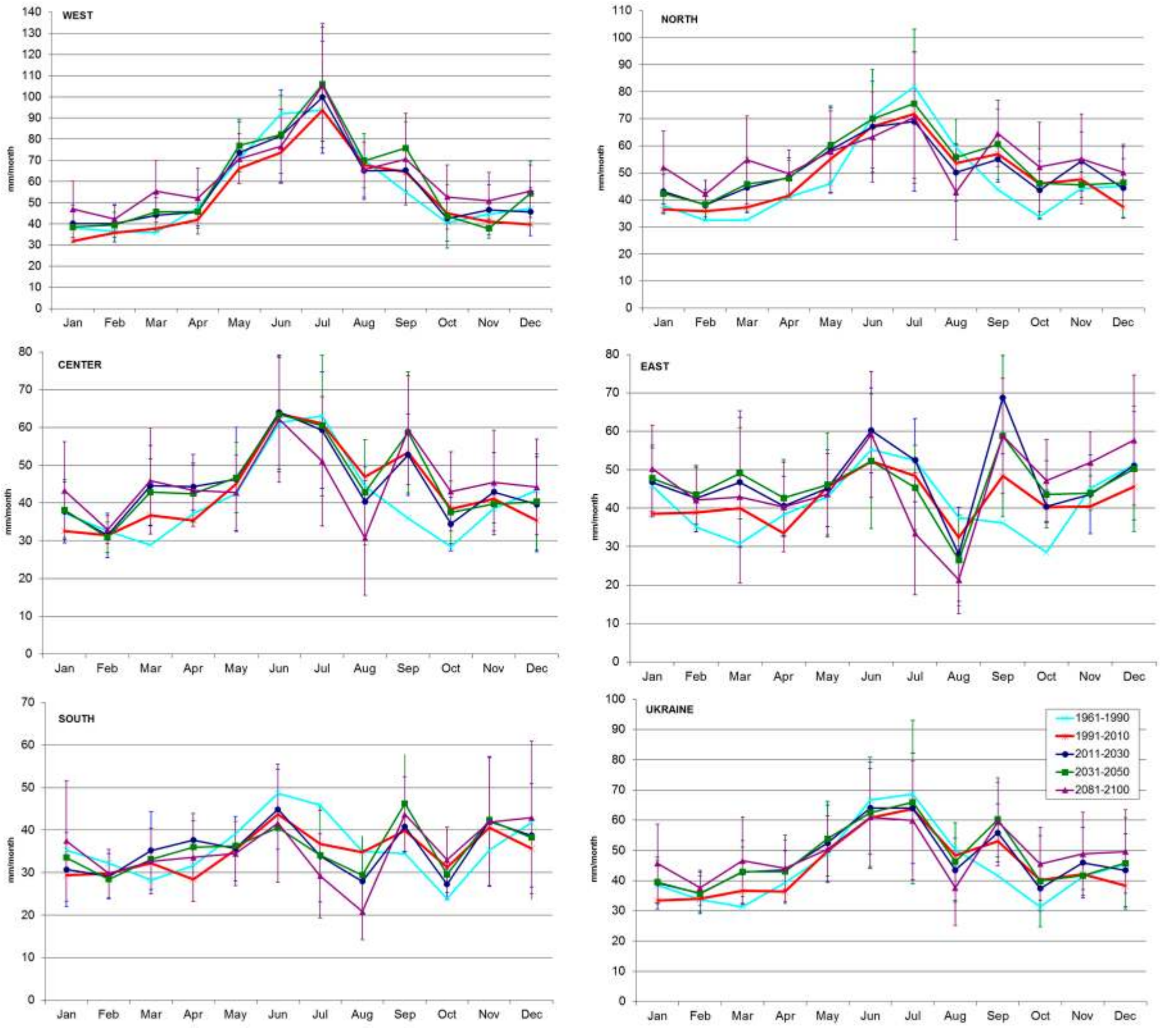


Figure 5. Change of precipitation sums for summer and winter for three projection periods (2011–2030, 2031–2050, and 2081–2100), compared to the recent period (1991–2010) based on the ensemble of four RCMs.

Potential evapotranspiration indicates expected levels of water stress. As shown in Figure 7, the potential evapotranspiration increase is large over the entire country and most dramatically in its southern part, reaching by the end of the century above 1600 mm year^{-1} under precipitation of 300 mm year^{-1}. This results in negative climatic water deficit over almost the entire territory of Ukraine by the middle of the century, reaching -1000 mm year^{-1} over the warmest and driest part in Kherson oblast and AR Crimea. CWD increases of some additional hundreds of millimeters by the end of the century causing shifting in bioclimatic zones of one category to drier climate, as the aridity–humidity index by Vysotsky–Ivanov shows (Figure 7). Actually, territory with semi-arid climate ($0.33 < \text{AHI} < 0.55$) in standard period (1961–1990) becomes arid ($0.12 < \text{AHI} < 0.33$) by 2031–2050 and dramatically enlarges by 2081–2100 in Southern region. At the same time, by the end of the century (2081–2100), the territory with humid climate ($1 < \text{AHI} < 1.33$) in standard period (1961–1990) converts to semi-humid ($0.55 < \text{AHI} < 1$) in Western and Northern regions, and semi-humid areas to semi-arid areas in Central and Eastern regions. Territory with extra-humid climate ($\text{AHI} > 1.33$), which widely surrounded the Carpathian Mountains in the standard period (1961–1990), will shrink significantly by 2031–2050 and almost disappear by the end of the century (2081–2100), remaining just over the highest peaks (Figure 7). Summarizing, significant changes in temperature and precipitation will definitely impact biodiversity and particularly require sustainable forest management with corresponding effective measures.

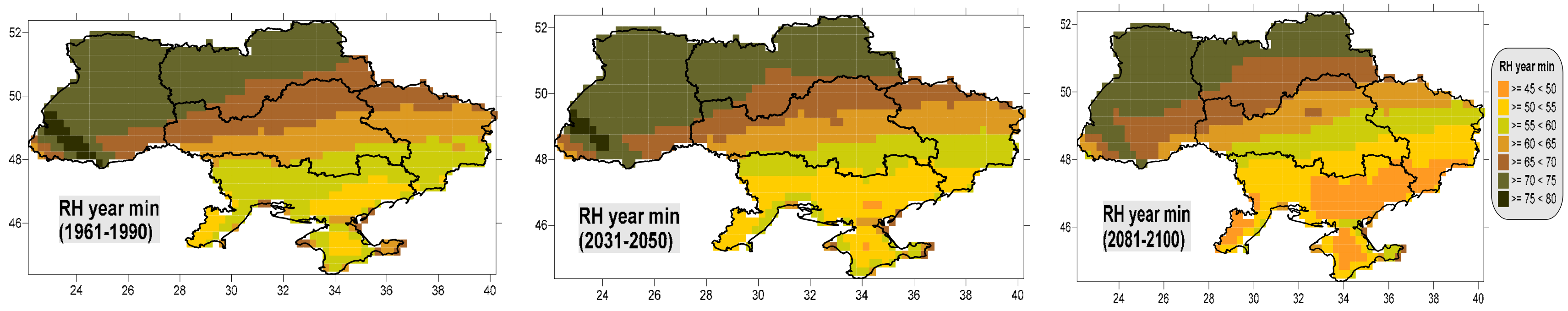


Figure 6. Minimal monthly means of relative air humidity (%) for 1961–1990, 2031–2050, and 2081–2100.

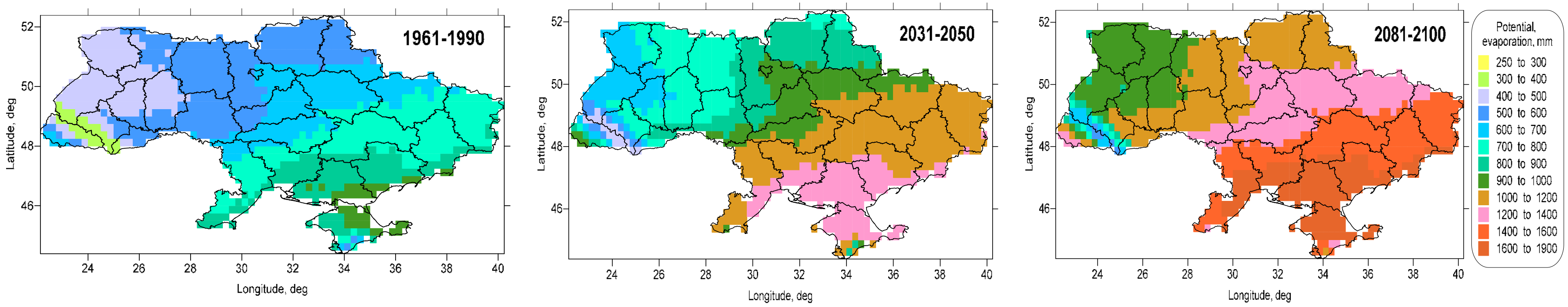


Figure 7. *Cont.*

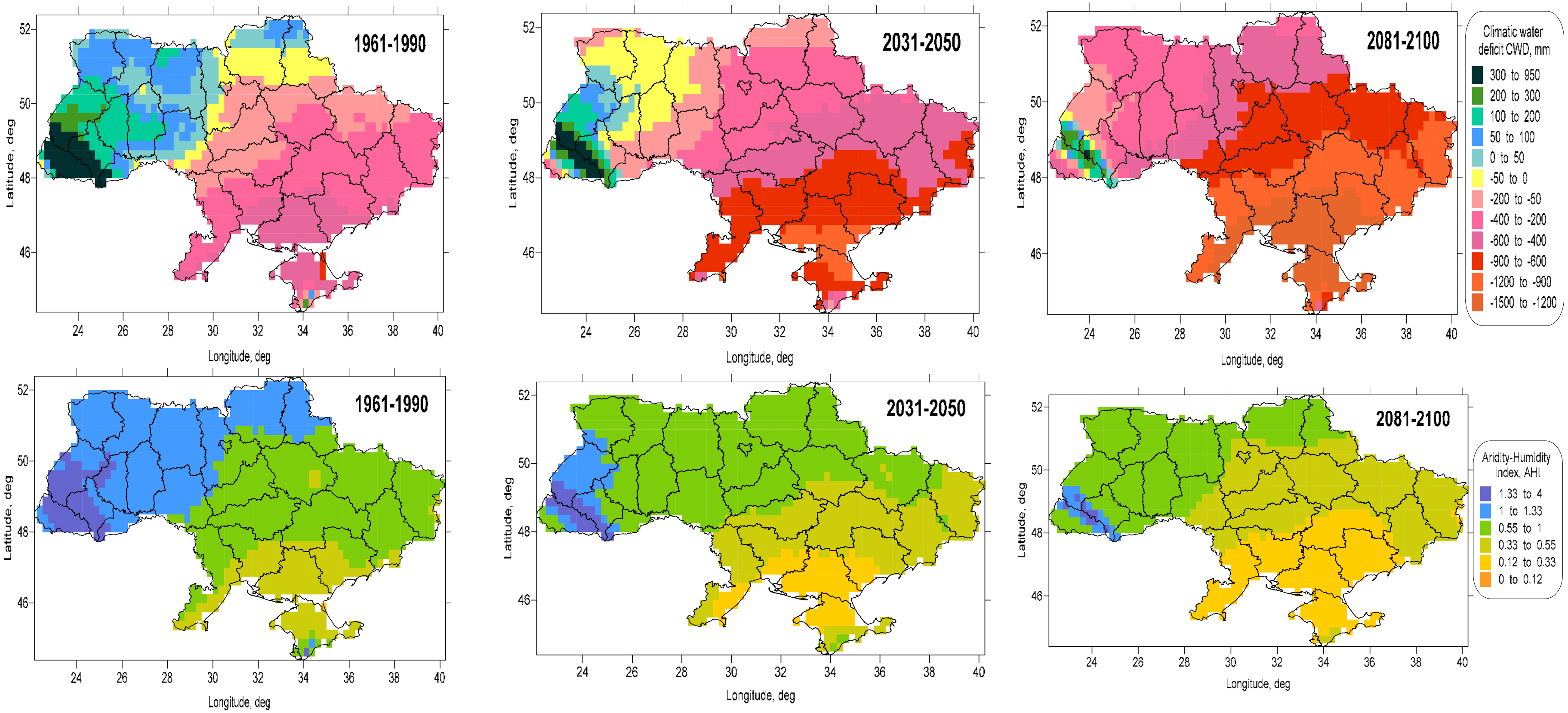


Figure 7. Potential evapotranspiration (**upper**); climatic water deficit CWD (**middle**); and aridity–humidity index by Vysotsky–Ivanov (**lower**) for 1961–1990, 2031–2050, and 2081–2100.

3.2. Forecast of Dynamics of Forest-Climatic Resources Based on Vorobjov Model

Dynamics of forest climatic zones by Vorobjov for the five periods according to Scenario A1B and some combinations of temperature/humidity for the last two periods for Scenario A1B±T±P are presented in Figure 8. As has been shown [43], the forest-climate types from very wet to fresh are the most suitable for growth and development of forests in Ukraine. Under dry climate, forests are able to grow in sites that have enough water supply. Natural forests are not able to grow in very dry climate (that is, the current climate of Crimea steppe). Extreme dry climate is a climate of semi-deserts. Realization of the balanced climate change scenario A1B supposes increasing drought across all territory of the country compared to the standard climatic period. Suitable forest-climate types will shift towards north. By end of the century, the area that would have conditions favorable for growth of forests (zones of humidity from very wet to fresh) will significantly decrease: such conditions in previously fresh climate will remain only in Western and Northern regions, and in small areas in the Central region. The drier conditions, which are typical for the steppe zone, will be formed over the rest of the plain territory of Ukraine. While in the current climate the very dry climate comprises 9.8% of the flatland territory of the country, its share will already increase to 21% in 2031–2050. Within the considered scenario, a new type of climate is expected by the end of the century—the extremely dry type, which will envelope a significant area of southern Ukraine—Crimea's steppe, coastal steppe of Odessa, Mykolaiv and Kherson oblasts and partially Zaporizhja oblast (totally, about 15% of the country's area). Such changes will cause a shift of bioclimatic zones: conditions that are favorable for forest-steppe vegetation will be formed in the north, for steppe vegetation over the rest of the territory, and for vegetation of semi-deserts in the south.

According to the Scenarios A1B±T±P (Figure 9, illustrations for periods 2031–2050 and 2081–2100), the lack of precipitation remains the major factor affecting Ukrainian forests in a clearly negative way. The most severe aridity of climate in Ukraine in this approach is expected for all scenarios with decreasing the precipitation. For the "warm-dry" Scenario A1B+T−P, compared to the balanced scenario, the zones of decreasing humidity will substantially shift towards northwest. By the middle of the century, zones of humid, moist and wet climate will substantially shrink in the western territories being replaced by zone of fresh climate. The area of dry climate will increase from current 7% to 22% by middle of the century and up to 35% by its end. Very dry climate will shift into the north and will comprise of 36–37% of the territory of Ukraine. By the middle of the century, the extreme dry conditions will appear and cover about 22% of the territory. By the end of the 21st century, the most favorable conditions for forests' growth (fresh and wet types of climate) will remain only in the Carpathians and in small western areas (Lviv oblast and foothills of the Carpathians) and this area will cover only 5.7% of Ukraine. The rest of Ukrainian territory will have the dry type of climate (37%, mostly in the west and north), very dry (35.4% in central and eastern parts) and extremely dry (21.9% in the south). If this scenario would be realized, changes of conditions for growth of forest vegetation will become critical, leading to impoverishment and degradation of forests over major part of Ukraine.

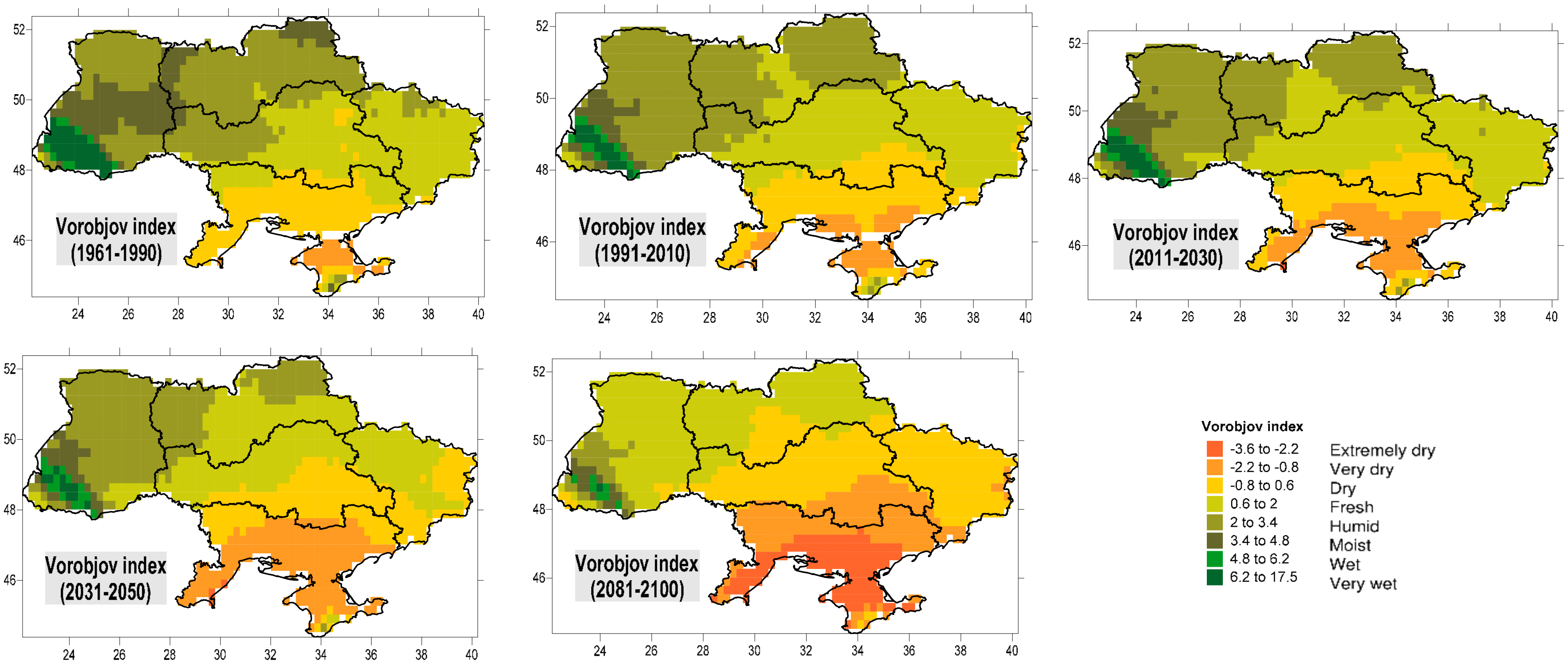


Figure 8. Dynamics of forest climatic zones by Vorobjov water availability index W for Scenario A1B. Extremely dry climate, $-3.6 < W \leq -2.2$; very dry, $-2.2 < W \leq -0.8$; dry, $-0.8 < W \leq 0.6$; fresh, $0.6 < W \leq 2.0$; humid, $2.0 < W \leq 3.4$; moist, $3.4 < W \leq 4.8$; wet, $4.8 < W \leq 6.2$; and very wet, $6.2 < W \leq 17.5$.

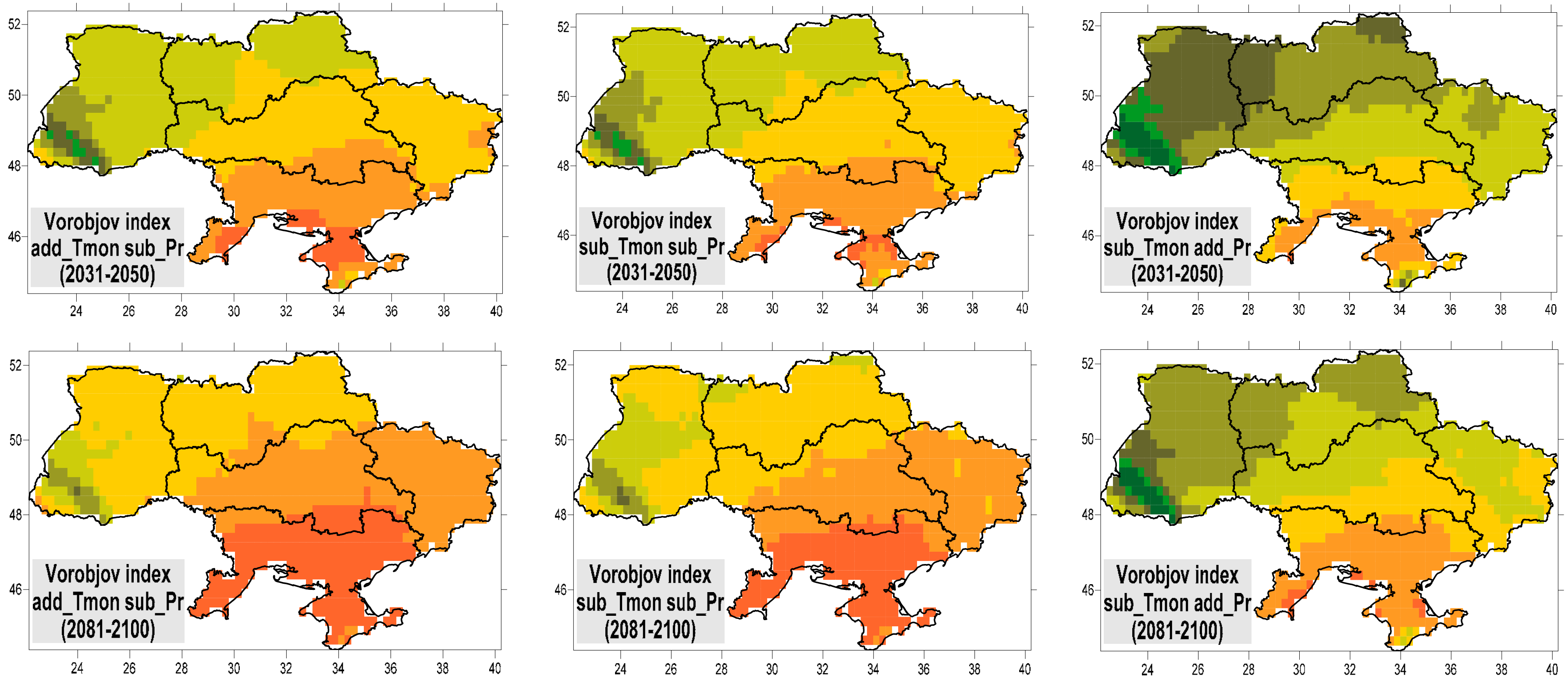


Figure 9. Dynamics of forest climatic zones by Vorobjov water availability index W for Scenario A1B±T±P. The legend is as in Figure 8. "ad(sub)_Tmon(Pr)" means the use in calculation 90(10) percentiles of monthly temperature (precipitation) by the ensembles of RCMs.

Considering heat availability (Figure 10), four types of climate by Vorobjov were indicated in Ukraine for 1961–1990: relative temperate (1.7% of the total area), temperate (35.4%), relative warm (49.0%), and warm (13.9%). By the middle of the century, practically everywhere, climate will switch by one category towards warmer types and new very warm climate occurs in the Southern region instead of just warm. By end of the century (Scenario A1B), the area with relative temperate climate will disappear, temperate climate will occupy 0.4%, relative warm 1.6%, warm 48.0% and very warm 31.5%; again, in the Southern region, new climate type will replace very warm climate to hot (18.4% of the total area). The situation will dramatically change in the Southern region where practically only two types will remain: very warm (36.7%) and hot climate types (63.0%).

Indexes of climate continentality by Ivanov and Khromov were calculated for the above five periods. Examples for the recent period (1991–2010), middle (2031–2050) and the end of the century (2081–2100) are shown in Figure 11. The boundary between values of Ivanov index of 100% means boundary between oceanic (<100%) and continental (>100%) climates. As it follows from the dynamics of these indicators, both indices project some weakening of continentality in southeastern part by the middle of the century. Overall, change of the climate continentality is substantial by the end of the century. However, this indicator will not play a notable role in future dynamics of forests because it is basically within the limits of tolerance of major forest forming species of Ukrainian forests to continentality.

Overall, based on Scenario A1B, the significant warming is expected over the major part of Ukraine by end of 21st century. Availability of heat during the growing season will be similar to those that are today in forestless Black Sea steppes of Southern Ukraine. These changes are explained by direct increase in temperature during the growing season and its lengthening. Two new types of climate, which have never been observed in Ukraine and are unsuitable for growth of forest, will occupy ~50% of the country area. This may cause significant changes in the availability and location of forests over the country's territory and affect their state, vitality, structure, growth, and productivity.

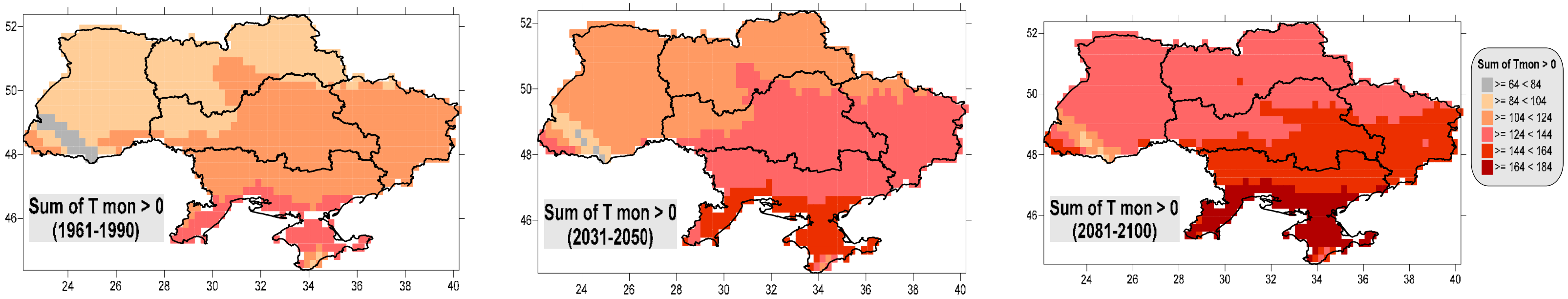


Figure 10. Dynamics of sums of positive monthly temperatures (indicator of heat availability by Vorobjov) for 1961–1990, 2031–2050 and 2081–2100 (Scenario A1B).

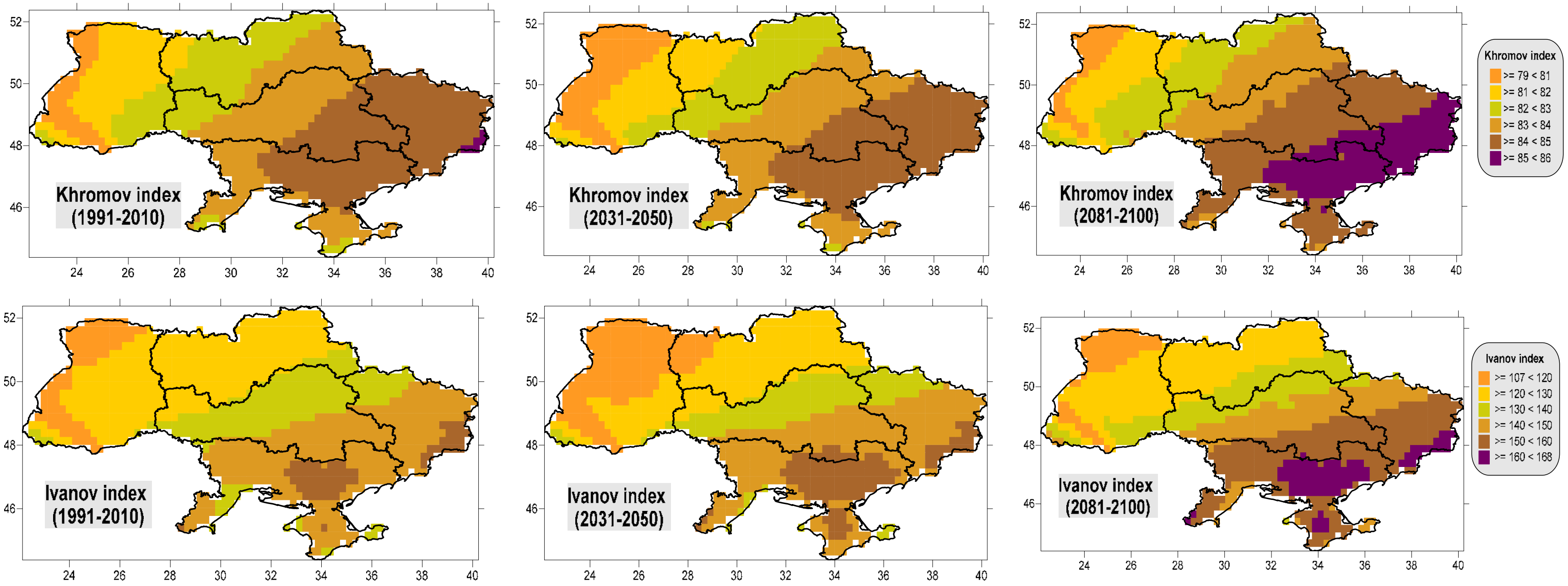


Figure 11. Indicators of continentality by: Khromov (**upper**); and Ivanov (**lower**) for the periods of 1961–1990, 2031–2050 and 2081–2100 (Scenario A1B).

3.3. Dynamics of Environment and Expected Reaction of Major Forest Forming Species to Climate Change

The zones of satisfyability of environment were assessed by Didukh's model and mapped for major forest forming species of Ukraine, for which ecological amplitudes of tolerance were defined for the above five periods and indictors of humidity, heat, cryoclimate and continentality (Figure 12).

A major limiting factor for oak (*Quercus robur*) is humidity. The conditions according to the three other climatic indicators were favorable (from optimal to suboptimal) practically over the whole territory of the country for 1961–1990. By index of humidity, oak was able to grow everywhere in plain Ukraine. The zone of ecological optimum for this species was rather wide and enveloped Western, Northern and partially Central regions, and suboptimal zone coincided with the southern boundary of forest steppe. The conditions were heavy in territories of steppe zone, and extreme in southern steppe. During 1991–2010, zones of optimum and suboptimum shrunk and shifted towards west; the boundary of satisfactory conditions moved towards northwest. Relatively small territories that are unsuitable for growth of oak have arisen in the south of the country. According to Scenario A1B, the tendency of shifting the zonal boundaries in northwestern directions will continue. Already by the middle of the century, the areas with conditions that are unsuitable for growth of oak forests will occupy 26% of the Ukrainian territory (mostly in the south). It is expected that growth conditions that would be favorable for oak (optimal and suboptimal) will remain only in the west—in the Carpathians and foothills—and satisfactory in Lviv oblast. The rest of the current zone of mixed-broad-leaved forests will have heavy and extreme conditions (the unsuitable zone for growth of oak forests will increase up to 56% of the Ukrainian territory). Hence, one can expect substantial changes of state of Ukrainian oak forests by middle of the century, practically for the entire country. Very likely, by end of this century oak forests will remain only locally, in areas of shallow soil water, in river valleys and along water reservoirs. One can expect the change of zonal vegetation over major part of the country's territory.

By climate continentality, the environmental conditions for Scotch pine (*Pinus sylvestris*) are favorable (optimal and suboptimal) over the entire territory and by cryoclimate—suboptimal and satisfactory. Growth and distribution of pine in Ukraine is limited by insufficient water availability. According with the forecast by Scenario A1B during 1961–1990, favorable conditions for pine by humidity were presented in limited areas (only in the Carpathians), satisfactory conditions in the west, partially in the north, and heavy and extreme conditions in the remaining territory. Unsuitable conditions existed in southern coastal steppe. Aridization of climate and shift of boundaries of satisfyability to the north compared with 1961–1990 continued over 1991–2010. The zone of unsuitable conditions has been increasing over Dnepropetrovsk *oblast*, and to south and east of the Eastern region; the zone of satisfactory conditions became substantially narrower in the Western region. The further aridization of climate will lead to increasing the zone of unsuitable conditions in eastern and central parts of Ukraine, and decreasing the zone of suboptimal conditions in the west. Finally, by end of the century, the conditions suitable for growth of pine (mostly heavy and extreme) will remain only in the west and small area in the north. The rest of the territory will be out of limits of tolerance capacity of Scotch pine. Such a level of climate changes will lead to impoverishment of pine forests in Ukraine and to the decrease of their area. Very likely, pine forests will remain only in areas where the root zone will have enough water during the growth period, i.e., in depressions, along rivers, etc.

Considering the studied parameters, the most vulnerable species to climate change in Ukraine are beech and Norway spruce. Overall, these species in Ukraine, particularly on plains, are on the edge of their natural habitat. European beech (*Fagus sylvatica*) is currently distributed in the Ukrainian Carpathians (at altitudes of 250–1400 m above sea level), in southern part of Volyn oblast and as small island forests, mostly planted, in western forest steppe. Growth of beech is limited by influence of the three factors: moisture's deficit, continentality in west and cryoclimate in north. The most dramatic changes in environmental conditions occur in terms of climate humidity: already in the current climate period, compared to the climatic norm, the area that is favorable for the growth of beech shrank substantially (from optimal to satisfactory conditions). Scenario A1B predicts that, by end of the 21st century, conditions suitable for beech growth will remain only in the Carpathian Mountains and their foothills in the west, and as a narrow belt in the Crimea Mountains.

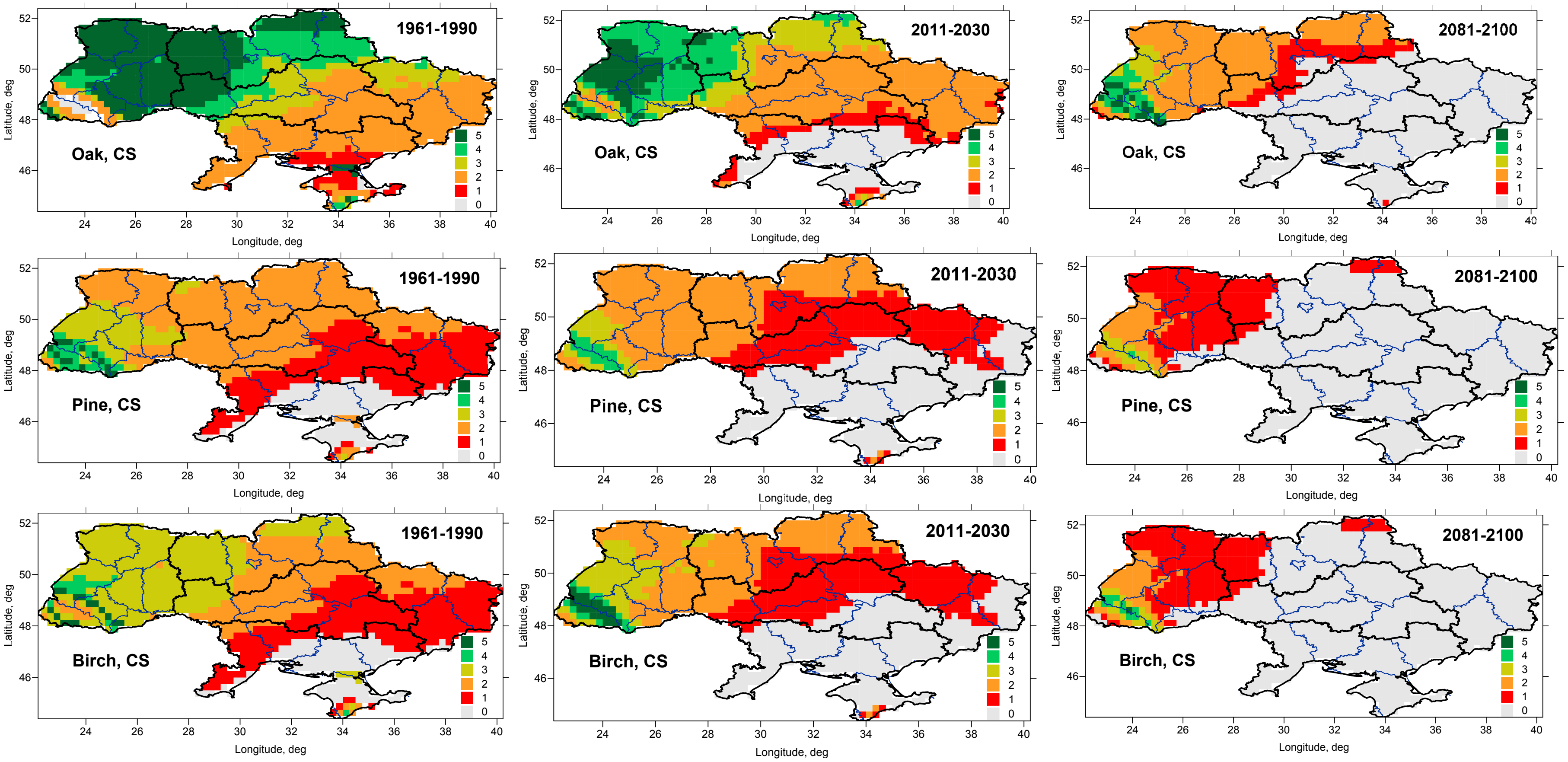


Figure 12. *Cont.*

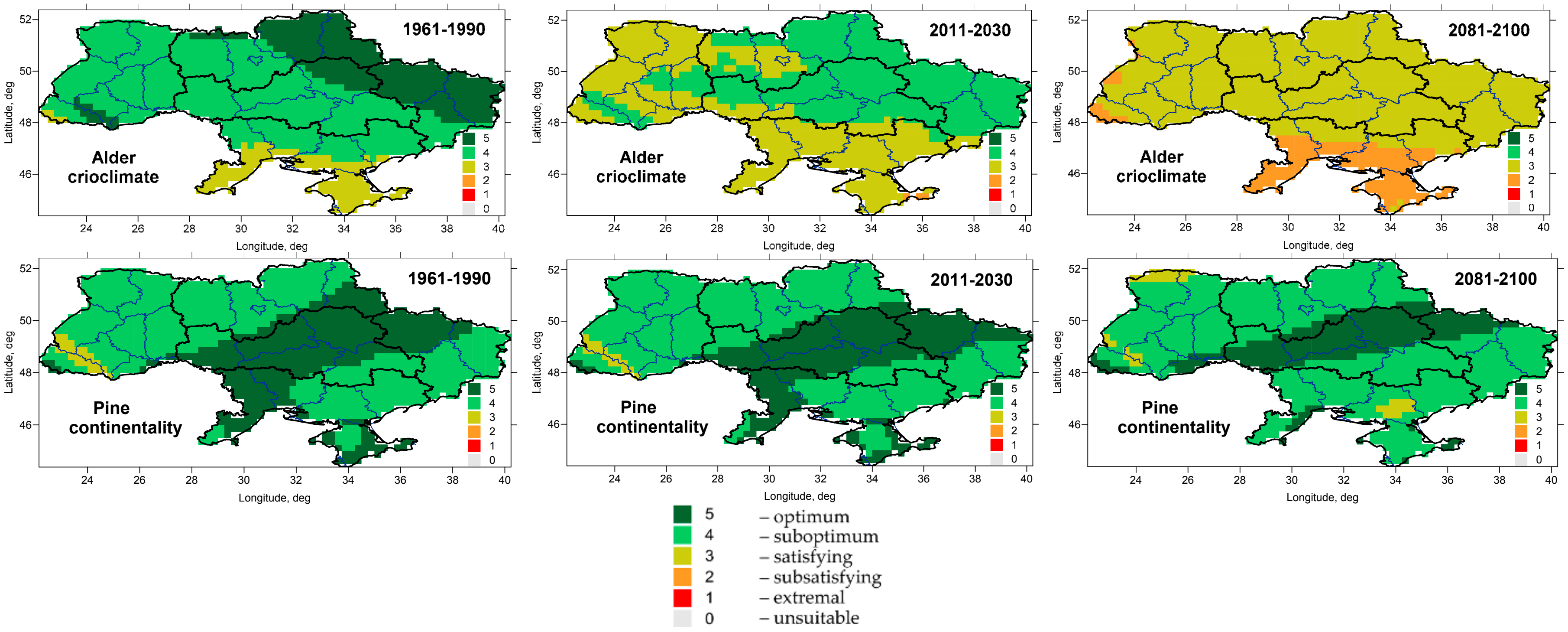


Figure 12. Dynamics of satisfyability of climatic conditions for growth of major forest forming species (examples). Three upper rows describe dynamics of coefficient of satisfyability (CS) of humidity for oak, pine and birch for 1961–1990, 2011–2030 and 2081–2100; the forth row shows the indicator of satisfyability of crioclimate for alder; and the 5th row shows the indicator of climate satisfyability of continentality for pine. All indicators are grouped by grades of climate satisfyability by Didukh: (0) climate is unsuitable (for a given species by indicated climate indicator); (1) extremal (pessimum); (2) subsatisfying; (3) satisfying; (4) suboptimum; (5) optimum.

Water stress is also a major limiting factor for Norway spruce (*Picea alba*). The current zone of tolerance by humidity for this species is very narrow and is limited by the Carpathians (optimum and suboptimum) and their foothills (heavy and extreme conditions). The rest of the country's territory has unsuitable conditions for growth of spruce. The projected changes of moisture conditions will lead to a more restricted zone with conditions suitable for this species. Practically, by the end of the century, the flatland territory of Ukraine will not have any suitable conditions for growth of spruce.

For the tolerance ranges of birch (*Betula pendula*) and alder (*Alnus glutinosa*), similar features are observed: lack of humidity is the limiting factor. Gradual shrinking and shifting of zones favorable conditions for growth of these species are observed now, and this trend will continue in the future. For all considered major forest forming species (oak, pine, birch, black alder, beech, and Norway spruce), the critical limiting factor is climate humidity. According to the forecast, a significant shrinking of zones of optimal growth by this indicator during the second half of the 21st century will be expected for all species, especially during 2081–2100. Under scenario A1B, it is expected that, by the end of this century, large areas will have unfavorable conditions for the growth of almost all tree species; there is a high probability of essential changes of zonal vegetation types. For large areas, a significant decrease of productivity of major forest forming species, gradual loss of reproductive capacity and possibility of natural restoration, destruction of cycles of seasonal development and ontogeny, reducing resistance to pests and diseases and increasing the threat of forest fires are projected. Scenarios A1B+T−P and A1B−T−P project a more pessimistic picture.

3.4. Dynamics of Hydrothermal Coefficient by Seljaninov

Figure 13 shows dynamics of HTCS for 1961–1990, 1991–2010, 2031–2050 and 2081–2100 (Scenario A1B).

Spatial assessment of HTCS allows us to make the following conclusions. Aridity is growing in the recent period (1991–2010) compared to the standard one in the Southern region; the territories with a very dry climate (HTCS < 0.7) arose in Northern Steppe (Zaporizhja oblast) and spread in the coastal zone of Odessa and Mykolaiv oblast; excessive moisture zone in northern Chernihiv oblast decreased and the complete disappeared during 1991–2010; and the area of wetlands in the Carpathians is reduced. The analysis of HTCS for future periods shows that, in the near future period (2011–2030), the arid climate zone (HTCS < 0.7) will move further north in southern forest steppe (Odessa region), and the insufficient moisture zone (0.7 < HTCS < 1) will spread north covering a major part of the Central and Southern regions and south of the Northern region. By mid-century (2031–2050), some weakening of aridity and even a return to state of the current period expected. However, at end of the 21st century, due to significant warming during the warm period and reduced precipitation in the summer, the aridity will substantially increase and spread. The zone of sufficient and excessive moisture will remain only in the Western region, while, in the Carpathians, the zone of very wet climate will almost disappear. The entire Southern region, along with the south of the Central region and the east of the Eastern region will be in the area of very dry climate. Some places in southern steppe will have HTCS with values < 0.5, which complies with semi-desert conditions. Central, eastern and southeast parts of Northern region will already be an area of low moisture (0.7 < HTCS < 1). Thus, projection of HTCS also showed substantial climate aridity strengthening over the vast majority of territories of Ukraine for 21st century, with a high probability of shift of bio-climatic zones at least for one gradation towards aridity, and following impoverishment and death of forests of southern, eastern and central parts of the country.

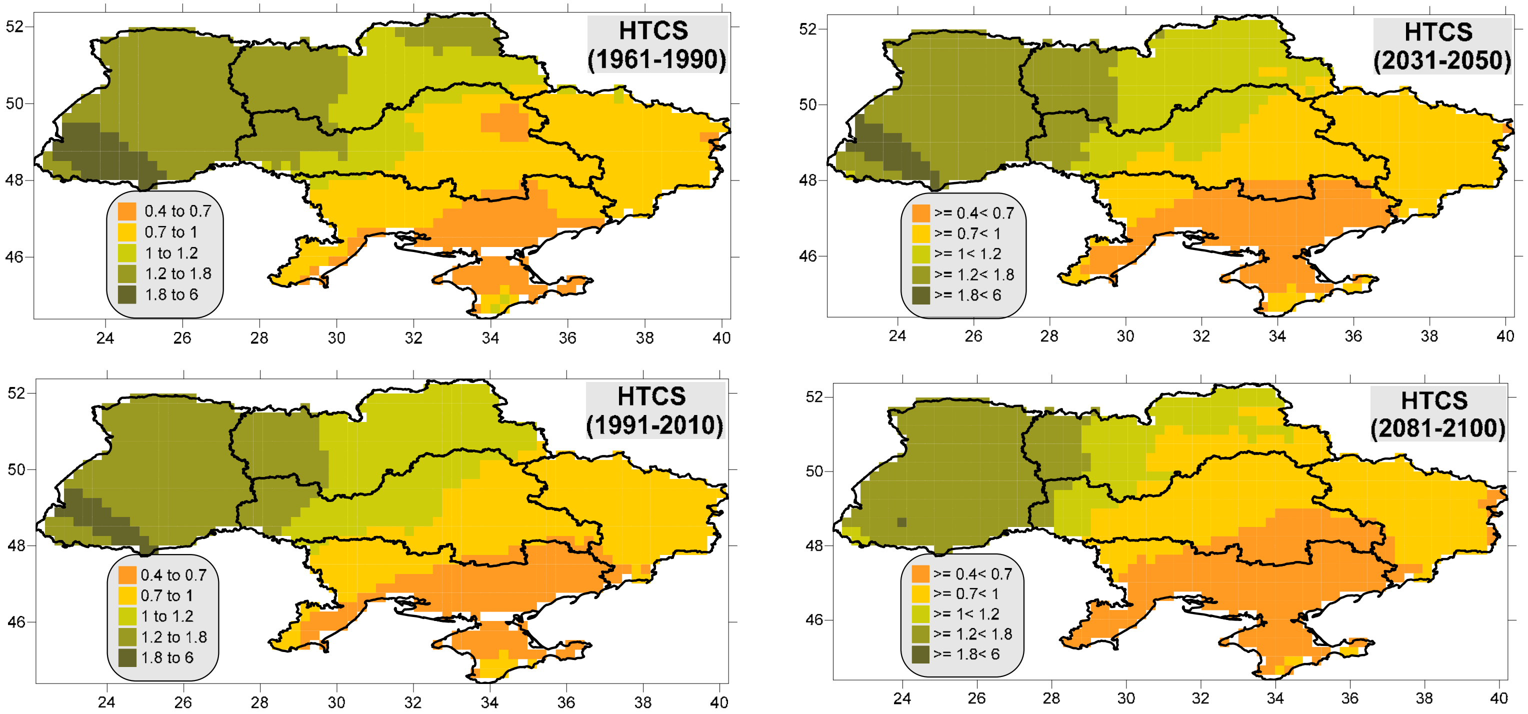
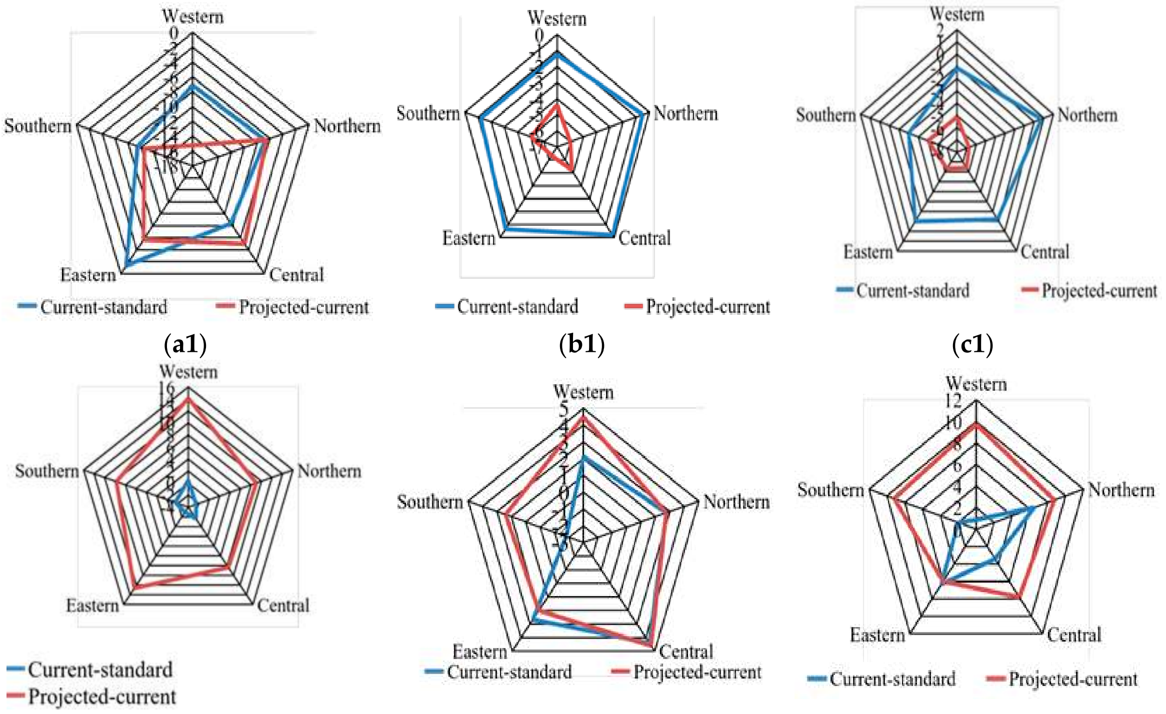


Figure 13. Dynamics of Hydro-thermal coefficient by Selianinov (HTCS).

3.5. Change of Reference Dates

The projections show that climate change will lead to a shift of dates of stable transition of temperature through reference points that might have serious consequences for forest ecosystems and forest management, particularly as part of adaptation strategies. Reference points define boundaries of climate seasons. The beginning of spring is usually defined by the date of steady transition temperature through 0 °C; vegetation period by the transition through either 5 °C or 10 °C; the duration of climatic summer by the period with temperatures over 15 °C; autumn by the period between the dates of stable transition temperature down from 15 to 0 °C; and winter by the period between the dates of air temperature below 0 °C [55]. Analysis of dates of stable transition of temperature through reference points was done for the recent period (1991–2010) compared to the standard period (average for 1961–1990) and period of near future (2031–2050) by Scenario A1B (Figure 14).



(**a1**) (**b1**) (**c1**)

(**a2**) (**b2**) (**c2**)

Figure 14. Shift of reference dates by region, days (examples): (**a1**,**a2**) free-frost period (**a1**) in spring and (**a2**) autumn; (**b1**,**b2**) vegetation period > 5 °C (**b1**) in spring and (**b2**) autumn; and (**c1**,**c2**) vegetation period > 10 °C (**c1**) in spring and (**c2**) autumn.

On average, the duration of the frost-free period in Ukraine increased in the recent period compared to the standard one by six days (maximum in the Southern region—11 days) and for 2031–2050 compared to the recent by 21 days (the biggest—29 days—in Western region, and the smallest—15 days—in Southern region). Date of transition through 0 °C in spring in the recent period preceded the date of the standard one by seven days, while, in the near future period compared with the recent one, by 10 days (Figure 14(a1,a2)).

The growing season for frost-resistant plants and forest plants with shallow root systems (i.e., the period with temperatures above 5 °C) in the recent period in Ukraine increased on average over the country by three days. For the near future period, compared with the recent one, the increase is expected by another 11 days. In the spring, this date has become earlier, in range of 1–6 days for the two periods examined (Figure 14(b1,b2)).

On average, for Ukraine, the growing season for most tree forest species is defined as period with temperatures above 10 °C. For 1991–2010, this period increased by three days compared to the standard period, and is expected to increase by another 14 days during the near future period (Figure 14(c1,c2)).

The duration of summer season is most important for thermophyte plants. Compared to the standard period, this number increased during 1991–2010 by only one day; however, during 2031–2050, the expected increase will be on average 12 days. This creates favorable conditions for the cultivation of introduced species, which is especially important if climate change leads to impoverishment and death of local species. The duration of summer will increase by around 15 days in the Southern and Western regions; in the Northern region by 13 days; and in the Central and Eastern regions by eight and six days, respectively.

End of summer (the date of transition through 15 °C) does not change on average over 1991–2010, but is very diverse by *oblast* (±7–10 days). In 2031–2050, summer ends seven day later than now, but, again, the spatial diversity is high. Winter starts on average 11 day later than now, with a high diversity—from 8–9 days earlier, in steppe, to 20–21 days later in eastern foothills of the Carpathians.

4. Discussion

Impacts of climate change on forests are usually described in terms of exposure, sensitivity, impacts, adaptive capacity, and vulnerability [56]. Ultimately, assessment of vulnerability is based on potential capacity of ecosystems to fulfill all diversity of ecosystem services. Adaptive capacity includes not only the historically conditioned inherent adaptive capacity, but also the socio-economic factors as a prerequisite for implementation of planned adaptation. In essence, human activities are recognized as an integral component of ecosystems [57], and vulnerability of ecosystems, particularly forests and agriculture, is an important part of human vulnerability to global change [58].

Shifting of boundaries of major forest forming species growing areas in Ukraine was a typical feature of the common Eastern European process during the last several centuries governed by growing anthropogenic impacts and by the overall aridization of climate over the continent [2]. These changes were rather similar—the shift of the eastern and northern boundary to west and south, respectively, and of forest growing in the xeric belt towards north. Thus, oak and other hard wood deciduous trees (beech, ash-tree, and hornbeam) disappeared in Southern Ukraine, and their eastern boundary shifted to the west. Beech endured a dramatic areal shrinking–currently this species remains only in the Carpathians and in some areas of their eastern foothills. A similar change was observed with flat spruce and fir forests [59]. However, the shift of the growing areas of impacted tree species was slow.

Conversely, the rate of projected changes is dramatic. Practically all approaches and models are applied in this study project a rather consistent picture of deterioration of forests over major part of flatland Ukraine due to increasing water stress, direct impacts of drought, and following weakening of resilience against insects, diseases and root pathogens. Particularly critical situation is expected in Southern, Eastern and part of Central regions, where projected climates envelope vast areas which very likely will be unsuitable for growth of forests.

The projected climate change, particularly over the southern part of Ukraine could be considered as a logical extension of expected climate changes in southeastern countries of the Mediterranean region where a substantial warming and pronounced decreasing precipitation, especially in summer, within IPCC Scenarios A2, A1B and B2 are expected [60,61]. Some studies suppose an overall positive effect of climate change on EU forests and increasing the forest areas over Europe, excluding the Mediterranean, as well as increasing wood production and supply, albeit the ecosystem services indicator is relatively neutral [56].

However, even if the growth of climate aridity in Ukraine will be noticeably lower than is predicted by A1B or A1B±P±T Scenarios (e.g., by only one grade of Vorobjov's classification of forest type-climate), the impacts on productivity and resilience of forests will be substantial. A case study on impacts of different by aridity forest types on productivity was provided for oak forests of two typological sectors—Pridonetsky sector of fresh temperate climate (T = 84–104 °C, W = 2.0 to 0.6, area

138.5×10^3 ha) and Derkulsky sector of dry relative warm climate (T = 104–124 °C, W = −0.8 to 0.6, area 92.9×10^3 ha), which are similar by relief, age structure of forest stands, and forest management. Indicators of productivity (growing stock volume (GSV) and increments) were assessed on sample plots along typological profiles established perpendicularly to water flows across studied forests. Major results of this case study were: (1) the difference in GSV of actual oak stands of two neighboring classes by humidity at 100 years was 86 m^3 ha^{-1}, or 31.9% (270 vs. 184 m^3 ha^{-1} in fresh and dry conditions, respectively); (2) for the reference (i.e., fully stocked) stands, this difference was even higher—165 m^3 ha^{-1}, or 33.5% (respectively, 493 vs. 328 m^3 ha^{-1}); lower productivity of the dry oak forests follows from the difference in site indexes (of ~1 class) and relative stocking (density); and (3) maximum of mean annual increment (MAI) occurs at the age of 42 years (3.2 m^3 ha^{-1} $year^{-1}$) in dry conditions, and at the age of 45 years (3.1 m^3 ha^{-1} $year^{-1}$) in fresh, while net growth occurs at the age of 30 years in both classes at the level 4.2 and 4.0 m^3 ha^{-1} $year^{-1}$, respectively). According to another study, productivity and growth of 72% oak stands, which grow in dry climate, corresponds to III site index, while 72% of oak of fresh conditions belongs to II site index [62]. On average, it gives the difference in major indicators of productivity at 20–25% for 100-year period of growth [63].

The systems consequences of the projected climate change might be much more dangerous than when considering only the direct impacts of climate. The beginning of this century is marked by several strong waves of decline of forests practically over the entire country's territory. Intensive processes of dryness and death of forests are observed in forests of major forest forming species—pine, spruce, oak and other hard-leaved species (e.g., beech and ash-tree). The southern part of the country is under particular risk where the losses of forests reach ~20–30% of forested area by individual steppe *oblasts* [15]. Particularly affected here are pine forests established on fluttering sands and other degraded lands of southern steppe [64]. The drying of pine forests is observed in flatland of Western region and western part of Northern region where ~6% of the area covered by this species are strongly affected by the curative drying [65]. Dryness of spruce stands enveloped huge areas in the Carpathians, particularly at lower elevations and in the forests established in unsuitable growing conditions—recent estimates of the affected area reach up to 20% of the total area of this species [66,67]. About 12% of oak stands are under severe drying in Northern and Western regions [68]. Ash-tree forests are under particular threat over all their growing area in Ukraine [69]. Local drivers of these processes are diverse: climate extremes, particularly droughts; change of hydrological regimes (basically decreasing the water table); diseases and pathogens (rots caused by fungi, like *Fomitopsus annosa*; ovarial fungal infection); insects (e.g., apical bark beetle and nematode worms); inconsistency of biology of planted forests to site conditions; ineffective forest management; etc. As a result, it leads to the decreasing resilience and—as the utmost stage—to the physiological collapse of the trees. However, all studies of pathological processes in Ukrainian forests point out that climate change (increasing temperature and incoming radiation, enhanced variability of weather, and shifting of climate reference dates) is a driver that launches a sophisticated mechanism of interconnection and interaction of environmental conditions, pest outbreaks and fungal deceases. Similar processes are observed now in forests of neighboring countries [70,71] up to the boreal zone [72]. However, there are enough facts to hypothesize that severity and injuriousness of such an integrated intervention is markedly increasing towards the xeric belts, which means that the projections based only on climate change are not able to describe the complete spectrum of risks and threats to future forests.

Overall, the received projections are logically consistent with other studies for adjacent territories taking into account the trend of increasing drought towards Eurasian southeast. The expected increase of drought is small in the Czech Republic and Austria, but substantial in Slovakia, Hungary [73] and Romania [74] with a clear acceleration in Southern Ukraine and Russia. A prediction of growth of forests in the West Carpathians by growth simulator SIBYLA and process-based model BIOME-BGC for 2012–2050 and 2071–2100 (used RCMs are based on Scenario A1B, warming from 3 to 4 °C, decreased summer precipitation at −10% and increased winter one at 10% by end of the 21st century) reported the expected substantial negative impact on growth of beech and Norway spruce, with substantial variation dependently on the elevation, particularly for the stands receding edge, but favorable conditions for oak [75]. Note that that study was limited by area of current ecological optimum for the considered species. The models used considered CO_2 fertilization effect and nitrogen deposition but does not include such crucial impacts as fire, drought, insect and pathogens outbreaks, and the major oak species were *Quercus petrea* and *Q. cerris*, which are more drought tolerant than *Q. robur* in Ukraine. Long droughts, especially those that are accompanied by heat waves, have already demonstrated special risks for European forests. Two severe heat waves that occurred recently in Western (2003) and Eastern Europe (2010) resulted in halved Net Primary Production for practically all forest forming species and death of forests over large territories, mostly due to biotic agents and fire [76,77].

The projected climate change will substantially impact ecosystem functions and services of Ukrainian forests, especially in eastern and southern parts of the country [21]. The negative impact on biodiversity is evident. Recent estimates reported the net sink of the country's forests around 2010 at ~11 Tg C year^{-1}, or 115 g C m^{-2} year^{-1} [12,15]. This is one of the highest estimates of forest sink in Europe at the national level and is basically explained by a large share of protective forests with a restricted regime of wood harvest (~50%) and dominance of young and middle-aged forests (~70%). However, according to the "business-as-usual" scenario of development of the Ukrainian forest sector, the C sink substantially falls by the 2030s (to ~30 g C m^{-2} year^{-1}) and to 66 g C m^{-2} year^{-1} in the progressive scenario if environmental changes are not taken into account. In a short term forecast, accounting for environmental changes does not impact these estimates much. Note that the mentioned numbers do not take into account protective role of forest elements on agricultural land and technological improvement of processing and use of wood and wood products [12]. The forecast by end of the 21st century supposes high risks for forests over large areas and high probability to reach a tipping point. It is very likely that overall, particularly if a consistent strategy of adaptation of Ukrainian forests to climate change will not be developed and implemented, the forests will become a net source of carbon to the atmosphere.

Ukraine belongs to countries with an insufficient supply of fresh water: the local river runoff averages 86,800 m^3 year^{-1} km^{-2} or 1000 m^3 year^{-1} per capita and in very dry years, 49,200 or 610, respectively. Distribution of river runoff is non-uniform. The area of irrigated land exceeded 2.6 mln ha in 1989. During the last five years, water content in rivers and water reservoirs reached only 80% of the long term year average, and contamination of water is high [78]. This put water protection and regulation services of forests at the same level of importance as the anti-erosion one that is directly connected to the problem of optimal structure and stability of landscapes, particularly in bioclimatic zones with an insufficient forest cover.

A crucial and understudied problem is the role of trees in development of sustainable structure of forest–agrarian landscapes under expected climate change. Many decades of research and large scale practical implementation of field protective afforestation in Ukraine showed an extremely high importance of forest protective elements for providing sustainable crop yields and ecological stability of the landscapes [13]. The existing area of forests, particularly in plain agricultural regions, is insufficient for environment protection. The regional estimates differ, but on average the optimal forest cover should be 7–10% in plain and 12–20% in hilly territories of the steppe zone depending on soil and slope; about 25–30% in forest steppe; and 40–50% in mountains [79]. However, the climate projections for major agricultural regions show substantial increasing water stress and high risk for survival of protective forests in harsh growing conditions. This might change important features of current understanding of impacts of forests on the hydrological cycle in dry land that requires specific research on the topic.

Change of dates of transition of temperature through reference points might change dynamics of important ecosystem processes and therefore impact of forest management activities in different aspects including inter alia substantiation of optimal time for planting forests; selection of the appropriate forest trees and shrubs for reforestation and afforestation; forecasting of outbreaks of pests and timely implementation of forest protection activities; selection of optimal periods of logging and removal of harvested wood and wood products; choice of priorities for time of clearing of burnt areas; development of windbreaks; etc. Among the many examples, we indicate a few. The earlier transition of temperature through 10 °C is important for adjusting deadlines of forest planting and planning activities on forest protection again pests. Changes of the duration of period between the dates of stable transition temperature through 5 and 10 °C can disrupt the synchronization of development of leaves of trees and dynamics of gnawing pests that will increase their harmfulness. Increasing the duration of summer may encourage re-flowering of some trees that leads to their weakening, as well as the emergence of additional generations of pests (e.g., some types of bark beetles). Autumn transition temperature through 5 °C means a deadline for the autumn planting of forests. In the system of forest protection, this is a period for supervision of dangerous pests, and the onset of dormancy of most pathogens and pests diapause. Logging after this date causes a minimal stress to forest ecosystems. Overall, the projected shift of reference dates necessitates the urgent reconsidering of forest regulations and manual terms of wood removal deadlines, periods of planting forests, timeliness of forest protection activities, etc.

Transition to sustainable forest management is of a vital importance for Ukrainian forests. This process can be successful only if it would be an inherent part of a national-wide strategy of transition to sustainable development of the society and the state, development of civil society of the European type and substantial purposeful efforts for acceleration of scientific and technological progress. The process of transition to sustainable forest management is inherently adaptive, and the adaptation has new sense and content. This is an adaptation to conditions that were not considered by previous experiences and have no professional traditions. Thus, to provide real progress in adaptation to climate change, it is necessary to have solid philosophy, strategies, scientific base, plans, corresponding legislative and regulatory base, and effective system of forest monitoring which would inform about early changes in the conditions and functioning of forests.

Solutions to the problem of transition of the Ukrainian forestry sector to adaptive sustainable forest management (ASFM) have different dimensions—political, social, scientific, institutional and financial [12,21,22]. Overall, this problem requires a special elaboration. Within professional forestry, the actions for transition to ASFM in countries of Central and Eastern Europe were considered in many studies. With respect to Ukraine, an outline of the current understanding of transition to the ASFM is as follows. Current philosophy of SFM, which is oriented at supporting the entire spectrum of ecosystem services (considering maximal productivity of forests and sustainable supply of wood and wood products as an important–but only one of many–ecosystem service of forests), remains the overall background of the current implementation of the paradigm of co-evolution of humans and forest. However, the system of forest management measures should be modified based on principles of risk resilient forest management. This supposes a system elaboration of relevant forms of forest management that would be able to reduce impact of disturbances—from close-to-nature forestry [80] and continuous forest-cover forms of SFM [81] through multifunctional forestry with defined management priorities to short-rotation energy plantation [82]. It defines a need for new approaches to understanding of technological and managerial specifics of thinning and regulation of final harvest. To decrease vulnerability of forests, development of complex by morphological structure uneven-aged, multi-layer and multi-species stands should be considered a major feature of reforestation and formation of future artificial and natural forests. Expected droughts require an anticipatory policy of purposeful change of species composition aiming at increasing of the share of drought tolerant species and use of drought resistant provenance. The change of disturbance regimes, which is already observed in Ukraine, supposes development of a new system of forest protection against biotic agents, fire and unfavorable weather conditions ([8,22,55], among others). Implementation of integrated land management on an ecosystem–landscape basis (including populated areas, agriculture, forests, and industry) is of a crucial importance to assess stability of natural landscapes and provide favorable living conditions for population.

It is not easy to estimate how much the current social and economic situation in the country is ready to start with an effective program of actions on transition to ASFM. Ukraine experiences a difficult period of profound political, social and economic changes. This process is complicated by military operation in the southeastern part of the country. However, the recent decision of the Ukrainian government to fundamentally reorganize the Ukrainian forest sector gives us hope that this vitally important national problem will find its proper solution.

5. Conclusions

Expected climate change will likely drive major part of Ukrainian forests to irreversible transformation. Probability of reaching the tipping points by flatland forests (excluding Western and partially Northern regions) is high. Transition to ASFM might minimize losses of major ecosystem services, or at least slow down impoverishment of forest ecosystems over the substantial territories of the xeric belt within the country. However, substantial and urgent efforts are required. Understanding of both regional vulnerability of Ukrainian forests to climate change and optimal ways for developing corresponding adaptation strategies remains poor. This defines priorities of some immediate research steps. One step is the development of an operative integrated forest monitoring system that would be able to provide early warning information on undesirable changes in forest ecosystems. The second one is development and implementation of an interdisciplinary science program on functioning and resilience of Ukrainian forests under ongoing and expected climate change. Development of adapted to regional conditions models, which include most probable trajectory of Ukrainian forests under expected environmental change and alternate sets of relevant forest management activities, should be of the highest priority. There are several clearly understood requirements to such models. First, the expected substantial worsening of growing conditions will lead to special attention to forest management decisions and technologies at the local scale. Thus, there is an urgent need to develop landscape–ecosystem models of a fine resolution (10–20 to 50–100 m). Second, forest should be substantial, but not a single focus of such models, and all land classes over the landscape should be included in consideration. This is especially important for major agricultural regions of the country. Third, the models should be integrated in the sense of joint consideration of forest ecology, forest management, and climate change impacts under expected economic and social conditions. Some existing models such as Landis-II+PnET [83] could serve as an initial prototype of the required models, provided they are substantially improved.

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