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The Status of Threat Assessment and Adaptation Measures in the Forestry of Ukraine due to Climate Change

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About the Project “Sustainable Forestry Implementation” (SFI)

The project “Technical Support to Forest Policy Development and National Forest Inventory Implementation” (SFI) is a project established in the framework of the Bilateral Cooperation Program (BCP) of the Federal Ministry of Food and Agriculture of Germany (BMEL) with the Ministry of Environment and Natural Resources of Ukraine (MENR). It is a continuation of activities started in the forest sector within the German-Ukrainian Agriculture Policy Dialogue (APD) forestry component.

The Project is implemented based on an agreement between GFA Group, the general authorized executor of BMEL, and the State Forest Resources Agency of Ukraine (SFRA) since October 2021. On behalf of GFA Group, the executing agencies - Unique land use GmbH and IAK Agrar Consulting GmbH - are in charge of the implementation jointly with SFRA.

The project aims to support sustainable forest management in Ukraine and has a working focus on the results in the Forest Policy and National Forest Inventory.

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Content

Introduction

Climate change is now recognised as one of the main global threats that is affecting and is expected to increase its impact on forest ecosystems in the future. Climate resources largely determine the functioning, growth, development, condition and productivity of forest ecosystems, so knowledge of climate impacts on forests and forecasting the dynamics of climate indicators should form the basis of forestry development strategies at the local and regional levels. A proper assessment and forecasting of forest vulnerability to climate change is a key precondition for the development of appropriate adaptation measures aimed at minimising the negative impacts of climate change on forests.

This report provides a brief overview of the current status of the assessment of threats to forests due to climate change in Ukraine and the development of adaptation measures in the forestry sector.

1. Projects and initiatives on climate change impact assessment on Ukrainian forests

Research on the impact of climate change on Ukraine's forests began in the 1990s by scientists at the H.M. Vysotsky Ukrainian Research Institute of Forestry and Agroforestry (URIFFM). The work was initiated within the framework of international cooperation under the US Country Studies Program, which involved 55 countries from different continents [15].

The general approach for conducting climate change impact assessments was based on the following steps: 1) defining the scope of the assessment process, 2) selecting scenarios, 3) conducting biophysical and economic impact assessments, 4) integrating the results of the impact assessment, 5) analysing adaptation policies and programmes, and 6) documenting and presenting the results to decision makers [21].

The toolkit for assessing the effects of climate change on climate-sensitive economic sectors (including the forestry sector) included the definition of a baseline socio-economic trend, the development of climate change scenarios based on global circulation models (GCM), the application of the Holdridge life zone classification model and GAP models of forest vegetation development [5]. These tools made it possible to assess the general trends in the biophysical impact of climate change on Ukrainian forests and revealed limitations in their application, which are associated with the low resolution of global models and their weak ability to take into account the impact of anthropogenic factors on forest plantations, in particular, the effects of forestry activities [20]. The basic information on the indicators of the forest fund of Ukraine was based on the data of the State Enterprise "Ukrderzhlisproekt" as of 01.01.1996.

The impact of climate change on the forests of Ukraine and the consequences of applying different forest management strategies were assessed using scenario analysis methods within the framework of the international project SCEFORMA - "Scenario analysis and prognosis of forest condition dynamics in the condition of anthropogenic changes of environment". The research was carried out using the EFISCEN large-scale scenario model of forestry, which is based on a matrix generator. The state of the forest is characterised by the distribution of plantation areas by age and stock classes, the number and size of classes are determined depending on the characteristics of the plantations of a given forest type. Growth dynamics is modelled by the transition of areas to higher age and stock classes, and harvesting and reforestation are included in the model as a probability of occurrence. Thinning and other selective harvesting are modelled as a downward movement of the area covered by harvesting by one stock class. The model is based on three groups of indicators:

1. Distribution of plantation areas by age and stock classes.
2. Growth dynamics as a percentage of growth over a 5-year period.

3. Parameters describing the management regime.

The results of modelling and forecasting until 2050 showed that the unbalanced age structure of the forest fund of Ukraine and the processes of natural forest aging in the context of climate change impact on forest phytocenoses will lead to deterioration of forests, reduction of biomass growth and decrease in greenhouse gas emissions in the coming years. The application of adaptive forest management principles, transition to differentiated ages of maturity, and expansion of the area of selective harvesting will help to increase the sustainability and productivity of forest stands [22,6].

The potential of the Ukrainian forestry sector to reduce climate change risk was assessed within the framework of the Ukraine-US Climate Change Initiative. The research results showed a positive impact on the dynamics of carbon sequestration of targeted forestry measures to support carbon sequestration in forested areas and increase carbon sequestration in afforestation [4,10].

With the assistance of FAO, Ukraine conducted research on the impact of climate change on forest ecosystems, which summarised the results of scenario analysis and forecasting of forest use under different climate change scenarios and identified areas of adaptation measures for forestry and set the prospects for research on climate change and forest management [2,16].

In cooperation with the Global Water Partnership (GWP), the Company conducted research on the impact of droughts on forests in eastern Ukraine (Luhansk, Kharkiv and Sumy regions) as part of the Integrated Drought Management Program. Based on the results of the assessment and forecasting of the impact of climate change on forests in eastern Ukraine, comprehensive measures to adapt forest management to regional forest characteristics were proposed.

An example of adaptation measures prepared in a pilot study within the framework of cooperation with the Global Water Partnership's "Integrated Drought Management" (GWP IDMP) programme is a differential approach to developing a system of adaptation measures in forestry based on the identification of zones of different vulnerability of forests in eastern Ukraine [17]: Zone A - the zone of highest vulnerability for forest vegetation: under current conditions, it corresponds to the arid climate of the southern steppe (e.g., Kherson region); Zone B - the zone of high vulnerability for forest vegetation: under current conditions, it corresponds to the climatic conditions of the steppe; Zone C - the zone of moderate vulnerability: under current conditions, it corresponds to the climatic conditions of the forest-steppe. Areas of adaptation and mitigation of the negative impact of climate change on forests should include the following measures (taking into account the typological characteristics of the forest fund):

- Conservation and formation of multi-age forests with complex structure and species composition.
- Protecting forests in areas at risk of deforestation through forestry activities that will help preserve the forest environment.

- Reconstruction, preservation and systematic supplementation of existing shelterbelts and other protective elements of agroforestry landscapes based on an understanding of the zonal specifics of their spatial and parametric structure.
- Expanding the use of drought-resistant tree species suitable for afforestation in semi-arid conditions.
- Preservation of the existing gene pool of native tree and shrub species through appropriate silvicultural measures.
- Use and adaptation of the best practices of sustainable forestry in the context of climate change and exchange of experience with countries with large areas of forests growing in drought conditions (Bulgaria, Romania, Greece, Israel, Turkey, etc.).
- Developing and improving the monitoring system for forests and protective plantations - implementing a comprehensive programme for national inventory and monitoring of forests and agroforestry plantations.
- Developing national and regional programs to prevent forest fires, developing a monitoring system for early detection and warning of forest fires.
- Providing special ground and aerial technologies for monitoring and fighting forest fires.
- Improving the comprehensive system for detecting forest damage and protecting them from the adverse effects of biotic and abiotic factors.
- Establishment of seed banks to preserve seeds of indigenous tree species and shrubs suitable for reforestation in semi-arid conditions.
- Establish a climate change-oriented system of protected and reference forest areas and implement appropriate forest management regimes in them.
- Attracting financing mechanisms to increase the resilience of forests to climate change.

Based on the methodological approaches of the US Country Studies Programme, URIFFM scientists have improved methods for assessing the vulnerability of Ukrainian forests to climate change based on the use of the forest-typology model of climate classification by Professor Dmytro Vorobyov [23]. This model is based on the Ukrainian classification of forest vegetation types, which is the basis for planning forestry activities and organising forest management in Ukraine. The forest typology model of climate classification by Professor Vorobyov takes into account the leading climatic factors - the presence of moisture and heat, which are crucial for the growth and development of forest vegetation. This model describes the relationship between forest classification and typological units and climate, which is manifested in the following:

- the formation of forest plot types with homogeneous soil-forming species and landforms is determined by the effect of moisture and heat;
- within the same forest plot type, the formation of forest types is also related to the continental climate;

- within the same forest type, the productivity of stand types is directly related to the amount of heat.

The analysis of these relationships allowed D.V. Vorobyov to develop a classification of climates as a component of the forest-typological classification of species with the classification of edaphic conditions [7]. In this case, the analysis of the impact of the most important climate factors - heat and moisture - on forest diversity concerns both soil fertility (formation of forest plot types), composition of plantations (forest types) and productivity (stand types). As a result, each forest plot type of the edaphic grid is quantified: T is a heat indicator, W is a humidity indicator, and A is a continental climate indicator. The climate indicators T, W, A are calculated using data from the nearest weather stations: T is the sum of positive monthly temperatures; W is the climate humidity index, which is determined by the formula: $W=P/T- 0.0286*T$, where P is the amount of precipitation for the warm season; A is the continental index - the difference between the temperature of the warmest and coldest months of the year. The magnitude of the degrees by which climates are divided, hence trophotopes and hygrotopes, is taken as T = 20° and W = 1.4. These climate indicators express the quantitative relationship between them and the edatop.

The forest-typological classification of climates makes it possible to predict forest plot types and soil and topographic conditions for their possible formation based on average monthly precipitation and temperature data. By combining the edaphic and climatic classification schemes (soil and climatic conditions), an edaphic-climatic classification grid was formed, which expresses the combined influence of three most important factors of forest formation: heat and moisture (climatic factors) and soil richness (edaphic factor) on the distribution and formation of forest vegetation types.

The methodology of bio-ecological studies of the impact of climate change on forest phytocoenoses is based on the principle that, relative to the gradient of a particular environmental factor, each plant species occupies a segment (tolerance amplitude) with maximum, minimum and optimal values of the environmental factor. The boundaries of the amplitudes determine the volume of the multidimensional space that characterises the species' ecological niche. Both high and low values of ecological factors relative to the optimum have a negative impact on the functions of organisms and can lead to their death in accordance with the rules of minimum by J. Liebich (1841) and maximum by W. Shelford (1913). The threshold values of a certain factor, above or below which an organism cannot exist, are called the critical or cardinal limit according to J. Didukh [9]. There is a lower critical limit - minimum and an upper critical limit - maximum, and the interval between them is called the zone of ecological tolerance or amplitude. Within this zone, the behaviour of a biological system changes depending on the intensity of the environmental factor. As noted by D. Tsyganov [12], there are zones of pessimums (approximately 7-8% of the length of the tolerance amplitude on both sides, in which the activity of the species is limited, then, where the activity increases, there are suboptimal zones (approximately 27-28% of the length of the tolerance amplitude between the zones of optimum and pessimum), and the middle zone forms the ecological optimum, which occupies 30% of the length of the tolerance amplitude [8].

Knowledge of the range of plant tolerance is necessary for diagnosing ecotope conditions, predicting the development of populations and phytocoenoses [1]. The ecological amplitudes of forest species in terms of both edaphic and climatic factors are much narrower compared to the amplitudes of species of other eco-groups (meadow, steppe, meadow-bog). This is explained by the peculiarity of forest ecosystems, in which unifiers play a significant ecological role in levelling the contrast of the impact of external environmental factors and maintaining the peculiarity of forest environment conditions.

In the vast majority of cases, the optima of forest species are located near the average values of the tolerance amplitude. The number of species that have optima at the edges of the tolerance range (less than 10% and more than 90% of its length) is insignificant and ranges from 0.1% to 1.2% of the sample size. The ecological optimum can be identified by plant parameters such as vitality, productivity, yield, biomass, height, height or diameter growth, density, abundance, leaf area, stand canopy closure and projective canopy cover of herbaceous plants, i.e. indicators that are quite easily determined by fairly simple measurements, some of which can be visually assessed.

To characterise the bioecological features of plants in phytoecological studies, integral scales of ecological amplitudes of natural flora species in relation to various environmental (edaphic and climatic) factors are used. Based on the critical analysis and unification of phytoindicative scales by D.M. Tsyganov, E. Landolt, T. Zazhytskyi, L.G. Ramenskyi, G. and Ellenberg, Professor Y.P. Didukh and his colleagues developed scales of ecological (climatic) amplitudes of species of natural flora of Ukraine, including forest species.

Based on an analysis of numerous publications and his own research, Professor Didukh [19] quantified the climatope as one of the main environmental factors that affects the distribution, condition and productivity of vegetation. Climatology is a complex environmental factor that combines several components. The author proposed 4 phytoindicative scales for the components that characterise the climatop:

- Radiation balance (thermal climate, Tm);
- Aridity or humidity (ombro regime, Om);
- Continentality (continental climate, Kn);
- Winter severity (cryoclimate, Cr).

The methodology of modelling and assessing the impact of climate change on forest phytocoenoses of Ukraine using the models of Prof. Vorobyov and Prof. Didukh is described in detail in a number of publications [18,11,1,13].

This methodology was improved within the framework of the European Union ClimaEast project, which, among other things, contributed to the assessment of the impact of climate change on the forests of Ukraine using the forestry database of the State Enterprise "Ukrderzhlisproekt" as of 01.01.2010 and the climate change scenarios of the Intergovernmental Panel on Climate Change (IPCC).

The research analysed various approaches and models used to assess forest vulnerability; analysed scenarios of projected climate change and selected the most adequate ones for Ukraine; assessed the current state and impact of climate change on Ukraine's lowland forests; modelled the impact of future climate change on the vulnerability of the country's lowland forests, the results of which are presented in the form of maps and tables describing the degree of vulnerability, risks and threats of forest degradation within the selected scenarios; and based on international experience and consideration of forest management practices that minimise risks to the sustainability of forest systems in a rapidly changing world, a framework of forest management actions that minimise forest vulnerability as part of the transition to sustainable forest management is outlined [13].

The A1B emission scenario of climate change proposed in the IPCC's SRES Special Report was used as the main one, which, if current trends continue in the world, is the most likely scenario for further development of society in terms of the level of anthropogenic impact on the planet's climate system. It was also modified to increase surface air temperature and decrease precipitation by the amount of the confidence interval calculated using the ensembles of regional climate models optimal for Ukraine, which resulted in a unique scenario A1B+T-P, i.e. warmer and drier than the baseline A1B. To assess climate impacts on forest vulnerability, bio-ecological characteristics were determined for the main forest-forming tree species of the plains of Ukraine. Forest vulnerability was considered in the regional aspect - within 5 climatic regions, homogeneous in terms of forest vegetation conditions and similar in terms of the nature of expected changes in climate conditions.

It was determined that the impact of climate change on the forests of Ukraine varies depending on the geographical location within the country, geomorphology and relief (mountains, plains), forest types and forest management regime. The state and dynamics of forest ecosystems are the result of a complex interaction and interdependence of impacts, ecosystem responses and feedbacks, as well as the influence of economic and social factors.

Trend changes in the main climate indicators (air temperature, precipitation) within current and expected values are less dangerous than climate variability, the frequency and severity of extreme situations (such as heat waves or droughts) and the natural disturbances they cause, such as fires or pest outbreaks. The most vulnerable forests are those of the steppe and southern forest-steppe, where there is a high probability of impoverishment, degradation and death of forest ecosystems over large areas. At the same time, the threat of increased forest vulnerability exists in other areas, especially under more severe climate change scenarios.

According to the A1B scenario developed by the IPCC, Ukraine is expected to experience significant climate warming and increased aridity in the second half of the 21st century. The assessment of the effects of climate change on forest stands was carried out by scientists of the URIFFM together with scientists of the International Institute of Applied Systems Analysis IIASA (Prof. Shvydenko A.Z.) and the Ukrainian Hydrometeorological Institute (PhD Krakovska S.V.) for three climatic factors (continentality, humidity and cryoclimate) by the categories of satisfactory environmental conditions, which makes it possible to assess the viability of forest species populations [1].

It has been established that the most critical (limiting) climatic factor for common oak and scots pine is climate humidity [3]. According to the forecast, in the period 2080-2100, there will be a significant narrowing of the zone of optimal growth for these species in terms of this indicator (Fig. 1, Fig. 2).

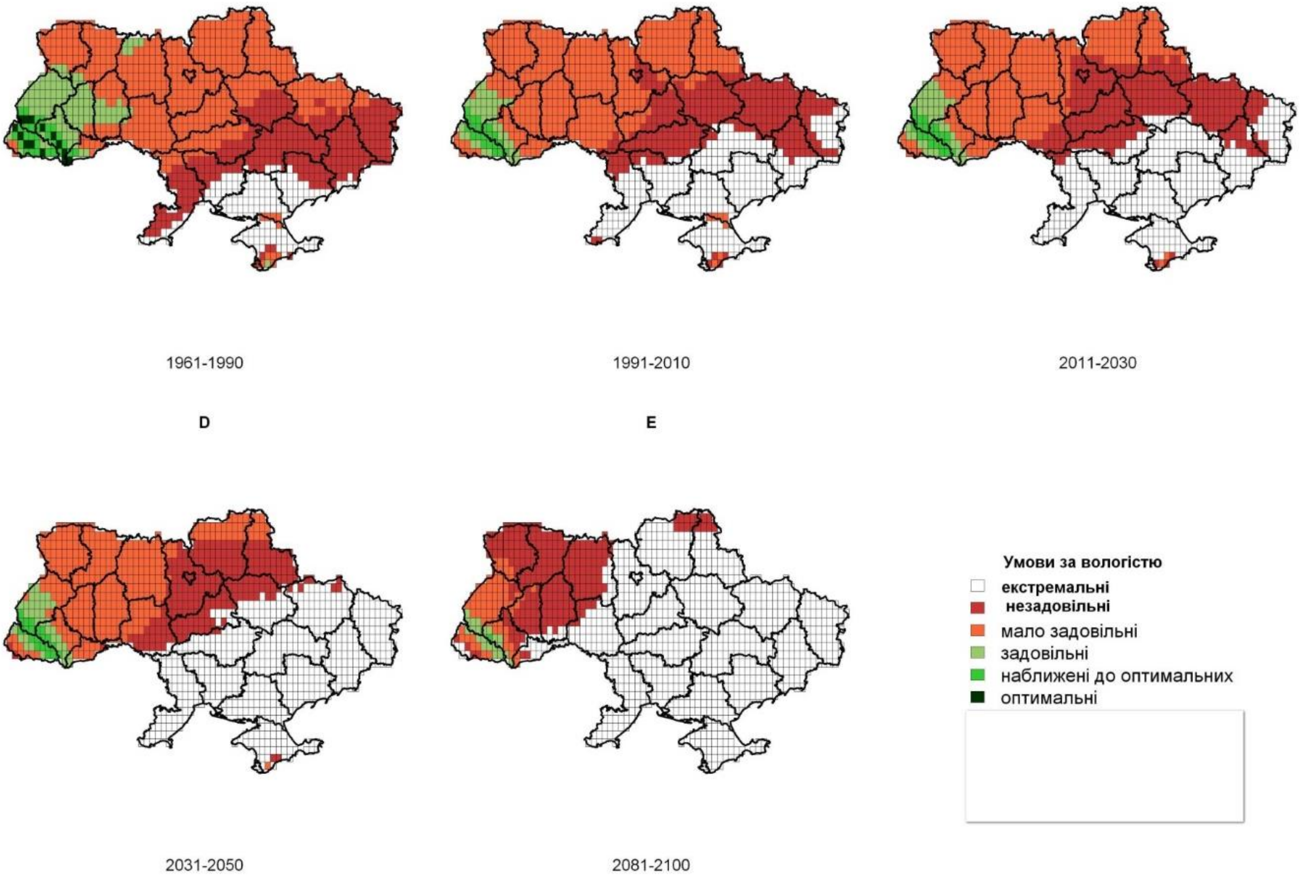

Figure 1. Forecast of the dynamics of environmental satisfaction for scots pine under the IPCC A1B climate change scenario.

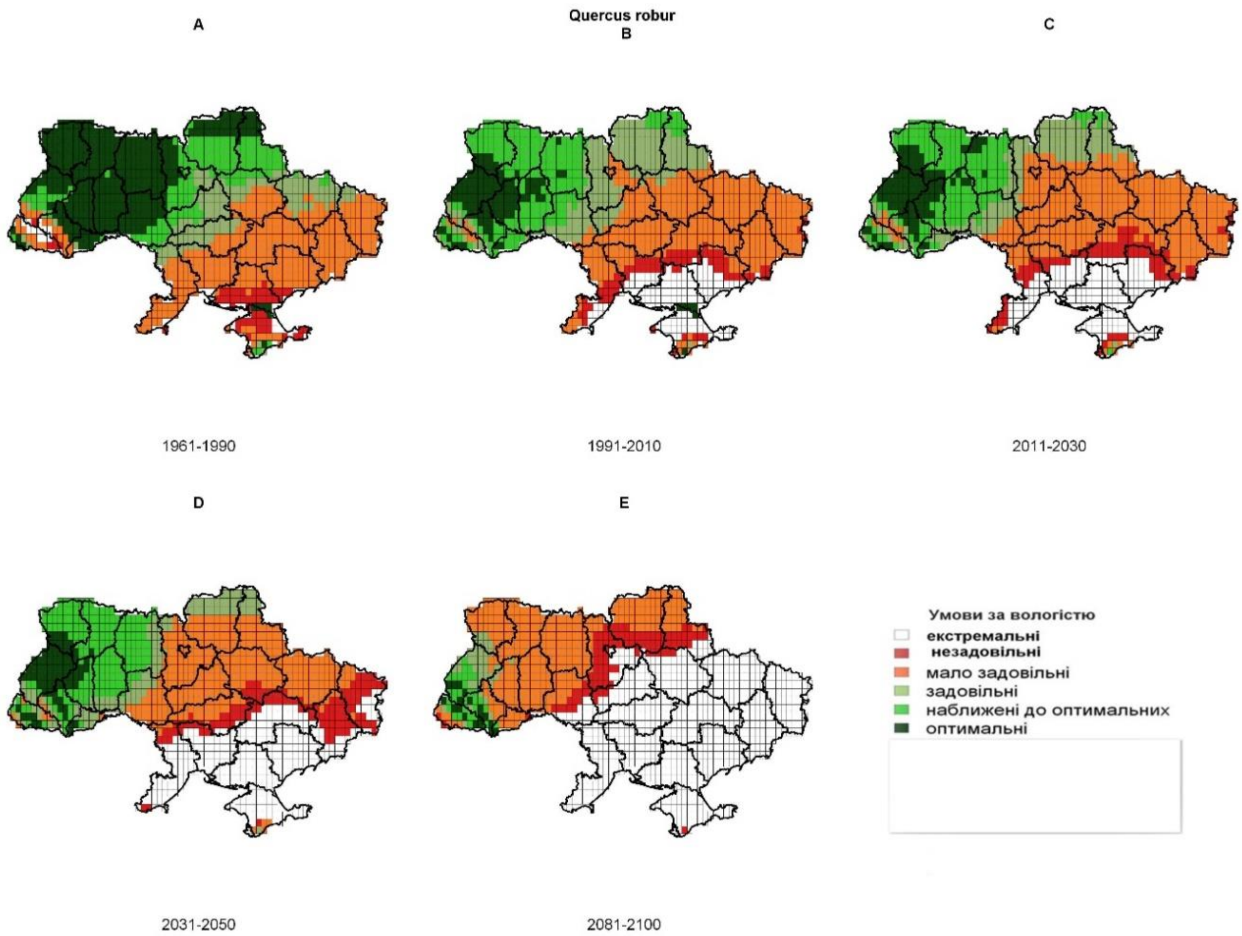

Figure 2. Forecast of the dynamics of satisfactory environmental conditions for common oak under the IPCC A1B climate change scenario.

As a result of climate change, by the end of the twenty-first century, quite significant areas with unfavourable conditions for the growth of the studied tree species and changes in the zonal types of placore vegetation are expected. In places with unfavourable climatic conditions, a significant decrease in the productivity of forest-forming species, a gradual loss of reproductive capacity and the possibility of natural regeneration, disruption of the cycle of seasonal development and even ontogeny, reduced resistance to pests and diseases, and an increased threat of forest fires are predicted. Smaller changes in the area favourable for forest growth and development are observed for common oak, and larger changes for scots pine, which is due, on the one hand, to expected trends in climate change, and, on the other hand, to the ecological and physiological characteristics of these forest species that determine their sensitivity to climate change [3].

The vulnerability of forests can be significantly reduced by developing and implementing strategies and a system of actions aimed at adapting Ukraine's lowland forests to climate change. It is of fundamental importance that adaptation strategies should be based on the principles of sustainable (non-exhaustive) forest management. A basic imperative for the transition to sustainable forest management (SFM) is the understanding that Ukrainian forests are not just a source of an important renewable natural resource, but also one of the main factors in creating comfortable living conditions for the nation and protecting the environment. An in-depth study, biophysical and economic assessment of the full range of ecosystem functions and services provided by forests, including their importance in environmental protection and protection of natural landscapes, create a scientific basis for society and the state to understand the true value of forests and to implement the SFM in practice. Given the supersectoral importance of forests and their role in environmental protection, it seems advisable to urgently develop a forest strategy for Ukraine at the state level, which would serve as a national basis for substantiating intersectoral relations of the forest sector, regulating land cover issues on a landscape basis, and creating a legal basis for sectoral decisions that ensure the transition to SFM in Ukraine. Based on the results of the ClimaEast project study, the article substantiates the main directions of adaptation measures for Ukraine's lowland forests aimed at reducing their vulnerability, and outlines the strategic prerequisites for the transition to sustainable forest management in the country in the current conditions.

With the assistance of the World Bank, the project "Assessment of Climate Change Impacts, Opportunities and Priorities in Ukraine" was carried out in Ukraine, within the framework of which a list of key climate indicators was substantiated to assess the impact on the main forest-forming species of the current climate and climate conditions under projected climate change scenarios. Based on the EURO-CORDEX climate projections, the key climate indicators were calculated for past periods (1961-1990 and 1990-2010) and for three future time periods (2030, 2050, 2080) under two scenarios in the context of forestry regions according to the comprehensive forestry zoning of Ukraine.

For the main forest-forming species, the scale for assessing the satisfactory conditions of the climatic environment was improved - the grades of the scale were built taking into account changes in stock growth, potential productivity and bonita classes of forest plantations. To assess the climate impacts on forests, indicators of bioecological characteristics (tolerance amplitudes) of the 8 main forest-forming species of Ukraine were calculated. Using the cross-platform GIS Q-GIS, cartographic models of the dynamics of climatogenic conditions of forest growth in Ukraine were built.

The study examines the impact of climate change on Ukraine's forests at a detailed level. The information on the state of the country's forests was processed on the basis of the forest management database compiled by the Ukrderzhlisproekt production association for the latest state forest inventory of Ukraine as of 01 January 2011. Climate change impact assessments were conducted for forest plantations of 8 main forest-forming species: Scots pine (Pinus sylvestris L.), oak (Quercus robur L.), beech (Fagus sylvatica L.), European spruce (Picea abies (L.) H.Karst.), hanging birch (Betula pendula Roth.), black alder (Alnus glutinosa (L.) Gaertn.), hornbeam (Carpinus betulus L.) and common robinia (Robinia pseudoacacia). Forest plantations dominated by these main forest-forming species in Ukraine represent more than 86% of the land covered by forest vegetation.

The effects of climate change were assessed using the models of Professor Vorobyov and Academician Didukh based on projections of changes in climate indicators, including temperature, precipitation and a number of other indicators for the time period covering the baseline climate of 1961-1990, the current climate of 1991-2010 and the forecast until 2100.

Based on the calculations of thermal, continental, aridity/humidity and cryoclimate indices (winter severity), the study calculated and constructed maps of climate favourability for 8 main forest-forming species in Ukraine. The timeframe of the study is the climatological standard period (1961-1990), the current climate (1991-2010) and 3 forecast periods (2021-2040, 2041-2060, 2081-2100) for the RCP2.6, RCP4.5 and RCP 8.5 climate change projections.

A summary of the results is as follows:

Changes in the temperature regime

The climate scenarios show a long-term warming trend. In the near future (2021-2040), the temperature increase relative to the 2000 baseline is expected to be in the range of +0.5 to +1.5 °C. By the middle of the century (2041-2060), the increase will range from +1.0 to +2.0 °C under the RCP 2.6 projection and from +1.5 to +2.5 °C under the RCP 8.5 projection, with the temperature value under the RCP 4.5 projection falling in between. By the end of the century (2081-2100), the differences are much larger, with the RCP 2.6 projection still in the range of +1 to +2 °C, while with RCP8.5 they are in the range of +4 to +5 °C.

In 2021-2040, under both projections (RCP 4.5 and RCP 8.5), the largest relative changes in average temperature relative to the baseline are projected in the Carpathians, Polissya and the Left-Bank Forest-Steppe, and the smallest in southern Ukraine. A similar trend of relative changes will continue in the middle of the century (2041-2060).

Changes in the rainfall regime

Forecasting precipitation is more complex and is characterised by high uncertainty. While the general trend is towards an increase in annual precipitation, there is a redistribution of precipitation by season. In the winter months, precipitation tends to increase relative to the baseline across most of the country (except for some central and southern regions). In early spring, there is a relative decline in the near future (2020-2040 period), especially under RCP 2.6 and RCP 8.5, but not under RCP 4.5. In later periods, the decline in precipitation in early spring becomes smaller, and in higher RCPs, there is a relative increase. The summer months show a relative decrease in precipitation under all RCP projections, especially under the more pessimistic scenarios. The decline in precipitation during the growing season increases over time. In general, a slight increase in annual precipitation is projected. In 2021-2040, the largest relative changes in total precipitation are expected in Polissia and the Forest-Steppe, and the smallest in the south (Southern Steppe and Mountainous Crimea). Under RCP 8.5, the amount of precipitation will gradually increase relative to the current level in all regions, with the maximum changes projected for 2081-2100: by 53.9-92.7 mm (Polissya, Forest-Steppe and Mountainous Crimea).

Main impacts of climate change on forests and key areas of adaptation

The projected changes in temperature and precipitation will lead to a significant increase in evapotranspiration and a decrease in climate humidity. The effects of climate change, especially in the case of the RCP 8.5 projection, will generally have negative consequences for the condition, productivity and biodiversity of existing forest vegetation, as rapid changes in climate conditions may cause disruption of the homeostasis of forest ecosystems.

Given that the average age of forest plantations in Ukraine is about 60 years, the adaptive capacity of mature trees to rapid climate change will be relatively weak, as mature plants are less able to adapt to changes in environmental conditions than young plants.

Less rapid climate change is assumed in the case of RCP 4.5 projection, so the consequences for forest plantations are expected to be less dramatic. The general trends of projected changes are similar for both projections, with a time shift of about 20 years (the changes projected under RCP 8.5 are expected to occur 20 years later if RCP 4.5 is implemented).

It should be noted that the estimates of climate change impacts on forest vegetation were modelled for flat plateau conditions, without taking into account the impact of terrain and soil features on the redistribution of precipitation and temperature conditions. Since local conditions have a significant impact on the growth and condition of forest vegetation, special studies of the response of forest species to climate change, taking into account the influence of factors such as topography, hydrological and soil conditions, are required to account for them.

Changes in the growth conditions of the main forest-forming species will occur in all natural zones of Ukraine. In the Ukrainian Carpathians, climate change will lead to changes in natural vegetation formations at different altitudes, in particular, it will cause a shift in the height of vegetation belts and an increase in the upper limit of forest distribution, as well as a decrease in the area of spruce distribution and an increase in the area of beech, as a more thermophilic species. In the flat part of Ukraine, the projected climate change will cause a shift of climatic zones to the north - conditions for forest growth in the Forest-Steppe zone will become similar to those in the Steppe, and in the Steppe, conditions will become even more extreme for forest vegetation. Significant changes in climatic conditions are also expected in the Mixed Forest Zone (Polissya).

Almost all of the main forest-forming tree species studied are sensitive to the level of moisture availability, which is likely to decrease as a result of a redistribution of the precipitation regime, rising air temperature and, as a result, increased evapotranspiration. Trend changes in the main climate indicators (temperature and precipitation) within current and expected values are generally less dangerous than rapid changes in the frequency, amplitude and severity of extreme events, such as heat waves and droughts. Increased climate aridity and the growing variability and extremes of climate events will create dangerous stress conditions for forest vegetation. The projected pace and scale of climate change in large areas may exceed the natural migration and adaptive capacity of growing tree species. The most vulnerable are spruce and beech forests, for which the area with conditions suitable for their growth is likely to decrease significantly due to a decrease in climate humidity. The risk of deterioration and drying out of the stands is expected to be quite high. There has already been a significant deterioration of spruce stands in the Carpathians and northern Ukraine in recent years, caused by the current increase in climate aridity.

The decrease in climate humidity will also affect stands of other forest-forming species (pine, oak, ash, birch, alder and hornbeam), but the scale of the negative impact is expected to be smaller than for spruce and beech. The projected climate change will have the least impact on robinia, so we can expect an increase in the expansion of this species in forest plantations, especially in the central part of the country.

The impact of climate change on Ukraine's forests can manifest itself in the following ways: Changes in typical regional edaphic and microclimatic regimes of forest ecosystems; shifts in the boundaries of forest distribution, replacement of plant formation types; reduction of forest viability, their resistance to pests and diseases, and drying out of forests; mass reproduction and spread of entomopest and diseases; spread of phyto-invasions in forest phytocoenoses; increase in the number and scale of fires; reduction in carbon sequestration; decrease in productivity and marketability of forest stands; changes in the species composition of forests; reduction in natural biodiversity (primarily of rare, endemic and those growing on the edge of their range).

Data on the state of Ukrainian forests over the past decades confirm that climate change has already had an impact on the country's forests. This is evidenced by the fact that spruce and pine forests have been dying off on a large scale in recent years, waves of drying out of oak and ash plantations, and the expansion of robinia in forests.

Climate change is a very important, but not the only factor in the deterioration of the future state and increased vulnerability of Ukraine's forests. The next most important is the level of scientific justification of forest management regimes and the ability to implement proactive management decisions. In response to the challenges posed by the impact of climate change on Ukraine's forests, the government should improve the legislative framework, develop a national forestry programme and relevant practical guidelines that take into account regional climate change characteristics.

The national regulatory framework governing the distribution of forest reproductive material should be updated to allow for the promotion of migration and selection of appropriate origins, taking into account current and projected climate.

In view of long-term climate change projections, the timeframe for forestry planning at the regional level should be extended and cross-sectoral interactions should be taken into account when designing adaptation measures with the involvement of all stakeholders (e.g., when developing measures to improve fire safety in forests). Priority should be given to planning and implementing measures to prevent climate change rather than responding to it. The expected disturbances in forests induced by climate change are usually accompanied by secondary disturbances, such as outbreaks of pests and diseases, increased scale and frequency of forest fires, increased soil erosion, etc. Risks of secondary disturbances should be promptly minimised by rapidly cutting down damaged trees, controlling the development of forest pests and diseases, reducing the amount of forest combustible materials, and implementing other preventive forestry measures.

The key areas of climate change adaptation in forestry include:

- Maintaining permanent forest cover and increasing the forest cover of the territory by growing forest plantations of species resistant to current and future climate change.
- Optimisation of the land use structure, increase in the area of forests, forest belts for various purposes, and strengthening of cross-sectoral coordination.
- Development and implementation of a national forestry development programme, taking into account the priorities of climate change, low-carbon development and cross-sectoral cooperation.
- Development of regional systems of adaptation measures for forestry aimed at preserving forest biodiversity, increasing their resilience and productivity in the face of climate change.
- Promoting the replacement of energy-intensive products made of metal, concrete, plastic, etc. with wood products grown under sustainable (balanced) forestry and legally harvested.
- Improvement of adaptive management practices based on the principles of Climate Smart Forestry and close-to-nature forestry.
- Ensure adequate funding for climate change adaptation and mitigation measures, build capacity and strengthen the ability of forestry to plan and implement relevant measures.

- Improving technical support and forest infrastructure.
- Ensure effective scientific support for measures to prevent and adapt to climate change, conduct genetic research and improve reforestation based on improved and adapted reproductive material.
- Implementation of best practices for controlling the spread of harmful insects and forest diseases, modern technical means and technologies for rapid detection of forest fires, and provision of modern fire extinguishing equipment.
- Support for permanent forest monitoring and forest inventory to properly inform management decisions, taking into account climate change trends.
- Ensuring continuous staff training and raising awareness of climate change issues in forestry.

The results of the research clearly show that climate change will inevitably contribute to an increase in the level of fire danger in Ukrainian forests, an increase in the density of forest fires and an increase in forest burning. The fire hazard of forest areas will increase not only due to changes in fire weather elements, but also due to the emergence and development of pathological processes in forests as a result of prolonged droughts.

As part of the thematic research plan of the State Forest Resources Agency, in 2020-2021, URIFFM conducted research work "Developing a strategy for adaptation of forests and forestry of Ukraine to climate change". All research departments of the Institute were involved in this research, which allowed to comprehensively consider and work out the problems of adaptation. The draft document "Strategy for Adaptation of Forests and Forestry of Ukraine to Climate Change" was considered at the end of 2021 by the Scientific and Technical Council of the SFRA of Ukraine and was recommended for revision. The document is currently being finalised and discussed in the professional community. The latest version of the draft document was considered at a meeting of the WWF- Ukraine INSURE project working group on 2 August 2022. After finalisation and completion of the review, consideration and approval procedures, the document should be made available to the public.

2. Institutions working on future climate forecasting in Ukraine

In Ukraine, the Ukrainian Hydrometeorological Institute (UHMI), which is subordinated to the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine (https://uhmi.org.ua/), is working on future climate forecasting. The structure of UHMI includes the following research units:

- Department of Agrometeorological Research (until November 2016)
- Department of atmospheric monitoring
- Department of Hydrological Research
- Department of Hydrochemistry
- Department of Radiation Monitoring of the Natural Environment
- Department of Applied Meteorology and Climatology
- Department of Technical Facilities Development, Metrology and Standardisation
- Department of Systemic Hydrometeorological Research
- Division of Climate Research and Long-Range Weather Forecasts
- Department of Atmospheric Physics
- Laboratory for the Study of the Impact of Climate Change on Water Resources
- Marine Department (Sevastopol) (until April 2014)
- Field Experimental Meteorological Base (Zhovtneve village, Dnipro region)
- Bohuslavska field hydrometeorological base
- Motor ship "Georgiy Gotovchits"

Scientists of the Department of Applied Meteorology and Climatology of the UHMI work with modern models and scenarios of climate change and have experience in localising and scaling modelling results for the conditions of Ukraine and its individual regions.

Sources of information

The main sources of available information on assessing the vulnerability of forest ecosystems and tree species to climate change and sources of information on adaptation strategies are presented in Annex A.

Summary

1. Research on the impact of climate change on forests in Ukraine began in the 90s of the last century, when scientists from the Ukrainian Research Institute of Forestry and Agroforestry named after H.M. Vysotsky (URIFFM) were involved in an international US programme to study the impact of climate change on the ecological and economic systems of 55 countries, including Ukraine.
2. Further research on the impact of climate change on the forests of Ukraine was carried out by Ukrainian scientists on a proactive basis within a number of international cooperation projects with the European Forestry Institute (EFI) and scientists from different European countries, forestry and climate experts from the United States (USAID, NEESPI, USA-UA Climate Change Initiative), the Food and Agriculture Organisation of the United Nations (FAO), the Global Water Partnership (GWP), the European Union (EU ClimaEast, IIASA), the World Bank and the World Wide Fund for Nature (WWF).
3. Within the framework of this international cooperation, scientific and methodological approaches to assessing the impact of climate change on forest ecosystems of Ukraine were developed, which are harmonised with the methods recommended by the Intergovernmental Panel on Climate Change (IPCC), forest-ecological, phytoindicative and biophysical models were improved to identify forest vulnerability, principles of integration of forest and climate data and methods of conducting comprehensive geospatial analysis of forest and climate data using modern geo-referenced data were developed.
4. Quantitative and spatial estimates of the impact of climate change on the forests of Ukraine were obtained using the information on climate indicators of the baseline climate period, climate models and climate scenarios (A1B, EURO-CORDEX scenarios), as well as available data from the forest management database "Forest Fund of Ukraine" as of 01.01.1996 (studies conducted before 2015), and as of 01.01.2011 (studies conducted after 2015).
5. The results of the assessment of the state and vulnerability of forests to climate change obtained in the framework of international studies are focused on the national level and are accordingly displayed on small-scale maps that are suitable for overview illustrations, but their scale is not sufficient to reflect regional specifics of forest and climate assessments.
6. To properly assess the vulnerability of Ukraine's forests to climate change, it is necessary to ensure access to up-to-date forestry geospatial information that presents the forestry characteristics of individual forest stands. The absence of a forest geographic information system in the forestry sector significantly hinders assessments of the impact of climate change on forest ecosystems.
7. Free access to foreign models of forest dynamics due to climate change and climate change scenarios creates good preconditions for research on

climate change impacts on Ukrainian forests, but it is necessary to ensure verification, calibration and validation of models, which is impossible without actual data on forest inventory and monitoring by ecoregion and forest vegetation type (forest type) and scientific personnel capable of performing such work.

8. The state order for research on climate change and forests was formed in 2020 as part of the thematic research plan of the State Forest Resources Agency (R&D topic "Developing a Strategy for Adaptation of Forests and Forestry of Ukraine to Climate Change"). The results are being discussed in the professional community and will be available after the review, consideration and approval procedures are completed.

Annex A. Information on projects and initiatives to assess the impact of climate change on forests and develop adaptation measures for the forestry sector in Ukraine

№	Project name	Duration	Participants	Main results	Sources of information
1.	US Country Studies Program	1995-2000	Experts from 55 countries, from Ukraine - scientists of URIFFM	The basic methodological framework for assessing the vulnerability, mitigation and adaptation of forests to climate change is defined	https://doi.org/10.1007/978-94-009-0303-6_1; https://link.springer.com/chapter/10.1007/978-94-017-3653-4_15
2.	Scenario analysis and prognostication of forest condition dynamics in the context of anthropogenic changes of environment - SCEFORMA	1998-2001	Scientists from 4 countries and the European Forestry Institute, from Ukraine - scientists from URIFFM	To quantify the prospects for timber production in the Czech Republic, Poland, Hungary and Ukraine, the degree of sustainability under different scenarios of forest growth and harvesting volumes, as well as the overall impacts of forest vulnerability to climate change and the impacts on future timber supply.	https://efi.int/projects/sceforma-scenario-analysis-sustainable-wood-production-under-different-forest-management ; Buksha IF, Pasternak VP 2001. Forecasting the dynamics of forest resources under anthropogenic environmental changes. Scientific Bulletin of the National Academy of Sciences of Ukraine. Issue 39. Forestry. K. 157-162.

№	Project name	Duration	Participants	Main results	Sources of information
3.	USA-UA Climate Change Initiative	2001-2002	USAID experts, from Ukraine - experts from URIFFM	Assessment of the contribution of Ukraine's forestry to climate change mitigation, projections of carbon sequestration in Ukrainian forests, training courses on "Carbon sequestration in agriculture and forestry" for senior ministry officials, natural resource specialists, representatives of industrial groups and NGOs	Buksha IF 2002. Contribution of the forestry of Ukraine to reducing the risk of climate change // Some aspects of global climate change in Ukraine: a collection of articles. Climate Change Initiative. K. 132-148.
4.	Regional Aspects of Climate-Terrestrial-Hydrologic Interactions in Non-boreal Eastern Europe	2008-2009	Experts from the non-boreal zone and the Black Sea region, IIASA, from Ukraine - scientists from URIFFM and Odesa State Environmental University	The sensitivity of global climate and regional biophysical models for assessing the impact of climate change on Ukrainian forests is investigated, and methods for modeling land use change are developed.	https://link.springer.com/chapter/10.1007/978-90-481-2283-7_16 https://doi.org/10.1007/978-90-481-2283-7 ;

№	Project name	Duration	Participants	Main results	Sources of information
5.	Climate change impact on forest ecosystems and the development of adaptation strategies in forestry of Ukraine	2009-2010	FAO experts from 15 countries under the coordination of FAO experts from Hungary, from Ukraine - scientists of URIFFM	A scientific publication was prepared on the impact of climate change on forest ecosystems, summarizing the results of scenario analysis and forecasting of forest use under different climate change scenarios, considering possible adaptation measures in forestry, and identifying the state and prospects of scientific research on climate change and forest management.	https://infoclimate.org/wp-content/uploads/2009/02/Forestclimatechange_EECA.pdf ; http://fasu.nltu.edu.ua/index.php/nplanu/article/view/482 Buksha I. 2010. Study of climate change impact on forest ecosystems, and development of adaptation strategies in forestry of Ukraine. Climate Change Impacts on Forest Management in Eastern Europe and Central Asia: Dimensions, impacts, mitigation and adaptation policies. Forests and Climate Change Working Paper 8. Ed. Csaba Matyas. FAO. 157-179. Buksha IF Climate change and forestry of Ukraine // Scientific works of the Forestry Academy of Sciences of Ukraine: collection of scientific works - Lviv: RVV NLtU of Ukraine. - 2009. - Issue 7. - P. 11-17.
6.	Integrating Climate Change into Vulnerable Ecosystems Management: natural parks in wetlands and forest areas (Ukraine)	2013	Experts of Association VERSeau Development (France), Ukrainian Society for Birds Protection (Ukraine), the Pyrenees National Park	Based on the RCMs' ensemble of models, the dynamics of climate indicators for the period 2011-2040 was forecasted under the A1B scenario. The ways of local adaptation to climate change in	https://www.researchgate.net/publication/272476391

№	Project name	Duration	Participants	Main results	Sources of information
			(France), scientists of UHMI, URIFFM (Polissya branch)	the management of vulnerable ecosystems (wetlands and forest protected areas) in Ukrainian Polissya, in particular, ways to increase the fire resistance of forests, are identified.	
7.	Assessment of drought impact on forest ecosystem	2013-2015	Scientists from 4 countries and experts of the Global Water Partnership, from Ukraine - scientists of the URIFFM	Assessment of the impact of droughts on forests in Bulgaria, Lithuania, Slovenia and eastern Ukraine, development of a system of adaptation measures for forestry to mitigate the negative effects of droughts.	https://www.researchgate.net/publication/289533828 ; Buksha I., Pyvovar T., Buksha M., Pasternak V. Impact of drought on the forest vegetation in North-Eastern Ukraine: the long-term prognoses and adaptation measures. Silva Balcanica. 20(3)/2019. P. 27-38.
8.	Pathways to Healthy Forests: Strengthening the resilience, viability and adaptive capacity of forests in the border regions of Ukraine and Slovakia	2014-2020	NGO "Agency for the Promotion of Sustainable Development of the Carpathian Region FORZA" (Ukraine), SE "Uzhhorod Forestry"	Proven ways to care for and protect forest plantations from climate change	https://forza.org.ua/sites/default/files/publikacia_osvedcene_postupy_web.pdf

№	Project name	Duration	Participants	Main results	Sources of information
			(Ukraine), State Forests of Tatran National Park (Slovakia), SE "Vyhoda Forestry" (Ukraine), Forests of Spisska Bela (Slovakia), Forests of Kežmarok (Slovakia)		
9.	Preparation of the Intended Nationally Determined Contribution (INDC) of Ukraine for the LULUCF sector and ensuring the INDC's compliance with Association Agreement provisions	2015	Experts from UNDP, USAID, EU Clima East and Ricardo-AEA, from Ukraine - scientists from URIFFM	A methodology for determining INDS was developed, sectoral climate change mitigation scenarios were validated until 2030, climate change mitigation scenarios were prioritized, and proposals for a draft Nationally Determined Contribution for the land use and forestry sector were prepared, taking into account greenhouse gas emission and	http://climategroup.org.ua/wp-content/uploads/2009/06/2015.08.12-INDC.pdf

№	Project name	Duration.	Participants.	Main results	Sources of information
				absorption scenarios, national development strategies, and the EU-Ukraine Association Agreement.	
10.	Assessment of vulnerability of Ukraine's flatland forests to climate change	2016	Experts from UNDP, USAID, EU Clima East and DAI Europe, from Ukraine - scientists from URIFFM	The article substantiates the choice of global climate and regional biophysical models for assessing the impact of climate change on Ukrainian forests, assesses the current impact of climate change on the main forest-forming species of lowland forests of Ukraine and models future impacts with a forecast of vulnerability of lowland forests under the climate change scenarios of the Intergovernmental Panel on Climate Change (IPCC).	https://europa.eu/capacity4dev/climaeastpolicyproject/book/31088/print; A. Shvidenko, I. Buksha, S. Krakovska and P. Lakyda. 2017. Vulnerability of Ukrainian Forests to Climate Change Sustainability 2017, 9, 1152; doi:10.3390/su9071152 Published: June 30, 2017 Multidisciplinary Digital Publishing Institute in Basel, Switzerland. MDPI: 36. https://www.mdpi.com/2071-1050/9/7/1152; Shvydenko A.Z., Buksha I.F., Krakovska S.V. Vulnerability of Ukrainian forests to climate change: monograph. Kyiv, Nika-Center: 2018. 184 c.

№	Project name	Duration.	Participants.	Main results	Sources of information
11.	Development of the GHG emissions inventory in the forestry sector in order to improve national reporting of Ukraine in accordance with the requirements of the UN FCCC and the Kyoto Protocol	2016	Experts from EU Clima East, IIASA, and Ukrainian scientists from URIFFM	Ways to improve the quality of carbon assessment in certain categories of the forest sector and for the forest sector as a whole are identified, recommendations for data quality control and quality assurance methods are developed to reduce uncertainty in the greenhouse gas inventory in the forest sector of Ukraine	https://europa.eu/capacity4dev/climaeastpolicyproject/wiki/clima-east-presents-recommendations-improvement-national-ghg-inventory-forestry-and-harvested
12.	Low Emission Development Strategy for Land Use and Forestry Sector of Ukraine (within the framework of USAID "Municipal Energy Reform Project")	2017	USAID experts, from Ukraine - scientists from URIFFM	A catalog of policies and measures (P&Ms) to ensure low-carbon development in the land use and forestry sector was developed, and the impact of policies and measures on reducing emissions and increasing carbon sequestration by 2050 was forecasted.	https://unfccc.int/sites/default/files/resource/Ukraine_LEDS_en.pdf

№	Project name	Duration.	Participants.	Main results	Sources of information
13.	Priorities for the prevention of climate change and adaptation to climate change in agriculture, forestry and fisheries of Ukraine and the action plan until 2030	2017-2018	FAO experts, from Ukraine - experts in the field of agriculture, forestry (scientists of the Ukrainian Research Institute of Agricultural and Forestry Sciences) and fisheries.	The results of vulnerability and risk assessments related to the impact of climate change on forests and forestry in Ukraine are summarized. The main climate change mitigation measures aimed at reducing emissions and increasing greenhouse gas sequestration in forestry are identified and priority areas for climate change adaptation in the forestry sector of Ukraine are proposed. A draft plan for the implementation of priority measures to adapt forestry to climate change has been prepared. A draft Strategy for Prevention and Adaptation to Climate Change in Agriculture, Forestry,	https://zakon.rada.gov.ua/laws/show/1363-2021-%D1%80#Text ; Tkach V.P., Buksha I.F. Strategic directions of adaptation to change climate in the forestry of Ukraine. The main problems and trends of further development of forestry in the Ukrainian Carpathians: Proceedings of the international scientific and practical conference. - Ivano-Frankivsk. Nair 2018. C. 128-139; Buksha IF, Pasternak VP Strategic directions of prevention and adaptation to climate change in the field of forestry of Ukraine / Climate adaptation in Ukraine: state, challenges and prospects (dedicated to the World Climate Protection Day): Materials of the First All-Ukrainian Scientific and Practical Conference. [Kherson, May 15, 2020]. Kherson: "KSAU", 2020. C.11-16.

№	Project name	Duration	Participants	Main results	Sources of information
				Hunting and Fisheries of Ukraine for for the period up to 2030, which was the basis for the Strategy for Environmental Security and Adaptation to Climate Change for the period up to 2030 (approved by the Cabinet of Ministers of Ukraine on October 20, 2021, No. 1363-p).	
14.	German-Ukrainian Agri Policy Dialogue on development of Ukrainian forest sector policies and measures on mitigation and adaptation to Climate Change	2019-2020	APA experts, scientists of URIFFM	The status quo of measures to prevent and adaptation to climate change in the forestry sector economy of Ukraine and proposals for Implementation of the Strategy for Adaptation to Change climate of agriculture, forestry, hunting and of Ukraine's fisheries by 2030	Buksha Ihor. Status quo of measures to prevent and adapt to climate change in the forestry of Ukraine and proposals for the implementation of the Strategy for Adaptation to Climate Change of Agriculture, Forestry, Hunting and Fishing of Ukraine until 2030 / Agricultural Policy Report. - German-Ukrainian Agricultural Policy Dialogue. APD/APB/12/2019. - 22 p.

№	Project name	Duration	Participants.	Main results	Sources of information
15.	Assessing the Impacts, Opportunities and Priorities from Climate Change in Ukraine	2020-2021	Experts from the World Bank, from Ukraine - scientists from URIFFM	The vulnerability to climate change of the most common forest-forming tree species in Ukraine (Scots pine, common oak, European spruce, forest beech, hanging birch, black alder, common ash, hornbeam, white fir) was assessed on the basis of regional climate change models EURO-CORDEX and biophysical models by Prof. Vorobiev and Prof. Didukh.	https://documents.worldbank.org/en/publication/documents-reports/documentdetail/893671643276478711/ukraine-building-climate-resilience-in-agriculture-and-forestry ; Buksha IF, Pivovar TS, Pasternak VP, Bondaruk MA, Tselishchev OG Assessment of the vulnerability of Ukrainian forests based on regional climate change models EURO-CORDEX. Proceedings of the International Scientific and Practical Conference "Forestry Science: State, Problems, Prospects for Development" (URIFFM - 90 years) (June 23-24, 2021, Kharkiv). Kharkiv. URIFFM. 2021. C. 160-162.
16.	Develop a Strategy for Adaptation of Forests and Forestry of Ukraine to Climate Change	2020-2021	Scientists of URIFFM	The Strategy for Adaptation of Forests and Forestry of Ukraine to Climate Change defines the main tasks of: - preservation of forest genetic resources; - protection and conservation of forests;	Scientific report of URIFFM on the topic №1 "Development of the Strategy for Adaptation of Forests and Forestry of Ukraine to Climate Change". Kharkiv, 2021.

№	Project name	Duration.	Participants.	Main results	Sources of information
				-priority research areas; -training of specialists; - financial support and economic incentives. An action plan for the implementation of the Strategy for the period 2022-2025 has been drawn up.	
17.	INSURE: Putting nature-based solutions on the Reform Agenda in Ukraine	2021	WWF-Ukraine experts, scientists of URIFFM	Established best nature-based practices aimed at increasing carbon dioxide sequestration and carbon storage in forests to prevent and climate change adaptation.	https://wwf.ua/our-work/nbs/

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