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ASSESSMENT OF RISKS AND VULNERABILITIES OF AGRICULTURE TO CLIMATE CHANGE IN UKRAINE

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LIST OF ABBREVIATIONS AND ACRONYMS

AD – atmospheric depressions
AR5 – Fifth Assessment Report of the IPCC
AR6 – Sixth Assessment Report of the IPCC
CMIP5 – Coupled Model Intercomparison Project Phase 5
CMIP6 – Coupled Model Intercomparison Project Phase 6
CID – Climatic Impact Driver
ETCCDI – Expert Team on Climate Change Detection and Indices
EURO-CORDEX – European Regional Climate Modelling Project
E-OBS – European Observational gridded dataset
FAO – Food and Agriculture Organisation of the United Nations
GCM – Global Climate Model
GSL – Growing Season Length
HTCS – Selianinov's hydrothermal coefficient
IPCC – Intergovernmental Panel on Climate Change
CMU – Cabinet of Ministers of Ukraine
RCP – Representative Concentration Pathways
SU – (Summer Days Index) number of days with $T_{max} > 25°C$
UAAS – Ukrainian Academy of Agrarian Sciences
WMO – World Meteorological Organisation
GDP – Gross domestic product
UN – United Nations
GHG – Greenhouse Gases
EU – European Union
APENA 3 – international technical assistance project "Strengthening the capacity of regional and local authorities to implement and enforce EU legislation in the areas of environmental protection, climate change mitigation and infrastructure project development" implemented by the European Union Delegation to Ukraine
RCM – Regional Climate Model
NASA – National Aeronautics and Space Administration (US government agency)
ENSO – El Niño-Southern Oscillation
FWI – Fire-Weather Index
JRC – Joint Research Centre (European Commission's Joint Research Centre)
LISCOAST – Large Scale Integrated Sea-level and Coastal Assessment Tool (https://data.jrc.ec.europa.eu/collection/liscoast) A large-scale tool for assessing sea level and coastal areas.

SCOPE AND PURPOSE

The summary report on the assessment of risks and vulnerabilities of agriculture to climate change (hereinafter referred to as the Report) contains an analysis of the impact of climate change on the development of agriculture, an assessment of threats and risks at the regional (zonal) and local levels, as well as an assessment of sensitivity and vulnerability, particularly in the areas of crop production and animal husbandry. Within the agricultural sectors, the nature of the risks and their potential impact are disclosed, and recommendations and adaptation measures are presented.

These measures are dynamic and may be supplemented in the event of a repeat risk and vulnerability assessment, as well as based on the results of identified changes, both positive and negative, during the assessment of the impact of climate change on agriculture in Ukraine.

The assessment of risks and vulnerabilities of agriculture to climate change and the preparation of a summary report were carried out in accordance with paragraph 1 of part two of Article 13 of the Law of Ukraine "On the Fundamentals of State Climate Policy" and paragraph 22 of Goal 3 "Adaptation to climate change, increasing resilience and reducing risks associated with climate change" of the Operational Plan of Measures for the Implementation of the 2024–2026 of the Strategy for the Formation and Implementation of State Policy in the Field of Climate Change for the Period until 2035, approved by Order of the Cabinet of Ministers of Ukraine No. 483-r of 30 May 2024.

The report contains key provisions reflecting the results of the analysis of the impact of climate change on agriculture, as well as approaches to assessing vulnerability, risks and adaptation solutions:

- identification of potential climate threats and risks and their possible consequences for plant growth and development, crop yields, animal health and resource availability;
- assessment of future climate threats based on climate scenarios with moderate (RCP 4.5) and intense (RCP 8.5) warming;
- assessments of the vulnerability of crop production and animal husbandry sectors, taking into account regional differences in the formation of climate risks and local environmental and economic factors;
- approaches to quantitative analysis of the impact of climate change on the productivity, resilience and adaptive capacity of the agricultural sector;
- recommendations and measures for adaptation and mitigation of negative impacts, increasing resilience and strengthening the adaptive capacity of agro-industrial production to climate change.

The terms and definitions used in the Report are defined by the laws of Ukraine and the legal and regulatory acts in the field of climate change (state climate policy), environmental protection, ecology and animal husbandry.

1. INTRODUCTION

Agriculture in Ukraine is traditionally based on two leading subsectors: crop production and animal husbandry. Official statistics from the State Statistics Service show that in 2023, crop production accounted for 81.1% of gross agricultural output (in constant 2021 prices), while animal husbandry accounted for 18.9%[1].

Global and regional climate change is already affecting production conditions in agriculture, as over the past six decades, the average temperature in Ukraine has risen by 0.4–0.6 °C per decade, and hot days, droughts and seasonal rainfall redistribution are becoming more frequent, especially in the south and east of the country[2] . In the agricultural sector, this leads to lower productivity, deterioration of soil water balance and increased risk of erosion, which causes fluctuations in crop yields and directly affects the export potential and incomes of farmers. That is why *the Strategy for the Formation and Implementation of State Policy in the Field of Climate Change until 2035 and its operational plan for 2024–2026*, approved by the CMU order of 30 May 2024№ 483-r[3] , require all sectors of the economy, and above all the agricultural sector, to start with a comprehensive assessment of risks and vulnerabilities as a starting point for planning adaptation measures to climate change.

The first thorough assessment of the impact of climate change on the agricultural sector was provided in the World Bank report "Ukraine: Building Climate Resilience in Agriculture and Forestry" (2021)[4] , which used the same Euro-CORDEX/CMIP5 regional climate projections as this study. However, its focus was limited to the biophysical impact of temperature and precipitation on the yield of five key crops. In particular, under the RCP 8.5 scenario, average yield declines of -23% and -21% were modelled for maize and sunflower by 2050, while wheat showed growth potential. Biophysical modelling based on daily data on temperature and relative humidity, precipitation and wind speed under two scenarios also showed that, provided adaptation measures are implemented, in particular optimal irrigation, the total value of the five crops considered could increase by 29% by 2030 and by 56% by 2050 compared to 2010.

At the same time, the World Bank report did not apply the recently published methodological approaches of the Intergovernmental Panel on Climate Change (IPCC, 2022) to assess climate risks and vulnerability based on Climatic Impact Drivers (CID), and therefore did not consider comprehensive hazard categories and extreme indicators (heat waves, droughts, heavy rainfall, strong winds, etc.) in order to plan specific types of

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[1] https://www.ukrstat.gov.ua/druk/publicat/kat_u/2023/zb/11/year_23_e.pdf
[2] https://www.climatecentre.org/wp-content/uploads/RCCC-ICRC-Country-profiles-Ukraine.pdf
[3]https://www.kmu.gov.ua/npas/pro-skhvalennia-stratehii-formuvannia-ta-realizatsii-derzhavnoi-polityky-u-sferi-zminy-klimatu-na-period-t300524
[4]https://documents.worldbank.org/en/publication/documents-reports/documentdetail/893671643276478711/ukraine-building-climate-resilience-in-agriculture-and-forestry

adaptation measures. Therefore, the current document logically continues the previous work, integrating the CID methodology of the IPCC and extending the analysis to a complete climate risk formula and vulnerability index, taking into account the sensitivity of the two main sectors of agriculture, namely crop production and animal husbandry, to each of the 32 CIDs in five main categories: heat and cold, wet and dry, snow, wind and coastal.

Crop production is one of the main elements of agriculture in Ukraine. It shapes food, economic, environmental and energy security, ensures the development of technologically related industries, and provides the socio-economic foundations for the development of the country and individual territories. In Ukraine, the agricultural sector accounts for an average of 16% of GDP and about 40% of export earnings. For example, in 2021, Ukraine harvested more than 100 million tonnes of grain, industrial and leguminous crops. According to the results of the harvest of crops such as corn, winter wheat, sunflower, barley and rapeseed, Ukraine accounted for between 3.5% (corn) and 30.5% (sunflower) of global production, allowing the country to consistently rank among the top 10 global exporters of these products[5] .

After the full-scale invasion of Russian troops into Ukraine in February 2022, the volume of cultivation of major agricultural crops was significantly reduced. As a result of military operations in the south and east of Ukraine, sowing areas in the Donetsk, Kherson, Luhansk and Zaporizhzhia regions were not sown. Almost all regions were forced to reduce their sowing areas compared to 2021, with the largest reductions in the Mykolaiv and Kharkiv regions, namely 1.5 and 2.15 times, respectively. At the same time, the area under cultivation in the west of the country increased by almost 30%. However, as these areas are relatively small, this increase did not have a significant impact on the total gross harvest.

In 2023, there was a general trend towards a reduction in barley acreage of between 3% and 34% compared to 2021. This estimate does not take into account data for the Kherson region, where the occupation led to a 30-fold reduction in acreage. At the same time, in the west of the country, mainly in the Khmelnytskyi and Chernivtsi regions, there was an increase in the area under cultivation: compared to 2021, the increase ranged from 12% to almost 40%. However, their share in the gross harvest remains insignificant. In 2024, it was possible to stabilise the production of major crops, and for some of them, in particular soybeans, a significant increase was achieved.

Despite the military actions in the south and east of the country, Ukraine remains one of the key producers of agricultural products in the world[6]. According to the results of 2024, Ukraine's share in the global production of sunflower, rapeseed, barley, wheat and

[5] https://www.fas.usda.gov/sites/default/files/2022-04/Ukraine-Factsheet-April2022.pdf
[6] https://www.statista.com/statistics/1379651/ukraine-global-agricultural-production-share-by-product/

corn was 24.7%, 4.2%, 3.7%, 2.8% and 2.2%, respectively. Thus, Ukrainian agriculture, and crop production in particular, plays a significant role in ensuring both the economic stability of the state and regional and global food security.

The structure of agricultural production in Ukraine by crop type as of 2021 was as follows: 26.2% – cereals and legumes; industrial crops – 22.5%; 1% – vegetables; up to 4% – fruit and fodder crops. This distribution was determined by both the availability of natural resources and demand on the international market. Grain cultivation occupies a leading position in crop production. Grain crops in Ukraine occupy 45–50% of the total sown area. In terms of acreage, the main grain crops are wheat, rye, triticale, barley, oats, millet, corn, and sorghum.

Winter wheat is most commonly cultivated in Ukraine, with spring wheat being grown to a much lesser extent. The main growing areas are located in the steppe and forest-steppe zones, mainly on chernozem soils. On average, approximately 23% of arable land is sown. The gross harvest in 2024 amounted to 2.8% of the world's total (8th place in the world and 2nd in Europe, after France).

The second important cereal crop is *barley*, which is considered one of the most undemanding crops, early maturing, drought-resistant, with a short growing season (60-90 days). Due to these characteristics, it is grown in the northern regions of the steppe and forest-steppe, in the foothills and mountainous regions of the Carpathians. In years when winter wheat freezes, barley is sown instead of damaged crops.

Corn is the leader among grain crops in Ukraine, requiring warmth and fairly high-quality soil. Corn for grain is cultivated in the steppe zone. Corn crops have a fairly high yield > 60 cwt/ha and large acreage, which allows for significant gross harvests, accounting for 2.2% of the world's total in 2024 (6th place in the world and 1st in Europe). This accounts for approximately 23% of agricultural exports.

Legumes include beans, soybeans and peas, which are important food and fodder crops. They are mainly grown in Polissya and the forest-steppe zone. The main legume crop is *soybeans*. It is a moisture-loving, soil-demanding crop that is intolerant to arid conditions. Over the past 25 years, the area under cultivation has increased 20-fold, and in the last three years alone, it has increased one and a half times. In the steppe and forest-steppe zones, soybeans are grown on irrigated soils, especially in the Cherkasy and Vinnytsia regions. The gross harvest accounts for approximately 1% of the global harvest (9th place in the world and 1st in Europe). Soybeans are mainly used for oil production and as a substitute for animal protein.

The main technical crops in Ukraine are sunflower, rapeseed and sugar beet, which are mainly used as raw materials for the food and light industries. *Sunflower* crops occupy approximately 22% of all cultivated areas in Ukraine and are grown in the steppe zone and in the south of the forest-steppe zone on chernozem soils. The largest areas of cultivation are in the Dnipropetrovsk, Zaporizhzhia, Kirovohrad and Kharkiv regions. Ukraine accounts for 28% of world production (2nd place in the world).

The second most important technical crop is *rapeseed*, whose acreage is constantly growing and accounts for about 1.7% of arable land. It is a moisture-loving and heat-loving plant that is grown in the western part of the forest-steppe zone: in the Khmelnytskyi, Ternopil, Lviv, and Vinnytsia regions. Rapeseed is used to produce industrial oil and relatively cheap biofuel, as well as animal feed. *Sugar beet* is another important industrial crop. Due to the significant labour and energy intensity of production, there has been a trend towards a reduction in the cultivation of this crop in recent years. It is mainly cultivated in the forest-steppe zone, covering approximately 1.1% of arable land, with half of this area located in the Vinnytsia, Khmelnytskyi, Kharkiv and Ternopil regions. Ukraine has a fairly high yield of more than 450 cwt/ha, and in terms of gross harvest, the country ranks in the top twenty with 1.9 million tonnes (2024) and third in Europe (after France and Germany).

Potato crops have remained virtually unchanged over the past decades and occupy approximately 5% of arable land, with a current yield of 161 centners per hectare. This plant is quite undemanding in terms of growing conditions and is therefore cultivated throughout almost the entire country. The largest areas are concentrated in Polissya and Prykarpattya. The gross harvest accounts for 6% of the world's total (1st place in Europe and 4th in the world).

Vegetable cultivation is mostly azonal in nature. The highest concentration of vegetable crops is found on farms located around large cities to provide the population with fresh produce. The most common crops are tomatoes, cucumbers, onions, table beets, etc. Melons, watermelons, and pumpkins are among the melon crops. Thus, cucumbers, carrots, table beets, and cabbage are mainly grown in Polissya, cucumbers, tomatoes, and onions in forest-steppe, and tomatoes, peppers, and eggplants in Steppe. Ukraine is one of the world leaders in terms of gross production of vegetables and melons and yield levels.

Important branches of crop production are horticulture and viticulture. The largest apple and pear orchards are located in the Forest-Steppe and Polissya regions, while cherry, plum, apricot, cherry, peach, and nut orchards are located in the steppe zone. In the central and southern regions of Ukraine, cherries, nuts, apricots and other fruit trees grow in planted forest belts, along motorways and in forests. Recently, the number of fruit tree plantations has increased in private households, especially around cities. Large vineyards are located in the south of the country and in Zakarpattia. About 80% of vineyards are concentrated in the Kherson and Odesa regions and the occupied Crimea.

Before the full-scale invasion of Ukraine, as of 01.01.2022, agricultural land in Ukraine amounted to 41,310.9 thousand hectares (68.5% of the total land area), as a rule, more than 90% of agricultural crops are grown in natural conditions due to the fact that Ukraine has about 25% of the most fertile black soil in the world, which, in a temperate climate, has given Ukrainian producers significant natural competitive advantages and unique agricultural potential. However, the climate changes that began at the end of the 20th century have had a significant impact on crop production in Ukraine. Over the past 20 – 25 years, the number of droughts has increased significantly, not only in the southern regions, but also in the central and eastern regions. Since 2000, as a result of climate change, there have been prolonged periods of drought, which have been quite intense and, accordingly, have had negative consequences. For example, the drought of 2003 reduced the gross grain harvest in Ukraine to 22 million tonnes and made exports completely impossible (that year, grain even had to be imported). The drought of 2007 also caused significant damage to the agricultural sector, when a lack of moisture was recorded in two-thirds of the country in the spring. In recent years, there have been significant droughts, particularly in 2010, 2015, 2017, and 2019–2020. Due to rising temperatures in winter, snowcover is disappearing, which led, for example, to the loss of 568,200 hectares of winter crops in 2020 as a result of insufficient moisture in the soil (Buono, 2021; Lazareva, 2021; Nalau & Verrall, 2021). It should be noted that in recent years, almost every year, one region or another has suffered from drought or other climatic phenomena. For example, in 2024, there was no rainfall in the central regions from July to September, which led to a significant decrease in the yield of corn and soybeans, almost by half. It is believed that these natural phenomena in Ukraine tend to spread to the northern and western regions, and given that they can occur at different stages of plant growth, they can affect the entire range of crops grown.

Cattle breeding is a branch of agriculture that deals with the breeding and use of farm animals. In Ukraine, animal husbandry is represented by several areas, namely: cattle breeding (breeding and use of livestock), pig breeding, sheep breeding, horse breeding, goat breeding and other areas that are smaller in terms of production and significance. Animal husbandry, and cattle breeding in particular, perform important socio-economic functions, namely:

- providing people with food;
- providing raw materials for the food, textile and pharmaceutical industries;
- providing organic fertilisers for the agro-industrial complex;
- providing draught power when necessary.

Cattle breeding dominates the structure of animal husbandry in Ukraine: livestock breeding (10.6%) and milk production (5.7%) together accounted for the lion's share of animal products according to the Statistical Yearbook of Ukraine – 2023[7], confirming its significant role in the country's food security. It should be noted that due to the Russian invasion and ongoing military actions, Ukraine's agro-industrial sector has suffered direct losses amounting to US$8.7 billion, while indirect losses are estimated at US$40.3 billion. According to FAO data, the war has led to a decline in livestock numbers and production, particularly in animal husbandry, with losses estimated at US$0.98 billion by the end of 2024[8].

As of January 2024, the number of livestock in all categories of farms was 2,233,600, which is 3.3% less than in January 2023. The distribution of livestock is as follows: 71% is concentrated in private households and 29% in agricultural enterprises[9] .

Due to the dominant role of cattle breeding in Ukraine's animal husbandry sector, it is precisely this sub-sector of animal husbandry that needs to be assessed first in terms of the impact of climate change. In addition, the assessment only considered the stable-pasture type of livestock, in which the impact of environmental parameters will be more significant and even decisive. In this report, the term "animal husbandry" is used exclusively to refer to livestock, as the most representative and resource-sensitive sub-sector in the context of climate change impacts. Other areas of livestock farming were not considered in this study.

It is known that climate change is already having and will continue to have a significant impact on natural and artificial ecosystems, the population and various areas of its activity. In this regard, it is necessary to conduct an expert assessment of the degree of vulnerability of economic sectors in order to use the results to reduce negative impacts, including on agriculture.

The approaches to assessing the impact of climate change in this study were based on the methodological recommendations approved by the Ministry of Environmental Protection and Natural Resources of Ukraine[10] with certain additions and updates that were applied during the development of Climate Change Adaptation Strategies for three pilot regions in the EU APENA 3 project, presented several times, discussed in professional circles and agreed upon by the Ministry of Environment before the start of this study at the first webinar on 8 January 2025.

To assess ***the vulnerability of*** any sector of the economy, ecosystem or asset at the initial stage, it is essential to determine ***the sensitivity*** of that object to the impact of climate change, i.e. to determine the extent to which the system or object is negatively (or positively) affected by climate change. ***Sensitivity*** is a property of the object itself and

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[7] https://www.ukrstat.gov.ua/druk/publicat/kat_u/2023/zb/11/year_23_e.pdf
[8] https://kse.ua/wp-content/uploads/2023/09/June_Damages_UKR_-Report.pdf
[9] https://avm-ua.org/uk/post/tendencia-skorocenna-pogoliva-vrh-v-grudni-2
[10] https://mepr.gov.ua/wp-content/uploads/2023/06/386nd1.pdf

therefore does not depend on geographical location**,** unlike ***vulnerability,*** which is determined by specific changes in climatic parameters in a specific area. In this assessment of vulnerabilities and risks, only the negative effects of climate change were considered, and sensitivity was determined through expert assessment, by determining weighting coefficients proportional to the negative response of major crops and livestock to certain changes in climatic parameters. An important point is that the weighting coefficients are represented by numerical values, which will subsequently enable a more accurate calculation of the ***risks*** posed by changing climatic conditions for the industry. The expert assessment for the sectors took into account the impact of changes in various climate indicators on the condition of major crops, animal health, the possibility of maintaining livestock numbers, live weight gain, productivity and reproductive capacity. The impact of climate change on the quality and quantity of feed resources and drinking water was also assessed.

Changes in climatic factors in the study were assessed mainly using standardised indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI)[11], which worked within the framework of the World Climate Research Programme[12].

The values of climate indices for the current period and future climate periods were determined based on climate projections of air temperature and atmospheric precipitation, humidity and wind speed characteristics obtained from the ensemble of regional climate models (RCM) of the EURO-CORDEX project for two Representative Concentration Pathways (RCP) scenarios, RCP 4.5 and RCP 8.5. All modelling results underwent statistical adjustment using observational data and are considered suitable for obtaining projections of basic and specialised climate indicators and their trends.

[11] https://www.wcrp-climate.org/etccdi
[12] https://www.wcrp-climate.org/

2. IMPACT OF CLIMATE CHANGE ON AGRICULTURE

Climate change is the result of a combination of a number of natural factors and human economic activity and manifests itself mainly in an increase in the average global and regional temperatures of the surface air, land surface and ocean. The consequences of this temperature increase are the melting of sea ice and glaciers in polar regions and high mountains, a reduction in seasonal snow and ice phenomena on inland water bodies, a rise in the level of the World Ocean with its acidification, uneven distribution of precipitation and a significant increase in the number and intensity of extreme weather events: heat waves and cold spells, droughts, floods, hurricanes, inundations, etc.

The climate system has always been subject to changes and fluctuations, but in *the industrial period* of human development, when large volumes of industrial emissions from the combustion of fossil fuels and other polluting impurities are released into the atmosphere, intensive ploughing of large areas of land, significant deforestation, and pollution of the environment with industrial waste and human waste products, such changes have accelerated and their impact on natural and artificial ecosystems has increased.

Scientific research and documents of the Intergovernmental Panel on Climate Change (IPCC) emphasise that current climate change is mainly due to anthropogenic factors, the impact of which has recently increased significantly. Based on the IPCC's 6th Assessment Report (2021), the global surface temperature was 1.09 [0.95–1.20] °C higher in 2011–2020 than in 1850–1900, with the temperature increase over land estimated at 1.59 [1.34–1.83]°C[13] . The reliability of the increase in the temperature of the surface air layer, the Earth's surface and the surface of the oceans has been confirmed by instrumental measurements using certified instruments and standard observation methods for at least the last century and a half. The IPCC's Sixth Assessment Report emphasises that, in addition to changes in the thermal regime, there is a restructuring of circulation processes, an increase in the frequency of meridional air mass transport, and the development of blocking processes, leading to an increase in the recurrence of extreme and hazardous hydrometeorological phenomena. For example, NASA researchers have concluded that with climate change, droughts that previously occurred only once every 10 years now occur 70% more often, while heavy rains that previously occurred once every 10 years now occur 30% more often[14] .

The direction and pace of this climate change remain unchanged today. According to data from the World Meteorological Organisation (WMO), the global mean air temperature for 2024 was 1.54°C (with a maximum error of ±0.13°C) higher than the pre-

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[13] https://www.ipcc.ch/report/ar6/wg1/

[14] Rodell, M., Li, B. Changing intensity of hydroclimatic extreme events revealed by GRACE and GRACE-FO. *Nat Water* 1, 241–248 (2023). https://doi.org/10.1038/s44221-023-00040-5

industrial level of 1850-1900. The global average annual temperature in 2024 was +11.5°C, which is 2.4°C above the climate norm and 0.7°C higher than in 2023. In general, 2024 is recognised as the warmest year in recorded history. At the same time, the intensity of temperature growth in Europe is higher than the global average and the average for other regions[15] .

The last year of 2024 in Kyiv, as in most regions of Ukraine, was also the warmest since records began (according to data from the Central Geophysical Observatory[16] and the Ukrainian Hydrometeorological Centre[17]). In 2024, the air temperature exceeded the long-term average in all months. The highest positive monthly anomalies were observed in Kyiv in February and September: 5.2°C and 5.7°C, respectively. Precipitation in Kyiv amounted to 642 mm, which corresponds to 104% of the climatic norm. However, it was distributed very unevenly over time: almost two monthly norms in April and June and only 23% and 36% of the long-term average in May and September. Thus, it can be concluded that in the current climate period, there are stable trends towards an increase in air temperature and a redistribution of precipitation in space and time through an increase in the intensity of precipitation, a decrease in the number of days with precipitation, and an extension of dry periods.

2.1. General assessment of Ukraine's climate

The current climate of most of Ukraine (85%) is temperate continental, or "cold," according to the Köppen-Geiger climate classification. There are several climatic zones in the country, including a zone without arid conditions and with warm summers (Dfb), which covers more than 70% of the territory in the west, north and centre of the country, as well as in the Mountainous Crimea, and corresponds to forest and forest-steppe zones. The humid continental climate zone with hot summers (Dfa) covers more than 14% of the country's territory, in the south-east and northern steppes. The cold semi-arid climate zone (BSk) corresponds to the southern steppe and occupies more than 14% of the south, including most of the Crimean peninsula.

Ukraine's climate has changed significantly over the past 60 years, with temperatures rising faster in recent decades. Since the late 1990s, the average annual air temperature has been consistently higher than during the 1961–1990 climate norm period. Since 2007 , it has exceeded the norm by 1.5°C. The last decade, especially the years since 2015, have been the warmest in the history of Ukraine and the Northern Hemisphere as a

[15] https://wmo.int/news/media-centre/wmo-confirms-2024-warmest-year-record-about-155degc-above-pre-industrial-level
[16] http://cgo-sreznevskyi.kyiv.ua/uk/
[17] https://www.meteo.gov.ua

whole. In some years, the increase in the average annual air temperature exceeded 2.0°C (2.2°C in 2007, 2.3°C in 2015, 2.7°C in 2019).

There is a general trend of an increase in the minimum daily temperature, most notably during the cold season, and in the maximum temperature during the summer. These changes have led to a reduction in the duration of the cold season, the number of frost days and the severity of winters. At the same time, the changes have led to a longer and hotter growing season and an increase in the number of summer days. The precipitation pattern in Ukraine has also changed: the annual amount of precipitation has remained virtually unchanged, but there has been a redistribution of precipitation between seasons. An increase in precipitation is observed in autumn, a decrease in winter, and an even greater decrease in summer. In addition, the unevenness of precipitation and its intensity in daily values has increased, resulting in longer periods of drought. Rising air temperatures and uneven precipitation have led to a decrease in soil moisture accumulation, resulting in an increase in the frequency and intensity of drought events. Over the past twenty years, the occurrence of droughts has almost doubled across almost the entire country, with a dangerous trend towards an increase in the recurrence of drought conditions in the Polissya region, as well as the emergence of drought conditions in the northern areas of the Forest-Steppe, i.e. in regions that were previously considered waterlogged according to hydrothermal indicators, where precipitation exceeds evaporation.

To determine the impact of current climate change on agriculture, the following indicators related to the phenological development of plants were analysed: changes in the beginning, end and duration of periods with average temperatures above 0° C (warm period), 5° C (vegetation period), 10° C (period of active plant vegetation) and more than 25^0 C (extreme temperatures), as well as the sum of effective temperatures above 5° C /10° C and the Selyaninov hydrothermal coefficient (HTCS). To determine these indicators, data from the European E-OBS database version 20.0 for the period 1991 – 2010 were used and compared with indicators for the previous WMO climate period 1961–1990 to assess the actual change in indicators over the last 60 years.

2.2. Warm period (t > 0°C)

The duration of the warm period in Ukraine in the period 1961–1990 increases from the northeast (220–240 days) to the south and southwest (320–340 days), which corresponds to the spatial distribution of the average annual air temperature and direct solar radiation (Fig. 2.1.). The latitudinal distribution was disrupted in the west of the country, where an increase in the duration of the warm period was observed over a significant area, with the exception of the Ukrainian Carpathians. In Transcarpathia, the warm season lasted 320–340 days, the same as in the southern regions of Ukraine. The disruption of the latitudinal distribution is due to the influence of the Atlantic and the peculiarities of atmospheric processes in these regions. Such patterns of spatial distribution of the indicator are characteristic of past and present climatic periods. The duration of the warm period in Ukraine during 1991–2010 changed relative to the climatic norm (1961–1990). These changes were not uniform across the country: in the forest-steppe and forest zones, there was an increase in the duration of the warm period, up to 20 days, most intensively in the Carpathian region and in the north of the Zhytomyr and Volyn Polissya. However, in the Ukrainian Carpathians and the steppe part of the country, the changes were insignificant, and in some areas of the Odesa region and the Autonomous Republic of Crimea, there was a decrease in the duration of the warm season (Fig. 2.1).

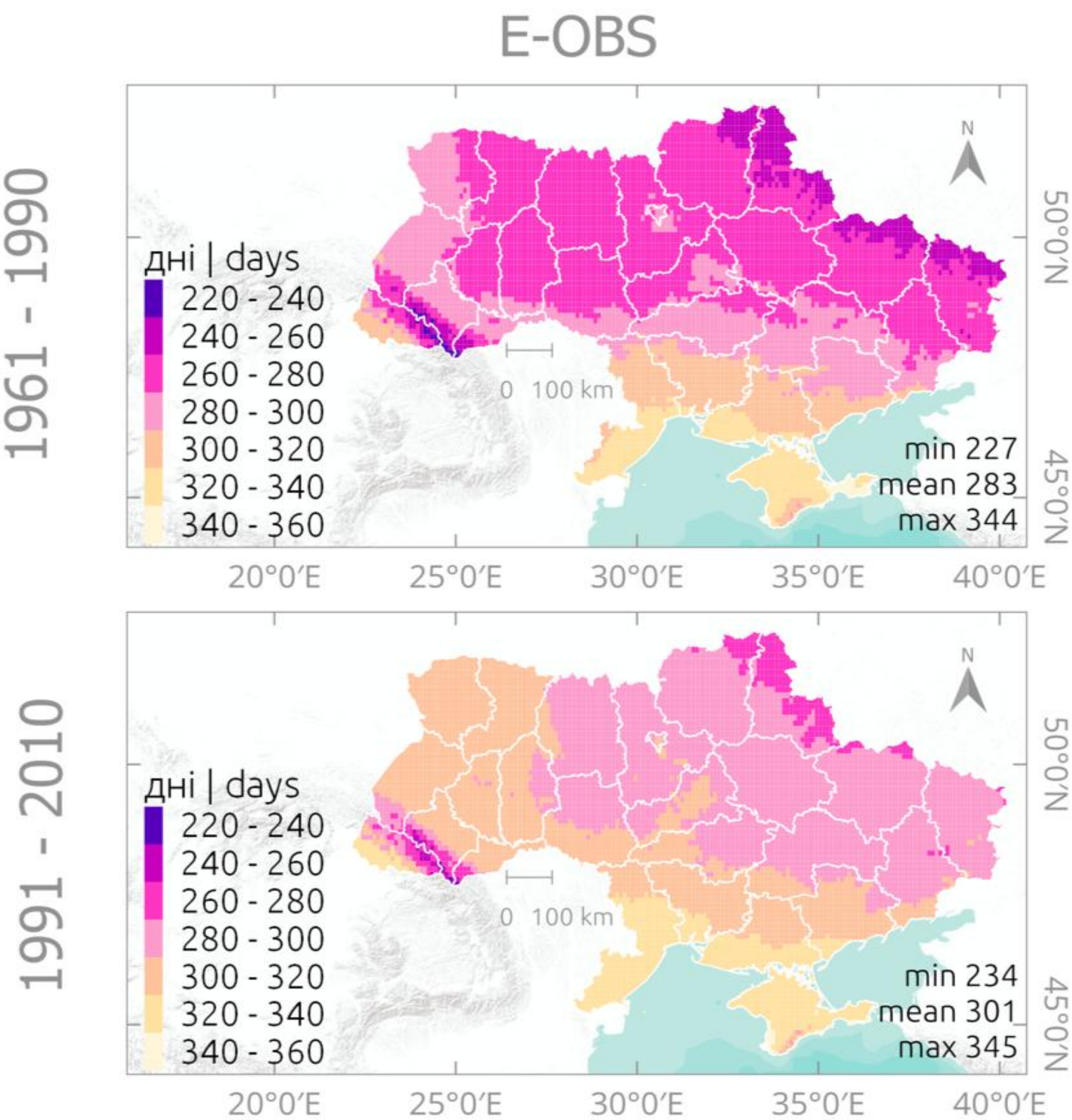

Figure 2.1. – Duration of the warm period according to E-OBS data

Such changes contribute to the cultivation of major agricultural crops on an industrial scale throughout almost the entire territory of Ukraine due to the availability of heat and a reduction in the period of sub-zero temperatures, especially for winter crops.

2.3. Growing season (t > 5°C)

The length of the growing season (GSL) is the most important factor for sectors such as agriculture and forestry, as it determines the duration of plant growth and development. This indicator is calculated in days based on data on the average daily surface air temperature. The growing season begins/ends before/after 1 July for the northern/southern hemisphere when the temperature is at least 6 consecutive days equal to or above 5°C, and ends/begins when the average daily temperature for 6 days or more falls/rises below/above this threshold value after/before 1 July for the northern/southern hemisphere.

The growing season in the past is characterised by the same spatial and temporal patterns as the warm period: an increase in duration from the northeast to the south and southwest from 200 to 290 days and more (Fig. 2.2). The early onset of the warm period causes early restoration of plant vegetation, which leads to an increase in the duration of the growing season and an increase in its heat supply. An increase in the duration of the growing season has been observed throughout Ukraine over the last few decades, with the most significant increases in the southern, south-eastern and north-western regions of the country, where it reached 7 to 14 days compared to the climatic norm (1961–1990).

Early resumption of vegetation is especially important for winter crops, when there is still sufficient moisture in the soil after the winter period, which lays the foundation for significant yield potential. A typical example is the conditions that prevailed in 2024, when there was an intensive resumption of winter crop vegetation in early to mid-April, when temperatures reached 20°C, which contributed to the formation of a significant amount of plant biomass, as a result of which there was no significant reduction in the yield of winter crops, although previous forecasts predicted a decline of almost 20%.

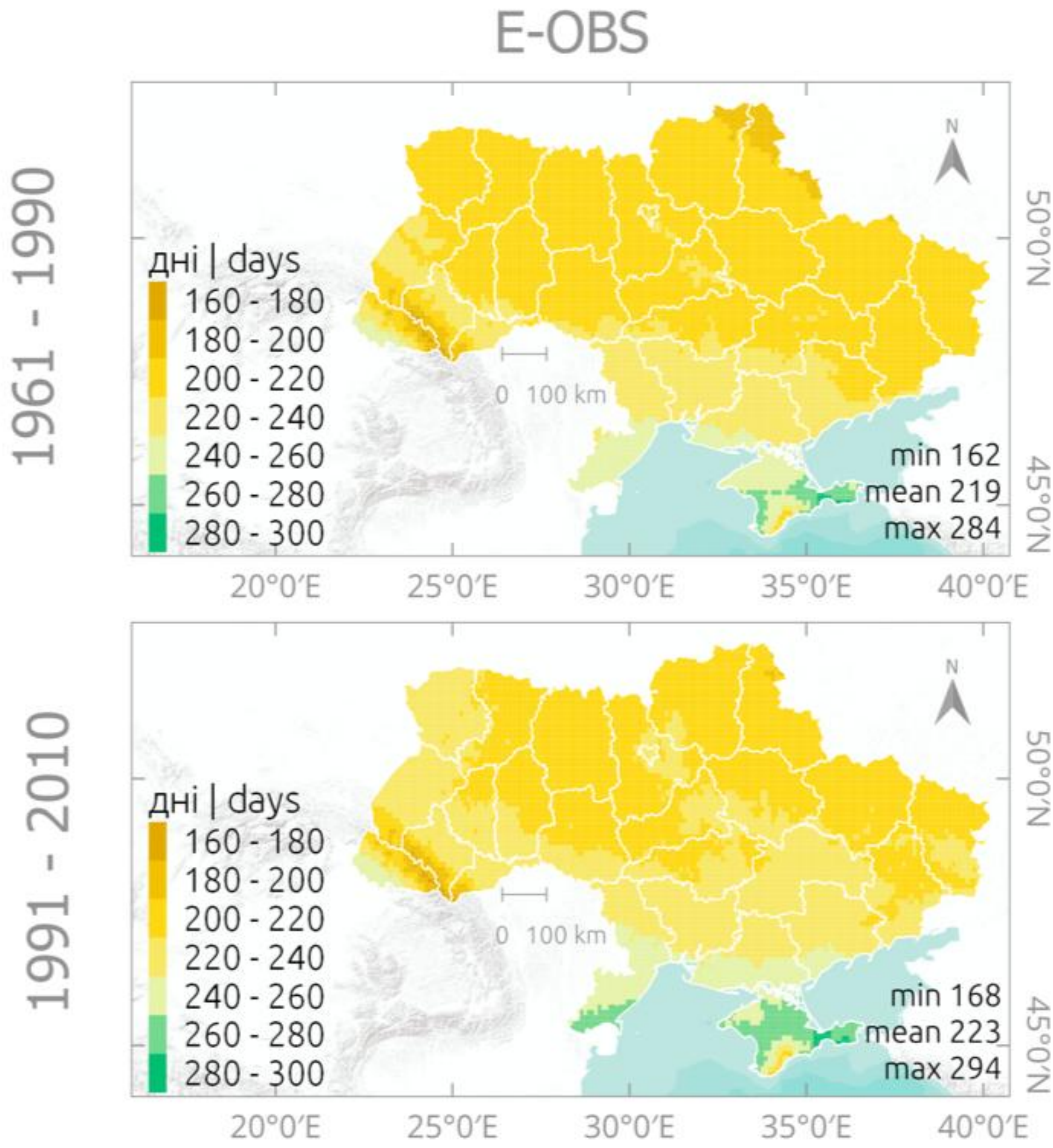

Figure 2.2. – Duration of the growing season according to E-OBS data

An early start to the growing season contributes to an increase in the sum of effective temperatures above 5°C. Over the past climatic period (1961–1990), this indicator has a significant spread of values across Ukraine and varies between 857 and 2915°C (Fig. 2.3). The minimum accumulated values are observed in the highlands of the Carpathians, where they amount to 857°C. This sum in the mountains varies significantly due to altitude zoning and is characterised by an uneven distribution: from 900 to 1900 on the peaks and slopes of the mountains, while in front of the Carpathians, the sum of effective temperatures is up to 2000°C (partly in the Lviv and Ivano-Frankivsk regions). In Transcarpathia, the sum of effective temperatures above 5°C is higher and reached 2400°C.

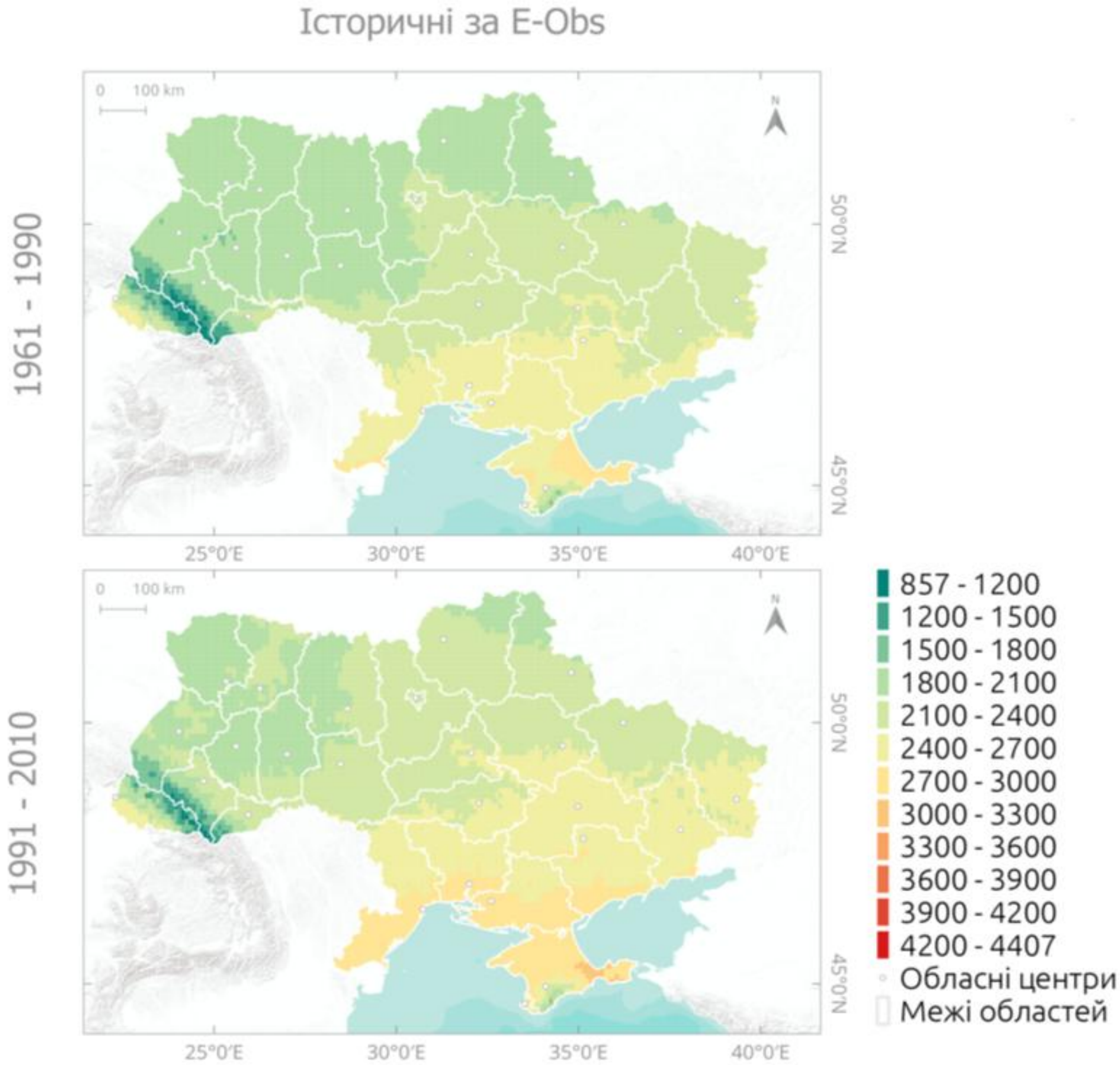

Figure 2.3. – Spatial and temporal distribution of effective air temperatures above 5°C according to E-OBS data

In the flat part of western and northern Ukraine, effective temperatures above 5°C generally range from 1900 to 2000°C. Lower values are typical for Volyn, parts of Ternopil, Khmelnytskyi and Vinnytsia regions, while higher values are typical for Rivne and Zhytomyr regions. Similar values of effective temperatures above 5°C with a sum of approximately 1900–2000°C cover the north of the Chernihiv and Sumy regions, i.e. Polissya. As one moves south, with an increase in solar radiation, the total effective temperatures increase. Mainly in the forest-steppe, these values increase from 2000°C in the north to 2300°C in the south. This includes Vinnytsia, the south of Kyiv, Chernihiv, and Sumy regions, as well as Cherkasy, Poltava, and Kharkiv regions. Meanwhile, in the steppe, the values increase from 2300°C at the northern border and range from 2300–2600°C across most of the territory (Kirovohrad, Dnipropetrovsk, most of Odesa, Mykolaiv, Kherson, and Zaporizhzhia regions), with the exception of the east and northeast of the steppe, where the minimum values are 2200°C and above, including the south of Kharkiv, Luhansk, and Donetsk regions. On the coast, these values are 2500–2600°C and above. This includes the south of Odesa, Mykolaiv, Kherson, Zaporizhzhia, and Donetsk regions and the entire Autonomous Republic of Crimea. The sum of effective temperatures reaches its highest values above 2800°C, with a maximum of 2915°C in the Ak-Monai Isthmus and Kerch Peninsula areas. Only in the highlands of the Crimean Mountains did the sum of effective temperatures above 5°C reach 1500–1600°C.

For the current 20-year base period (1991–2010), compared to the previous climate period (1961–1990), the values of accumulated effective temperatures above 5°C have increased and vary from 1028°C in the highlands of the Carpathians to 3074°C in the extreme south, in the area of the Ak-Monai Isthmus and the Kerch Peninsula (Fig. 2.3). That is, the accumulated temperatures have increased by 83.5–223.5°C. The greatest changes are characteristic of the south-west and south of the steppe (Odesa and Kherson regions, Kerch Peninsula, Crimea), as well as Polissya – Volyn, Rivne, Zhytomyr and Chernihiv regions. For the base climate period (1991–2010), the lowest values of accumulated effective temperatures are characteristic of the mountainous region of the Carpathians, where the minimum is 1028°C. In general, due to the complexity of the relief and different altitudes, the values of effective temperatures above 5°C vary significantly from 1028°C to 2100°C on the slopes and within 2200°C in front of the eastern (Lviv, Ivano-Frankivsk, Chernivtsi regions) and western slopes of the Carpathians (Zakarpattia region). Meanwhile, in the flat Zakarpattia region, these sums are 2500°C and above.

In western Ukraine and Polissya, the sum of effective temperatures is generally between 2000 and 2200°C. This includes the flat part of Lviv, Ivano-Frankivsk, Ternopil, Volyn, Rivne, Zhytomyr, as well as the north of Chernihiv and Sumy regions. The Chernivtsi region is characterised by uneven terrain, so in the west, in the mountains, the values vary from 1100°C to 2300°C and above in the flat eastern part.

As you move east and southeast, the sum of effective temperatures increases. In the north of the forest-steppe, it is 2200–2300°C, which is typical for the north of Vinnytsia and Kyiv, and the south of Chernihiv and Sumy regions. Moving south, it is 2300–2500°C, covering the south of Vinnytsia, Cherkasy, Poltava, and Kharkiv regions. In the steppe, lower values of accumulated effective temperatures are observed in the east, where they are 2300°C and above (south of Kharkiv, Donetsk, and Luhansk regions).

At the same time, in the south-west and south of the steppe, effective temperatures above 5°C are 2500–2700°C and higher on the coast, in particular for the Odesa, Mykolaiv, Kherson, Zaporizhzhia, and Donetsk regions, and in some areas 2800°C and higher. The highest values of accumulated temperatures are observed in the Kerch Peninsula area and will reach a maximum of 3074°C. Only in the highlands of the Crimean Mountains is the sum of effective temperatures above 5°C 1700°C.

A significant increase in effective temperature across almost the entire territory of Ukraine allows two crops to be grown on the same field, including grain, oilseeds and vegetables. The successful cultivation of crops in intermediate crops, which makes it possible to obtain two harvests per year on the same area, depends primarily on the duration of the frost-free growing season, moisture conditions, and the thermal and light regimes of the year. The length of the growing season and the flow of solar radiation increase from north to south, and the length of unused favourable growing time for the main crops in crop rotations increases similarly, since with the move south, most plants accelerate their vegetation, i.e. they reach fodder or full maturity faster. This makes it possible to grow two crops per year in southern regions. There are plenty of examples of this in the south and in Crimea (until 2014): many agricultural enterprises in the Autonomous Republic of Crimea sowed soybeans after winter barley grown for grain, with the first crop yielding 45–60 cwt/ha and the second crop yielding 15–25 cwt/ha.

In experiments conducted by the Corn Institute of the Ukrainian Academy of Agrarian Sciences, buckwheat was grown after winter wheat for grain with a yield of about 60 centners per hectare, with a seed yield of 15–20 centners/hectare. The total yield of winter barley and post-harvest millet on irrigated lands in the Republic of Crimea exceeded 100 centners/hectare. Good results are obtained in southern Ukraine by combining winter barley and post-harvest corn, with a total yield of 87.5 cwt/ha of grain. The agroclimatic resources of southern Ukraine make it possible to obtain two harvests of oilseeds and vegetable crops on the same area. In practice, the combination of winter rapeseed for seed and sunflower, winter rapeseed and soybeans has proven itself well. The yield of winter rapeseed reached 35, and sunflower – over 25 cwt/ha; the yield of soybeans – 20–25 cwt/ha.

2.4. Active growing season (t > 10°C)

The duration of the active growing season in 1991–2010 in a significant part of Ukraine was mainly 160–180 days. In the south of the country, it was 180–200 days, and on the southern coast and in some eastern regions of the Crimean Peninsula, it was 200–220 days. The only exceptions were the extreme north-eastern regions and the Ukrainian Carpathians, where the duration varied from 140 to 70 days (with a minimum in the highlands). During 1991–2010, the duration of active vegetation in Ukraine changed compared to 1961–1990, especially in the north-west of the country, where it increased by 10 days or more. The beginning of the period with temperatures above 10°C is an important characteristic for determining the sowing dates of spring crops, as earlier sowing dates allow plants to increase the growing season and improve crop productivity.

Early sowing dates increase the effective temperature above 10°C, which is calculated during the active growing season of agricultural crops and is also important for heat-loving plants. The base historical climate period of 1961–1990 is characterised by the sum of effective temperatures above 10°C, which varies between 228 and 1724°C across Ukraine. The minimum values are characteristic of the highlands of the Carpathians, while the maximum values are in the extreme south, namely the Ak-Monai Isthmus and the Kerch Peninsula of the Autonomous Republic of Crimea (Fig. 2.4).

In the mountainous region of the Carpathians, the sum of effective temperatures above 10°C varies from 228°C to 900°C on the slopes. In the Precarpathian region and in the west in general, as well as in Polissya, the values are characterised by a relatively uniform distribution 900–1000°C. Such values are characteristic of the flat part of Lviv, Ivano-Frankivsk, as well as the entire Ternopil, Khmelnytsky, Volyn, Rivne, Zhytomyr, and the extreme north of Sumy regions. In the flat part of Zakarpattia, these values are 1100–1400°C, and in Chernivtsi, 1000–1200°C. As one moves east and south, the sum of active temperatures rises above 10°C. In this part of Polissya, for Kyiv and most of Chernihiv and Sumy regions, the values will be 1000–1200°C.

In the forest-steppe, these values increase and fluctuate between 1100–1200°C in the north and 1300°C in the south. This includes Vinnytsia, the south of Kyiv, Chernihiv, and Sumy regions, Cherkasy, Poltava, part of Kirovohrad, and the north of Kharkiv region. For the steppe, the sum of effective temperatures above 10°C varies significantly from 1300°C to 1600°C and above on the eastern coast of Crimea. In the steppe, mainly in the east, the sum of effective temperatures above 10°C varies from 1300°C to 1400°C (eastern Dnipropetrovsk, southern Kharkiv, all of Donetsk and Luhansk regions), i.e., it is more homogeneous compared to the west. However, as they move towards the sea coast, they increase to 1400-1500°C and above, reaching maximum values of 1724°C. Only in the highlands of the Crimean Mountains is the minimum sum of effective temperatures above 10°C about 800°C (Fig. 2.4.).

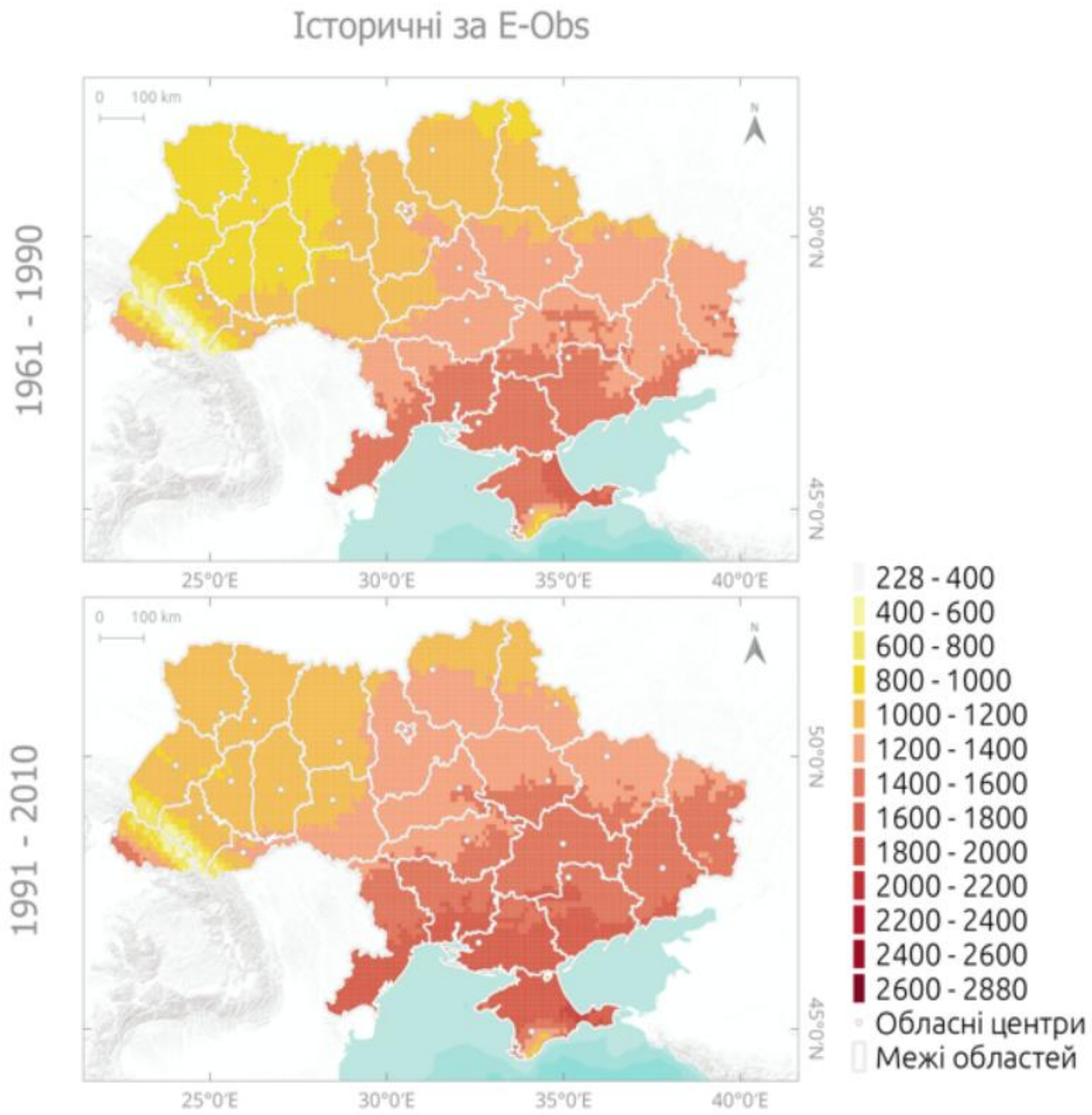

Figure 2.4. – Spatial and temporal distribution of effective air temperatures above 10°C according to E-OBS data.

Over the current twenty-year base period (1991–2010), compared to the previous climate period (1961–1990), the accumulated effective temperatures above 10°C increased by 70.0–182.3°C. The largest increase is characteristic of the south-west and south of the steppe (Odesa and Kherson regions, Ak-Monai Isthmus, Kerch Peninsula, Crimea), as well as Polissya – Volyn, Rivne, Zhytomyr, and Chernihiv regions. For the base climate period (1991–2010), the minimum values of accumulated effective temperatures above 10°C are 347°C in the highlands of the Carpathians and the maximum is 1858°C in the south of Crimea. The unevenness of the mountainous terrain and differences in altitude cause significant fluctuations in effective temperatures above 10°C, ranging from a minimum of 347°C to 1000°C on both the western and eastern slopes of the Carpathians. Meanwhile, in the flat part of Transcarpathia, these sums are 1400–1500°C and above. In general, in the flat part of western Ukraine (the flat part of Lviv, Ivano-Frankivsk, all of Ternopil, Khmelnytskyi, and Chernivtsi regions), as well as

Polissya (Volyn, Rivne, Zhytomyr, northern Chernihiv and Sumy regions), the sum of effective temperatures is generally within the range of 1100–1200°C.

Towards the south, the sum of effective temperatures increases. At the northern border of the forest-steppe, it is 1200°C, which is typical for the north of Vinnytsia, the north of Kyiv, and the south of Chernihiv and Sumy regions. Meanwhile, the maximum values in the south reached 1500°C. Such effective temperature sums within the region cover the south of Vinnytsia, Cherkasy, Poltava, and partly Kirovohrad and Kharkiv regions. For the steppe, the values vary from 1400°C to 1600°C and above in the extreme south. In the east, slightly lower values are observed for Donetsk and Luhansk regions. Values of 1600°C and above are observed in the extreme south and along the sea coast. The highest values of accumulated temperatures above 10°C are observed in Crimea, with maximum values of 1858°C. Meanwhile, in the Crimean mountains, the minimum sum of effective temperatures is 800°C.

A significant increase in the sum of temperatures above 10°C has made it possible to significantly expand the area and range of cultivation in Ukraine of such heat-loving plants as corn and soybeans. Figure 2.5 shows a graph of changes in corn acreage in all regions since 2000. Almost all regions have seen a trend towards an increase in acreage since 2000, which is particularly noticeable in the northern and western regions.

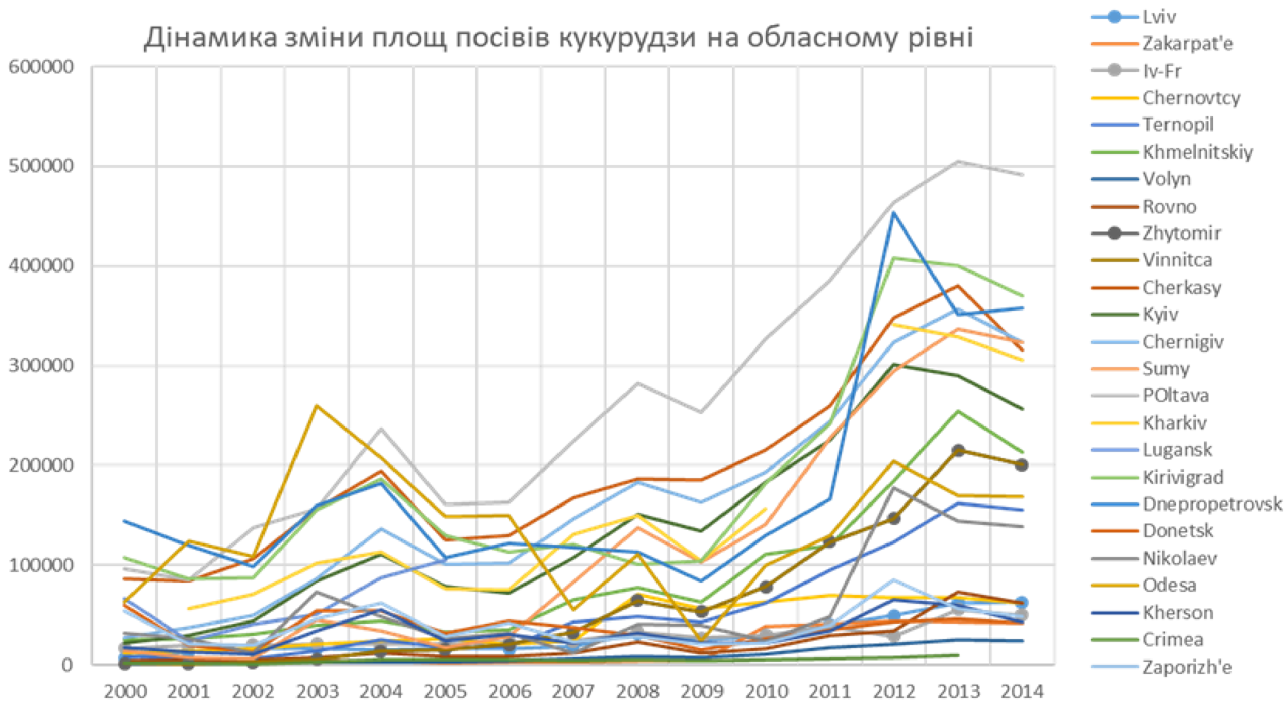

Figure 2.5. – Dynamics of changes in corn acreage at the regional level since 2000

A similar trend can be observed for soybean crops, with the area under cultivation in the country increasing almost 40-fold since 2000. It is believed that one of the main factors contributing to the increase in the area under cultivation is climate change, with significant warming in various regions of Ukraine and an increase in the effective temperature of more than 10°C, which is conducive to the development of these plants.

2.5. Extreme temperatures

One of the main consequences of climate change is warming, and while a general increase in temperature may have a positive effect on crop production, it also contributes to extreme temperature increases in summer, which have a negative impact on plant development. To assess this, we can use the change in the number of summer days, i.e. days with a maximum temperature above 25°C (SU). The vast majority of Ukraine's territory has statistically significant positive trends in the number of summer days. The analysis showed that the spatial distribution of SU trends is pronounced, with areas of lower values in the east and south-east and minima in the Carpathians. The average value of the trends in the number of summer days is 2.84 days/10 years and varies from 2.38 to 5.00 days/10 years.

The northern region has the highest trends, averaging 3.13 days/10 years. The highest SU index trend values were found in the Zhytomyr region – 3.37 days/10 years. In the Kyiv and Chernihiv regions, the average is 3.14 and 3.09 days/10 years, respectively. The minimum values of 2.86 days/10 years are observed in the Sumy region.

In the eastern region, the average trend values are 2.07 days/10 years, which is the lowest indicator among the regions. The highest trend values are in the Donetsk region, where the average trend value is 2.35 days/10 years. In the Kharkiv and Luhansk regions, the average values are lower: 1.99 and 1.88 days/10 years, respectively. For the southern region, the average SU trends are 2.85 days/10 years. The highest values are observed in the Odesa region – 3.46 days/10 years and in Crimea – 3.33 days/10 years. In the Mykolaiv region, the average SU trends are 2.94 days/10 years, and in the Kherson and Zaporizhzhia regions: 2.50 and 2.25 days/10 years. In the western region, the average SU index trends are 3.08 days/10 years.

The highest trend values are in the Volyn, Lviv and Chernivtsi regions: 3.24, 3.14 and 3.18 days/10 years, respectively. In the Rivne, Ternopil, Khmelnytskyi and Zakarpattia regions, the average index values are lower, ranging from 3.02 to 3.09 days/10 years. The minimum SU index values are in the Ivano-Frankivsk region – 2.85 days/10 years. In the central region, the average trend values are 2.80 days/10 years.

The highest trend values are in Vinnytsia and Cherkasy regions: 3.30 and 3.15 days/10 years. In Kirovohrad and Poltava regions, the average trends are 3.40 and 2.73 days/10 years. The lowest values are in Dnipropetrovsk region – 2.06 days/10 years.

Based on this analysis, it can be stated that over the past 60 years, the average number of days with maximum air temperatures above 25 degrees in Ukraine has *increased by approximately 20.* It can be assumed that this increase also affects the number of days with extreme temperatures. It is important to note that extreme temperatures have the greatest negative impact on plants when they are in critical stages of development. For example, when corn crops are going through the main physiological stages of development (flowering, pollination), an increase in air temperature to 30–35°C significantly reduces the viability of corn pollen, grain size and, ultimately, yield. For soybean crops, extreme temperatures reduce the number of pods formed and, accordingly, productivity, while for sunflower crops, grain weight decreases by up to 10% at temperatures > 35ºC, as does oil content.

An example of this is the situation that arose in July-August 2010, when, according to data from the Ukrainian Hydrometeorological Centre (Fig. 2.6), temperatures above 30ºC were observed in some regions of Ukraine for up to 51 days. According to statistics, late crops in the east and south of the country were particularly affected.

Figure 2.6. – Maximum air temperature in July-August 2010 (top) and number of days with temperatures above 30ºC (red). Data from the Ukrainian Hydrometeorological Centre

2.6. Drought phenomena

Rising air temperatures and uneven precipitation have led to a decrease in soil moisture accumulation, resulting in an increase in the frequency and intensity of droughts in Ukraine. The Selyaninov hydrothermal coefficient (HTCS) is used to determine the severity of droughts. This coefficient is an indicator of soil moisture during the active growing season, i.e. between the stable dates when the air temperature rises above 10°C.

It is important for the growth and development of agricultural crops and has several gradations. It is calculated using the following formula and includes the following indicators:

$$\text{ГТКС} = \frac{10 \times \sum P_{T \geqslant 10}}{\sum T_{T_{av} \geqslant 10}},$$

where the numerator is the sum of daily precipitation in mm calculated for the period of active vegetation, increased by a factor of 10, and the denominator is the sum of effective temperatures for the period of active vegetation, i.e. with air temperatures above 10°C, summed between the dates of a stable transition above 10°C in spring and autumn. The following HTCS gradations are distinguished according to moisture characteristics:

- from 1.8 to 6.0 – excessive moisture;
- from 1.2 to 1.8 – moist;
- from 1.0 to 1.2 – sufficient moisture;
- from 0.7 to 1.0 – insufficient moisture or arid;
- from 0.4 to 0.7 – very arid.

For the historical baseline climate period of 1961–1990, based on E-OBS observations, the territory of Ukraine has different moisture coefficients as it moves from north-west to south-east (Fig. 2.7). The entire Carpathian region falls within the zone of excessive moisture, where the GTCS is 1.8–6. The humid zone, where the GTCS is 1.2–1.8, includes the flat part of Zakarpattia, Lviv, Ivano-Frankivsk, and Chernivtsi regions, as well as most of Polissia, which includes Volyn, Rivne, Zhytomyr, and part of Kyiv regions, as well as the north of Chernihiv and Sumy regions. This zone also includes the western forest-steppe, namely Ternopil, Khmelnytskyi, and Vinnytsia regions. Meanwhile, the zone with sufficient moisture with a GTCS of 1.0–1.2 is located mainly in the forest-steppe and in the south of Polissya. This zone includes such territories as the south of Vinnytsia, practically the entire Kyiv, south of Chernihiv, Sumy regions, Cherkasy and north of Poltava regions.

As we move south, the coefficient continues to decrease for the forest-steppe and steppe zones, indicating an increase in aridity. For most of the Poltava region, the entire Kirovograd region, and the southern parts of the Kharkiv, Luhansk, and Odesa regions, the GTKS is 0.7–1.0, which indicates insufficient moisture or an arid zone. A GTKS of 0.4–0.7, which corresponds to a very arid zone, is characteristic of the sea coast. That is, it extends to the south of the Odesa and Mykolaiv regions and covers the entire Kherson region and the Autonomous Republic of Crimea, except for the highlands, the south of Dnipropetrovsk, most of Zaporizhzhia, and the south of Donetsk regions. Meanwhile, in the highlands of the Crimean Mountains, this coefficient varies from insufficient moisture to wet as the relief height increases.

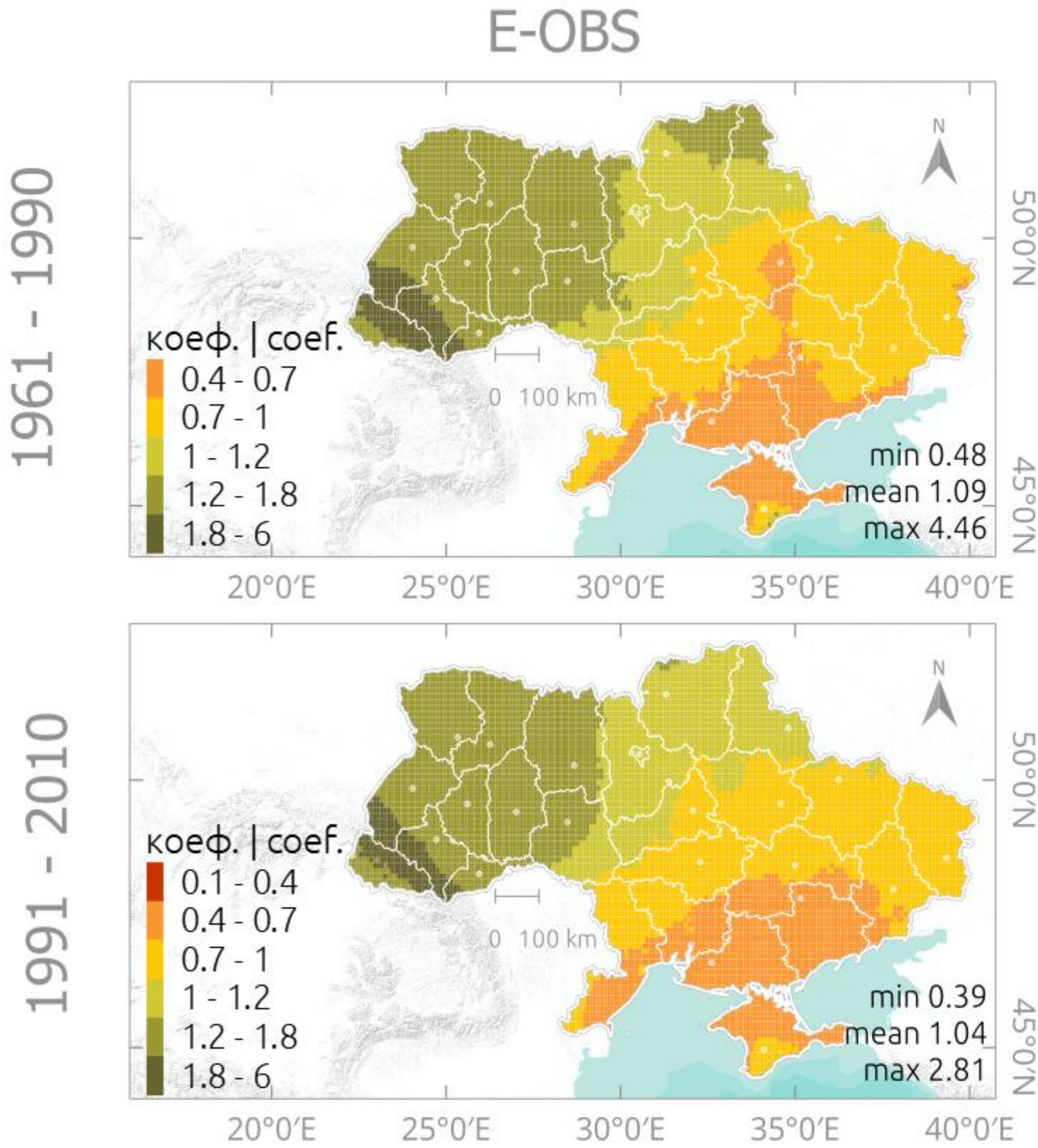

Figure 2.7. – Spatial-temporal distribution of the Selyaninov hydrothermal coefficient according to E-OBS data

As we move south, for the partially forest-steppe and steppe zones, the coefficient values continue to decrease, which indicates an increase in aridity. For most of the Poltava region, the entire Kirovograd, Kharkiv, Luhansk, most of the Odesa, Mykolaiv, Dnipropetrovsk, and Donetsk regions, the GTK is 0.7–1.0, which indicates insufficient moisture or an arid zone. A GTKS of 0.4–0.7, which corresponds to a very arid zone, is characteristic of the sea coast. That is, it extends to the south of the Odesa and Mykolaiv regions and covers the entire Kherson region and the Autonomous Republic of Crimea, except for the highlands, the south of Dnipropetrovsk, most of Zaporizhzhia, and the south of Donetsk regions. Meanwhile, in the highlands of the Crimean Mountains, this coefficient varies from insufficient moisture to wet as the relief height increases.

In the subsequent historical climate period of 1991–2010, there were some changes compared to the previous period of 1961–1990 (Fig. 2.7). In the north of the Chernihiv and Sumy regions, the humid zone (GTKS 1.2–1.8) disappeared and was replaced by a zone of sufficient moisture (GTKS 1.0–1.2). The humid zone shifted slightly westward from the west of the Kyiv region and the south of the Vinnytsia region. The very arid zone (GTKS 0.4–0.7) also expanded in the south, extending to the north of the Odesa region, half of the Mykolaiv region, as well as to the south of the Dnipropetrovsk region and the entire Zaporizhzhia region.

Over the past 60 years, the number of droughts has increased significantly, not only in the southern regions, but also in the central and eastern regions. Significant droughts occurred both in the second half of the 20th century and since the beginning of the 2000s. Over the past 20–25 years, as a result of climate change, there have been prolonged periods of drought, which were quite intense and, accordingly, had negative consequences. For example, the drought of 2003 reduced the gross grain harvest in Ukraine to 22 million tonnes and made exports completely impossible (that year, grain even had to be imported). The drought of 2007 also caused significant damage to the agricultural sector, when a lack of moisture was recorded in two-thirds of the country in the spring. In recent years, significant droughts have been observed in 2010, 2015 and 2017. It should be noted that almost every year, one region or another of Ukraine suffers from drought. For example, in 2024, there was no precipitation in the central regions from July to September, which led to a significant drop in corn and soybean yields, almost twice as much. These natural phenomena in Ukraine tend to spread to the northern and western regions, and given that they can occur at different stages of plant growth, they can affect the entire range of crops grown.

2.7 Impact of climate change on soil degradation processes

Climate change has a serious and multifaceted impact on the state of soils in Ukraine. This impact is manifested in the physical, chemical and biological properties of soils, as well as in changes in their ecosystem functions. Since Ukraine has a powerful agricultural sector and significant areas of fertile soils, in particular chernozems, the problem of soil degradation due to climate change is extremely relevant.

According to numerous studies by domestic and international scientists, climate change is a key factor exacerbating degradation processes in the soil cover. In Ukraine, these processes are particularly acute due to a combination of climatic, anthropogenic and military factors.

It should be noted that over the past 60 years, Ukraine has seen: an increase in average annual temperatures by 1.2–1.5°C (in some years, the increase in average annual air temperature exceeded 2.0°C), a decrease in precipitation during the growing season, especially in the southern and central regions, and an increase in extreme weather events such as droughts, heavy rains, hailstorms, and spring frosts. All these factors have a complex and negative impact on the condition of the soil cover, accelerating its degradation, reducing fertility, and causing the loss of ecosystem functions and resistance to anthropogenic and natural stresses.

Among the main soil degradation processes, the following can be identified:

1. Accelerated loss of humus and increased greenhouse gas emissions. Rising air temperatures and decreasing humidity significantly affect the humus content in soils, contributing to its accelerated loss. Under conditions of rising temperatures and moisture deficiency, microbiological activity in the upper soil horizons intensifies, leading to intensive mineralisation of organic matter. As a result, humus decomposes faster and organic carbon is released in the form of carbon dioxide (CO_2), which reduces the total carbon stock in the soil ecosystem. Degraded soils lose their ability to sequester carbon, making them a source rather than a sink for CO_2. This creates an additional feedback loop that amplifies global warming.

Elevated temperatures cause mineralisation processes to prevail over humus formation, leading to a steady decline in humus content. According to research by the O.N. Sokolovsky Institute of Soil Science and Agrochemistry, a National Scientific Centre, the annual loss of humus in chernozems can exceed 0.1%, which is a critical indicator for maintaining soil fertility.

As a result, in drought conditions, the biological productivity of plants decreases, in particular, the mass of root residues, the main source of organic matter for the soil, is significantly reduced. This, in turn, limits the supply of substrate for humus formation processes, leading to further depletion of soil organic carbon.

In turn, the loss of humus reduces the aggregate stability of the soil, making it more vulnerable to erosion. A decrease in moisture further exacerbates degradation processes: compaction and cracks occur, and moisture retention capacity decreases. Also, as a result of humus loss, soils lose their ability to retain carbon, which not only reduces their fertility but also contributes to global warming.

2. Deterioration of the water regime. Climate change has a significant negative impact on the water regime of soils, which manifests itself in a number of degradation processes. These include a decrease in moisture retention capacity, deepening water shortages, disruption of capillary moisture rise, and the development of erosion and compaction phenomena.

The reduction in precipitation causes a chronic moisture deficit in the soil environment and reduces the infiltration of atmospheric moisture into deeper layers. This complicates the water supply to the root zone and worsens the water supply to plants. At the same time, soil compaction is observed, which further limits water exchange. It should be noted that even if the annual amount of precipitation remains unchanged, its structure is changing: steady rains are increasingly being replaced by short but intense downpours. Such precipitation has low infiltration capacity – water quickly flows over the surface without penetrating deep horizons, which limits moisture accumulation in the soil, especially during critical periods of crop growth.

The reduction in atmospheric precipitation and the lowering of the groundwater level lead to a disruption in the capillary rise of moisture from the lower layers to the root zone. This is particularly noticeable on light, low-humus soils, where moisture does not remain for long periods of time anyway. Moisture deficiency negatively affects the structural and aggregate state of the soil: cracks and compaction form, and water permeability decreases. As a result, the soil loses its ability to effectively accumulate and retain moisture, which limits the productivity of agroecosystems.

Intense short-term precipitation after a long period of drought causes surface water runoff, which contributes to the development of water erosion. Decreased moisture also increases the risk of wind erosion, as the moisture that binds soil particles disappears, making the top layer more vulnerable to wind transport.

In addition, rising air temperatures significantly increase moisture evaporation from the soil surface, leading to a decrease in its water supply. This, in turn, complicates the cultivation of agricultural crops, especially in conditions of precipitation deficit and the absence of effective irrigation systems. This process is most pronounced in the southern, central and eastern regions of Ukraine, contributing to the drying out of the soil profile during the active growing season.

3. Development of erosion processes. Climate change significantly affects the intensity and spatial distribution of erosion processes, in particular water and wind erosion, which are among the key forms of soil degradation. The intensification of these processes is caused by a number of interrelated climatic and environmental factors.

The increase in the frequency and intensity of precipitation, particularly in the form of short-term downpours with thunderstorms, leads to the formation of powerful surface runoff, especially after prolonged dry periods. Such downpours have high kinetic energy, which contributes to the destruction of the soil structure and the washing away of the most fertile humus layer. As a result, micro- and macro-relief of an erosive type (furrows, gullies) is formed, which further worsens conditions for plants.

On the other hand, a decrease in atmospheric precipitation combined with an increase in air temperature causes prolonged periods of drought. The surface horizons of the soil dry out and become more vulnerable to wind erosion. This is particularly noticeable in open, unprotected areas (in particular stubble fields and arable land without mulch), where soil particles are easily lifted into the air and carried over long distances.

The deterioration of soil structure – due to degumification, reduced organic matter content, compaction and cracking – reduces its water retention capacity and ability to resist erosion. Such soil quickly loses its cohesion and becomes vulnerable to mechanical destruction by both water and wind.

Of particular importance is the reduction in vegetation cover, which is often the result of declining crop productivity or degradation of natural vegetation. The absence of a vegetation layer deprives the soil of its natural biological protection – the root system and plant residues play a key role in fixing soil particles and reducing the force of water or wind impact.

According to estimates by the O.N. Sokolovsky National Scientific Centre "Institute of Soil Science and Agrochemistry", with increasing climate risks, areas affected by water and wind erosion may increase by 10-15% in the coming decades, primarily in the steppe and forest-steppe regions of Ukraine.

The consequences of soil erosion go beyond agricultural losses. They include reduced fertility, degradation of soil biota, loss of nutrients, disruption of the water balance, and secondary pollution of water bodies with suspensions and agrochemicals. Therefore, monitoring, prevention and control of erosion processes in the context of climate change should become priority areas of modern land management policy.

4. Increased risk of salinisation and sodification. Climate change, in particular the increase in average annual temperatures, the decrease in atmospheric precipitation and the decline in groundwater levels, contributes to the intensification of soil salinisation and sodification processes, especially in the southern and eastern regions of Ukraine.

One of the key factors is the intensification of evaporation: under high temperatures, water actively evaporates from the soil surface, causing a rise in capillary flow, which transports dissolved salts from lower horizons to upper ones. In the absence of effective natural or artificial drainage, salts accumulate in the upper layers, particularly in the root zone.

Changes in the water balance and direction of water flow in the soil profile caused by a decrease in the groundwater level worsen the conditions for salt leaching and contribute to their accumulation. In steppe zones, these processes are particularly intense due to natural aridity and moisture deficiency.

Limited moisture due to reduced precipitation reduces the ability of natural soil purification processes (in particular, salt leaching), leading to further salt accumulation in the profile. As a result, water and air exchange conditions deteriorate and soil structure is disrupted.

Irrational irrigation poses a particular threat, especially when using water with high mineralisation. In the context of climate change, such practices can significantly accelerate the development of secondary salinisation, especially on irrigated lands in southern regions.

Soil salinisation is accompanied by an increase in alkalinity, degradation of structure, reduced permeability, disruption of water and air regimes, and a significant decrease in biological activity. This leads to a reduction in the availability of nutrients for plants and the creation of toxic conditions for their development.

According to estimates by the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine, in the absence of adaptation measures, the area of soil with a potential risk of salinisation could increase by 15–20% by 2050.

Thus, climate change significantly increases the risks of soil degradation due to salinisation and alkalisation. This requires systematic monitoring, improvement of irrigation management systems, implementation of land reclamation measures and adaptive land use aimed at preserving soil fertility.

5. Deterioration of agrophysical properties. The agrophysical properties of soils – structure, density, water permeability, porosity and moisture capacity – are key indicators that determine their fertility and ability to provide plants with optimal conditions for growth. In the context of climate change, these properties are significantly deteriorating due to rising temperatures, reduced precipitation, increased frequency of extreme weather events and water regime disturbances.

Changes in soil structure: High temperatures and low humidity contribute to the formation of a hard crust on the soil surface, which impairs water permeability and aeration, hindering root system development. Frequent alternation between moisture and drying leads to the destruction of soil aggregates, deterioration of the granulometric structure, and a decrease in water and air permeability.

Soil compaction: Prolonged absence of precipitation combined with the use of heavy equipment on dry soils causes soil compaction, reduced porosity and water stagnation after heavy rains. This negatively affects the availability of oxygen to the root system and the development of soil biota.

Decreased water retention capacity: Deterioration of soil structure and loss of organic matter in conditions of moisture deficiency reduce the soil's ability to accumulate and retain moisture, which is critical during the growing season of agricultural crops.

Disruption of natural moisture: Lowering of the groundwater level and degradation of soil structure due to climate change complicate the capillary rise of moisture to the root zone, especially on light and sandy soils.

Changes in soil temperature: Rising temperatures contribute to rapid warming of the surface soil layer, but also accelerate moisture evaporation. This can lead to overheating of the root system, which negatively affects plant development.

Such processes are particularly pronounced in the southern and central regions of Ukraine, where climatic extremes threaten the physical condition of the soil. The systematic deterioration of the agrophysical properties of soils reduces their productivity and requires the introduction of adaptive agricultural technologies, such as: no-till farming, mulching, the use of organic fertilisers, agroforestry and moisture conservation technologies.

6. Deterioration of quality indicators. Climate change significantly affects not only the physical parameters of the soil, but also its quality characteristics, which directly affects its fertility, ecological functionality and ability to self-regenerate.

Among the main changes in soil quality caused by climate change, the following should be highlighted:

- decreased biological activity: high temperatures and moisture deficiency negatively affect microbiological activity, change the structure of soil biocenoses, and reduce the number of beneficial microflora, earthworms, and other components of the soil biota;
- deterioration of chemical composition: as a result of dehydration and intense evaporation, the concentration of salts in the soil solution increases, the risk of secondary salinisation increases, the acid-base balance changes and the toxicity of the soil environment increases;
- impaired buffering capacity: degumification and reduced organic matter content reduce the soil's ability to neutralise harmful substances. This increases the risk of contamination and impairs the ecological stability of agricultural landscapes;
- weakening of sorption properties: the destruction of the organic part and the reduction of the colloidal fraction lead to a decrease in the ability of soils to retain nutrients. As a result, nutrient losses due to leaching or erosion processes increase;
- change in nutrient availability: due to uneven moisture, leaching and redox fluctuations, the availability of both major elements (nitrogen, phosphorus,

potassium) and trace elements (boron, zinc, manganese, etc.) changes, which complicates plant nutrition.

7. Change in biological activity. Biological activity is one of the key indicators of soil fertility, as it ensures the transformation of organic matter, the circulation of nutrients, structure formation and detoxification. Climate change, in particular rising air temperatures and decreasing precipitation, has a significant negative impact on biological processes in the soil environment.

Soil degradation is accompanied by a reduction in the number and activity of soil biota. According to the National Academy of Agrarian Sciences of Ukraine, a decrease in microbial diversity weakens soil fertility and reduces the resistance of ecosystems to stress factors. High temperatures and moisture deficiency limit the vital activity of key microorganisms – bacteria, fungi, actinomycetes – especially in surface horizons. Disruption of the hydrothermal regime causes an imbalance in the soil microbiota: the proportion of conditionally pathogenic or stress-resistant forms increases, inhibiting the development of symbiotic microorganisms (in particular, nitrogen-fixing bacteria and mycorrhizal fungi).

Soil dehydration and degumification processes have a negative effect on enzymatic activity: the action of hydrolases, oxidases and other enzymes responsible for the mineralisation of organic matter and the transformation of nutrients is reduced. Moisture deficiency also negatively affects soil meso- and macrofauna (earthworms, mites, springtails), contributing to the deterioration of soil structure, aeration and overall biological activity.

Due to the reduction in the intensity of microbial decomposition of plant residues, humus formation processes slow down and humus content decreases, which in the long term worsens soil fertility.

According to research by the O.N. Sokolovsky Institute of Soil Science and Agrochemistry, a national scientific centre, in some regions of Ukraine, particularly in the southern steppe, soil biological activity has decreased by 25–40% over the last two decades.

2.8. Impact of climate change on crop production

According to FAO recommendations on optimal temperatures, almost all crops that develop at optimal temperatures of 15–20°C, 25–30°C, and 20–30°C can already be grown in the country (Table 2.1), with the exception of perennial crops that cannot withstand the long periods of low temperatures observed in Ukraine in autumn and winter.

Table 2.1. Optimal temperature values for growing different types of agricultural crops[18]

Optimal temperature for photosynthesis (°C)				
15–20	25–30	30-35	20 - 30	25–35
Sugar beet Beans Wheat Barley Oats Potatoes Lupins	Soy Rice Cassava Sweet potatoes Yams Peanuts Cotton Tobacco Banana Coconut	Sorghum Millet Setaria Sugar cane	Corn	Sisal Pineapple

Currently, there is a consensus among experts that the main climate changes are caused by rising temperatures, and the only tool for assessing the impact of temperature on crop yields is biophysical modelling. The results of modelling confirm the importance of known key physiological processes, such as a reduction in crop maturation time with an increase in average temperature (Iqbal et al., 2009), a reduction in the formation of productive plant organs when high temperatures are observed during flowering (Moriondo et al., 2011), and increased stress due to water shortage at high temperatures during the growing season (Lobell et al., 2013a). The response of plants to optimal temperatures for crop development and productive organ formation is well known, but the impact of prolonged periods of temperatures exceeding the optimum for plant development is not as well studied (Craufurd and Wheeler, 2009).

For example, it is assumed that temperatures above 32–34°C after flowering rapidly accelerate wheat ageing (Asseng et al., 2011; Lobell et al., 2012). However, there is not much experimental data to confirm this effect. Accordingly, a more sophisticated analysis of these data is needed to separate the effect of wheat ageing from, for example, drought, because extreme temperatures are usually accompanied by a prolonged rainless period. Biophysical models of agricultural crops can be used to quantitatively assess such abiotic stresses at the level of individual fields or farms, but the quality of the result on a regional scale is not entirely clear. Despite the lack of specific understanding on this issue, regional statistical analysis data (Schlenker and Roberts, 2009) and models demonstrate a clear negative impact of temperatures above 30°C to 34°C on crop yields, regardless of the crop (Fig. 2.8).

[18] https://www.fao.org/4/x5648e/x5648e0e.htm

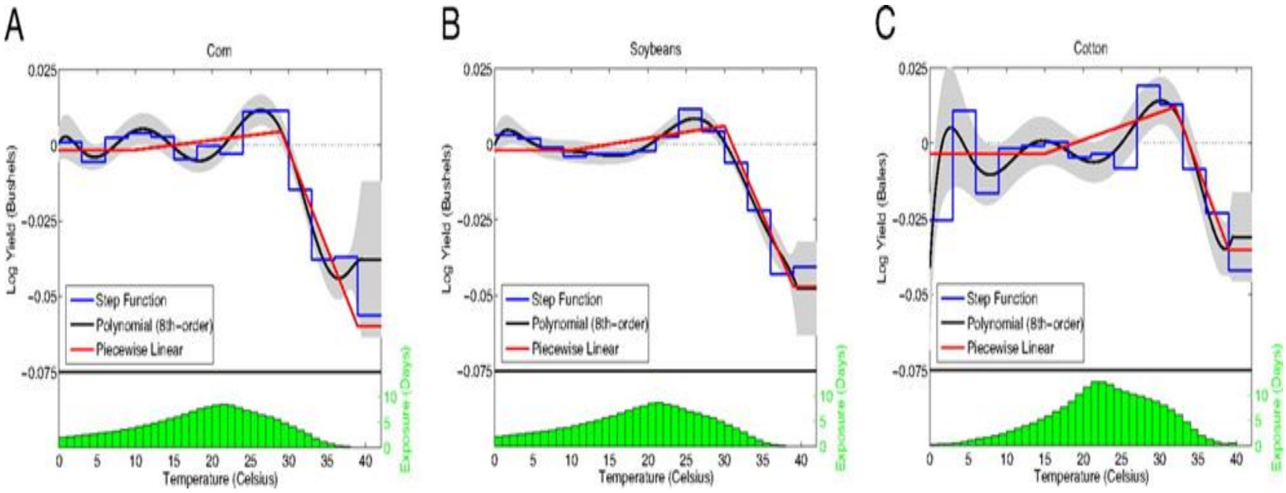

Figure 2.8. Non-linear relationship between temperature and yield, maize, soybeans and cotton (Schlenker and Roberts, 2009)

The overall relationship between weather and yield often depends on the crop and region, differences in basic climatic conditions, management practices (agronomic management) and soil quality, as well as the duration and timing of extreme weather events affecting the crop. Another factor affecting yield, also dependent on climate change, is pests, animals and (non-viral) pathogens. On average, worldwide crop losses for major crops due to this, in the absence of any physical, biological or chemical plant protection, are estimated at 18% and 16% respectively (Oerke, 2006), but the greatest potential losses are caused by weeds (34%).

Climate change will alter the potential losses from many pests and diseases, as rising temperatures may lead to geographical shifts due to changes in extreme seasons and, thus, for example, overwintering and summer survival. The scarcity of long-term studies of plant diseases and pests is a challenge for assessing the impacts of climate change, but there are a few examples of the potential for such analysis. Experiments with wheat, ongoing at the Rothamsted Research Station in the UK for over 160 years, have revealed changes in wheat leaf pathogens associated with precipitation, temperature and sulphur dioxide (SO_2) emissions (Bearchell et al., 2005; Shaw et al., 2008). The risk of wheat rust has been found to respond to El Niño and the Southern Oscillation (ENSO; Scherm and Yang, 1995). Over nearly seven decades in Finland, earlier and more frequent epidemics of potato blight and more frequent pesticide use have been observed, associated with changing climatic conditions and the absence of crop rotation (Hannukkala et al., 2007).

Climate change is expected to affect the geographical range of certain insect species and diseases for different crop-growing regions. For example, Cannon (1998) suggested that migratory insects may colonise more crops as a result of rising temperatures, with a subsequent decline in crop yields. Climate change may also be a factor in the northward expansion of agronomic and invasive weeds (Ziska et al., 2011). Overall, the ability to predict the impact of $CO_{(2)}$ /climate change on pathogen biology and subsequent changes in crop yields is limited because, with a few exceptions (Savary et al., 2011), experimental data are not available and analyses focus on individual diseases rather than the full range of important diseases. Elevated CO_2 may reduce yield losses due to weeds for C_3 crops (soybean, wheat, and rice). However, both $C_{(3)}$ and $C_{(4)}$ weed species are found in agriculture, and there is a wide range of responses of these species to current and projected $CO_{(2)}$ levels (Ziska, 2010).

2.9. Impact of climate change on animal husbandry

Recent studies paint a complex picture of the current and future impacts of climate change, pointing to widespread deterioration of ecosystems and a decline in the planet's ability to adapt to these impacts, as well as outlining the associated negative socio-economic consequences, including species loss and mass die-offs in terrestrial and marine ecosystems, some of which are irreversible. In addition, the negative impact of climate change on agriculture, both crop production and animal husbandry, is being felt in all regions of the planet.

Animal husbandry, due to greenhouse gas emissions from manure use, intestinal fermentation of livestock and the use of fossil fuels, is one of the causes of climate change, but on the other hand, it itself suffers from climate change and therefore needs to adapt to it[19].

Climate change has already affected animal husbandry, both directly through heat stress, which affects animal mortality and productivity, and indirectly through its impact on pastures, the spread of diseases and plant pests. Between 1961 and 2006, crop losses due to droughts and changes in precipitation and droughts are estimated at 25%. Observed and projected future impacts on food systems are presented in Chapter 5 of the IPCC Working Group II report (2022). Studies cited in the working group report predict that by the end of the century, the risk of extreme heat stress will increase for all animal species in many regions of the world. This impact will increase as global temperatures continue to rise, and the IPCC warns that as temperatures rise, animals eat on average 3–5% less for every additional degree of warming, which harms their productivity and fertility.

Livestock may also be vulnerable to more diseases. The IPCC notes that zoonoses — diseases that can be transmitted from humans to animals — are more sensitive to climate change than pathogens that are specific to humans or animals. The ranges of disease-carrying insects and other arthropods will expand as the climate warms, while more extreme weather events caused by climate change will also contribute to the spread of disease.

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[19] https://openknowledge.fao.org/server/api/core/bitstreams/b596217c-a6c9-47ad-ab4b-83bd760d291c/content

Under current climatic conditions, animal husbandry and feed production in Ukraine are experiencing negative impacts depending on the following factors:

- an increase in the average annual air temperature and average monthly air temperatures, especially in spring and summer;
- an increase in the number of days with abnormally high temperatures, which negatively affects the condition of plants and animals;
- increased frequency of droughts, particularly in combination with extremely high temperatures;
- sharp temperature fluctuations between seasons and during individual months and days, causing a decrease in the stability of many fodder crops;
- an increase in the frequency of extreme weather events during the warm season (heavy rains, thunderstorms, tornadoes, squalls, hail);
- a decrease in the frequency of precipitation and an increase in its intensity, which hinders the accumulation of soil moisture and worsens conditions for harvesting, grazing and keeping animals;
- increased unevenness of precipitation during certain periods of the year, which affects the supply of drinking water to livestock;
- lack of stable snowcover, which, with a significant drop in temperature, hinders the accumulation of moisture in the soil and reduces the yield of fodder crops;
- favourable weather conditions (high temperatures and humidity) for the spread of pests, diseases and invasive plant species, which can reduce productivity, fodder crop cultivation and affect the health of livestock;
- an increased likelihood of fires, which disrupts the stability of ecosystems, causes crop losses, reduces the sector's adaptive capacity to climate change and increases the impact of each climate factor.

According to current climate change assessments, the animal husbandry sector worldwide is expected to face additional accumulated heat stress on livestock, which will intensify as the climate warms.

Chapter 5 of the IPCC Working Group II report (2022) also emphasises that with a warming of only 2°C, livestock numbers will decline by 7–10% by 2050, which could result in economic losses of between 10 and 13 billion US dollars. Studies have shown that up to 34% of existing areas for growing crops and animal feed will become unsuitable by the end of the century at the upper limit of the projected temperature increase. The regions most at risk are those where the world's largest livestock-producing countries are located, such as Brazil, China and India.

Under the most extreme IPCC scenario, corresponding to a global temperature increase of 4.3° C, one-third of global food production could be pushed beyond the safe climate space (SCS) by 2081–2100. The latest report by IPCC Working Group II (2022) predicts that by mid-century, 10% of the land currently used for growing major crops and raising animal husbandry will become unsuitable for this purpose. The impacts of climate change on food production will be even more severe if global temperatures rise above 2°C. Under current policy trends, the world is on track for warming of approximately 2.7°C.

Rising temperatures will also cause water resources to become depleted. Animal husbandry, particularly the production of animal feed, currently consumes 30% of all water used in agriculture. With a 2.7°C warming, water consumption by livestock is projected to increase by 13%, which could exacerbate competition between human needs and agricultural production. It should also be noted that highly productive animal husbandry systems can consume more water than grazing or mixed systems.

According to the report, losses in beef and milk production in tropical and subtropical regions could be even greater, leading to annual economic losses of around $9 billion for dairy products and $31 billion for beef production by the end of the century. This represents approximately 7% and 20% of the global production value of these commodities (in constant 2005 prices).

2.10. Future threats of climate change

In this report, future climate change threats to agriculture were analysed using modern methodological approaches presented, in particular, in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Working Group I (IPCC AR6 WGI, 2021) and tested in the APENA 3 project. In particular, climatic impact-drivers were calculated and assessed, which, according to the IPCC glossary "physical conditions of the climate system (e.g., averages, events, extremes) that affect an element of society or ecosystems. Depending on the vulnerability and resilience of the system, factors and their changes can be harmful, beneficial, neutral, or a mixture of each of the interacting system elements and regions."

A total of 32 CIDs were considered (Table 2.2), divided into 5 types, in which 14 categories were selected that correspond to the climate of Ukraine, according to the IPCC classification (Table 12.2 WGI AR6, 2021[20]).

First and foremost, these are the following types:

- heat and cold (average and extreme temperature indicators);
- wet and dry (average and extreme factors);
- snowfall and snowcover (average and extreme snowfall);
- wind (average speed and gusts);
- coastal (sea level and storm surges).

That is, each type includes categories that characterise changes in both average and extreme factors of climatic influence.

[20] https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-12/

Thus, a total of 32 indicators were analysed, almost half of which characterise the temperature regime. Specifically, five CIDs characterise the negative impact of rising mean air temperatures: over the year and in the central months of all seasons (January, April, July and October), and a negative impact is also expected from a reduction in the length of the growing season. Four CIDs characterising the negative impact of rising heat indices are based on daily maximum and minimum air temperatures. To assess the negative impact of climate change, two categories with four CIDs have also been identified, relating to the possible increase in cold spells and, accordingly, the increase in degree days of the heating period, and the number of frost days and days with freezing temperatures, which cannot be ruled out even with general warming, especially in the current period 2021–2040.

The category of wet and dry also includes factors based on the average amount of precipitation per year and in the central months of the seasons, with a negative impact expected from a decrease in these average indicators, while for factors characterising the extremity of the precipitation regime, the negative impact corresponds to their increase. To assess the degree of impact of increased aridity, an index was used that characterises the maximum duration of the dry period. This category also includes an index of the increase in the number of days with fire-hazardous weather conditions, which are recognised as exceeding a value of 30 for the Fire Weather Index (FWI).

The category of factors characterising snowcover includes two based on average indicators (annual precipitation in the form of snow and the number of days with snowcover over 30% of the territory), a decrease in which indicates a negative impact, and an increase in the number of days with snowfall exceeding 10 mm per day is also included to assess the impact of changes in extremes.

The negative impact of changes in wind patterns was assessed by the increase in average wind speed, as well as the number of days per year with wind gusts exceeding 6 on the Beaufort scale (10.8 m/s).

Coastal indicators of sea level rise and storm surge height were determined using data from the Joint Research Centre (JRC) LISCOAST global model for all coasts of the World Ocean. The negative impact corresponded to an increase in the values of both factors.

Table 2.2. Categories of climatic impact-drivers (CID) and limits for determining the degree of impact of their changes (from 0 to 1)

IPCC CID	IPCC CID Category	CID name	Units	Negligible 0		Low 0.25		Medium 0.50		High 0.75		Very high 1
HEAT AND COLD	↗ MEAN AIR TEMPERATURE	↗ Annual near surface air temperature	°C		0.5		1.0		2.0		4.0	
		↗ January mean air temperature	°C		0.5		1.0		2.0		4.0	
		↗ April mean air temperature	°C		0.5		1.0		2.0		4.0	
		↗ July man air temperature	°C		0.5		1.0		2.0		4.0	
		↗ October mean air temperature	°C		0.5		1.0		2.0		4.0	
		↘ Growing season length	days/year		-2		-5		-10		-15	
	↗ EXTREME HEAT	↗ Mean of maximum daily air temperature in summer	°C		0.5		1.0		2.0		4.0	
		↗ Days with very high and extreme heat	day/year		5		10		20		30	
		↗ Tropical nights	day/year		10		20		30		50	
		↗ Humidex index for the mean maximum air temperatures in summer	u.o.		25		30		35		40	
		↗ Cooling Degree Days (CDD))	degree days/year		50		100		200		300	
	↗ COLD WAVES	↘ The temperature of very cold days in the winter months	°C		-0.5		-1.0		-2.0		-4.0	

		↗ Heating degree days	degree days/year		50		100		200		300	
	↗ FROST	↗ Frost days	day/year		0		5		10		20	
		↗ Ice days	day/year		5		10		20		30	
WET AND DRY	↘ MEAN PRECIPITATION	↘ Annual precipitation	%		-5		-10		-15		-20	
		↘ January precipitation	%		-5		-10		-15		-20	
		↘ April precipitation	%		-5		-10		-15		-20	
		↘ July precipitation	%		-5		-10		-15		-20	
		↘ October precipitation	%		-5		-10		-15		-20	
	↗ HEAVY PRECIPITATION AND PLUVIAL FLOODS	↗ Maximum 5-days precipitation	mm		5		10		15		20	
		↗ Maximum 1-day precipitation	mm		2.5		5.0		7.5		10.0	
		↗ Very heavy precipitation annual sums	%		0		10		20		30	
	↗ DROUGHT	↗ Maximum duration of drought in 20 years	day/year		30		40		50		60	
	↗ NUMBER OF DAYS WITH FIRE WEATHER FWI >30	↗ Fire hazard index > 30	day/year		5		10		15		20	
SNOWFALL AND SNOWCOVER	↘ SNOWFALL AND SNOW COVER	↘ ANNUAL SNOWFALL	mm		-3		-10		-20		-30	
		↘ NUMBER OF DAYS WITH SNOWCOVER ≥30%	day/year		0		-20		-40		-60	
	↗ NUMBER OF DAYS WITH SNOWFALL ≥ 10 MM PER DAY		day/year		0.1		0.3		0.5		1.0	
SURFACE WIND SPEED	↗ AVERAGE WIND SPEED		m/s		0.01		0.10		0.20		0.30	
	↗ WIND GUSTS ≥ 10.8 M/S (6 BEAUFORT)		day/year		0.1		2.0		3.0		4.0	
COASTAL	↗ RELATIVE SEA LEVEL RISE		m		0.05		0.15		0.30		0.45	

	EXTREME SURGE STORM LEVEL (COASTAL FLOOD)	m		2.0		2.5		3.0		3.5	

Climate change in Ukraine in the near and distant future was determined based on data from 34 regional climate models (RCMs) of the EURO CORDEX project for representative concentration pathway scenarios (Representative Concentration Pathways) RCP 4.5 and RCP 8.5, where the numbers correspond to additional radiative heating in watts per square metre by the end of the 21st century. The models have a detailed spatial (0.11°) and temporal (daily) resolution, which made it possible to form high-quality time series of key climate indicators and calculate climate indices based on them. The values of the climate indices themselves serve as a measure of the intensity of the impact of climate change on natural and artificial ecosystems.

To assess climate change, as well as vulnerability and risks to agriculture, the territory of Ukraine was divided into five main geographical regions, taking into account administrative divisions, the similarity of climate-forming factors and, accordingly, the similarity of climatic conditions (Fig. 2.9):

- the **Western** region includes Rivne, Volyn, Lviv, Zakarpattia, Ternopil, Khmelnytskyi, Chernivtsi and Ivano-Frankivsk regions;
- **The North region** includes Zhytomyr, Kyiv, Chernihiv and Sumy regions;
- The **East** region includes Kharkiv, Luhansk and Donetsk regions;
- **the Centre** region includes Poltava, Dnipropetrovsk, Kirovohrad, Cherkasy and Vinnytsia regions;
- and the **South** region includes Zaporizhzhia, Mykolaiv, Kherson, Odesa regions and the Autonomous Republic of Crimea

There are also three specific geographical zones in Ukraine, namely two mountainous areas of the **Carpathian** and **Crimean** Mountains, which are defined as being more than 400 m above sea level, as well as the **coastal** area of the Black and Azov Seas as areas along the coasts and estuaries with a buffer of 0.1° from the coastline.

According to the calculations, the changes expected in the current period of 2021–2040 are comparable in both scenarios and will be most pronounced in the western, northern and southern regions. By the middle of the century, in the period 2041–2060, according to the RCP 4.5 scenario, a further increase in air temperature in Ukraine is expected. The average annual temperature will increase at a rate of 0.27^0 /10 years, and in this regard, there will be an increase in the values of indices based on high temperatures. This will increase the number of summer days at a rate of 3.0/10 years and tropical nights at a rate of 2.5/10 years. Climate indices based on low temperatures will decrease, for example, the number of frost days by -3.2/10 years. Precipitation indices for this period show a predominantly positive trend of +2.39 mm/10 years. According to the RCP 8.5 scenario, the increase in air temperature will be more intense at a rate of 0.68^0/10 years. Obviously, the number of extreme events caused by high temperatures will increase. For example, the number of tropical nights will increase by 7.9/10 years. Indices based on low temperatures will decrease sharply, with the number of frost days decreasing by -6.9/10 years. For this period, a slight increase in the number of days with heavy precipitation is forecast at 0.16/10 years.

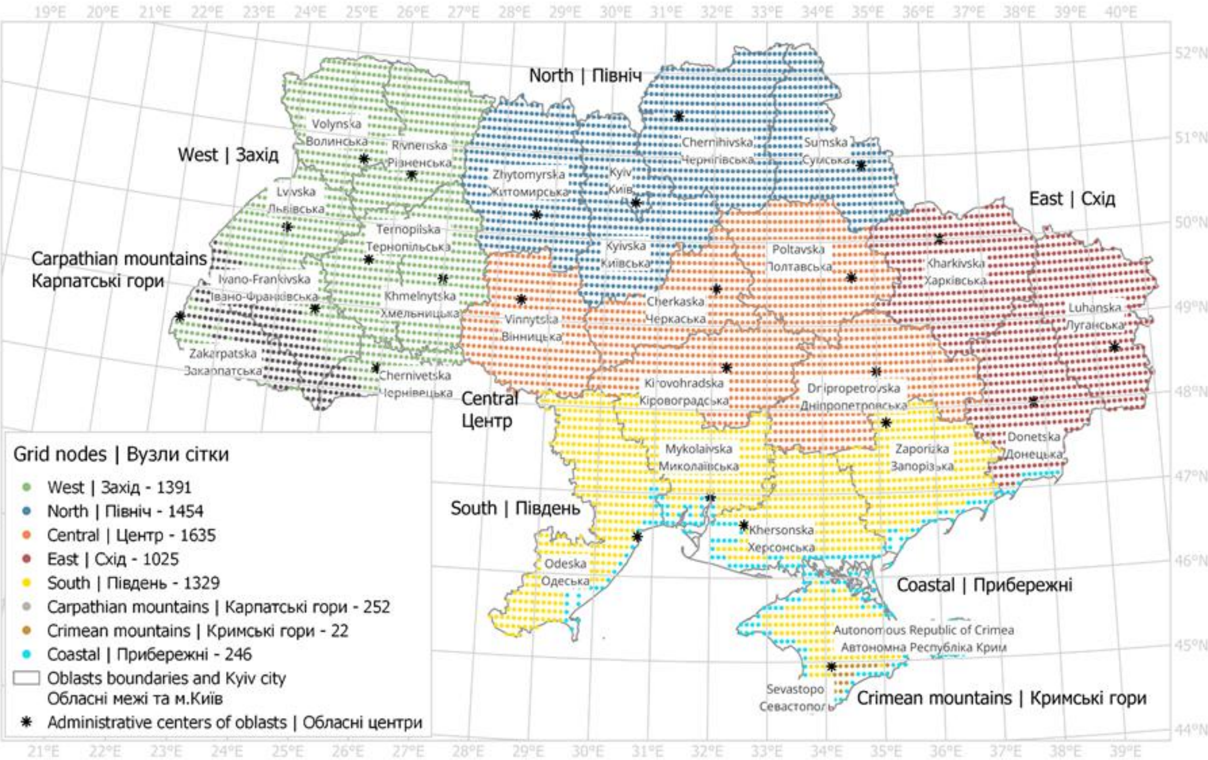

Figure 2.9. – Zoning of Ukraine by region

For the distant future at the end of the century, in the period 2081–2100, according to modelling data, more intense changes are to be expected compared to the middle of the century, especially in the rate of increase in air temperature in the southern, eastern and central regions. It should also be noted that for this period, a significant difference in the rate of change in air temperature and values of indices based on high temperatures is expected; for the RCP 8.5 scenario, the background values and rates of change will be the highest. For the RCP 4.5 scenario, there is a greater increase in annual precipitation totals than for RCP 8.5, while the number of days with heavy precipitation is comparable.

In addition to the average values of negative impacts by category, it is clear that risk assessment also requires the identification of those factors whose changes are expected to have the greatest negative impact. Therefore, in the specified categories, the maximum degree of impact in the category where there was more than one factor was also found and analysed at each node of the calculation grid.

For convenience and to enable comparison of the impact of threats both within the region itself according to scenarios and categories of factors, and with other regions, six histograms were constructed for each region for two scenarios and three periods until the end of the 21st century, where colours with numbers indicate the contribution of each category of factors to the overall threat from changing climatic conditions (Figs. 2.10–2.17).

To this end, the maximum degrees of impact for each of the threats were determined in each region in fractions of a unit (Table 2.2), which were multiplied by 10 to transform them into scores within a range of 10 points, which were then summed for all 10 categories except for the two coastal ones. Thus, for all regions except the coastal ones, for the maximum possible score for the 10 threat categories will be 100%, and for coastal regions it will also be 100% due to the combination and determination of the maximum threat among a pair of wind CIDs (average speed and gusts) and a pair of coastal CIDs (sea level rise and increase in extreme storm surge height). At the same time, for each category, the maximum threat level can be identified by the points shown in the columns. The absence of colour indicates no threat from changes in CIDs in the relevant category; 2.5 corresponds to a low threat; 5 is a medium level of threat; 7.5 and 10 are high and very high levels of threat, respectively (Figs. 2.10–2.17).

For the **Western** region throughout the 21st century, for all periods and both scenarios, there remains a very high threat of increased extreme precipitation, which can lead to heavy rains and flash floods (10 points in Fig. 2.10). Also, for the RCP 4.5 scenario, there is a very high threat of an increase in days with snowfall exceeding 10 mm, although for the RCP 8.5 scenario, it gradually decreases, apparently due to more rapid warming and less precipitation in the form of snow. This confirms the observed increase in the threat of a decrease in snowcover and snowfall from high in the current period to very high in the future for both scenarios.

The threat of an increase in mean temperature and extreme heat is very high only at the end of the century under the RCP 8.5 scenario, in previous periods it is high, and for the RCP 4.5 scenario it is only medium. Also, for both scenarios, the threat of increased droughts is medium for both scenarios, with only the middle of the century under the RCP 8.5 scenario showing a high threat of an increase in this category. Droughts are directly related to a decrease in precipitation, but in the western region, only a low level of threat of change in this CID is obtained for all periods under the RCP 8.5 scenario, and for RCP 4.5 only in the current period.

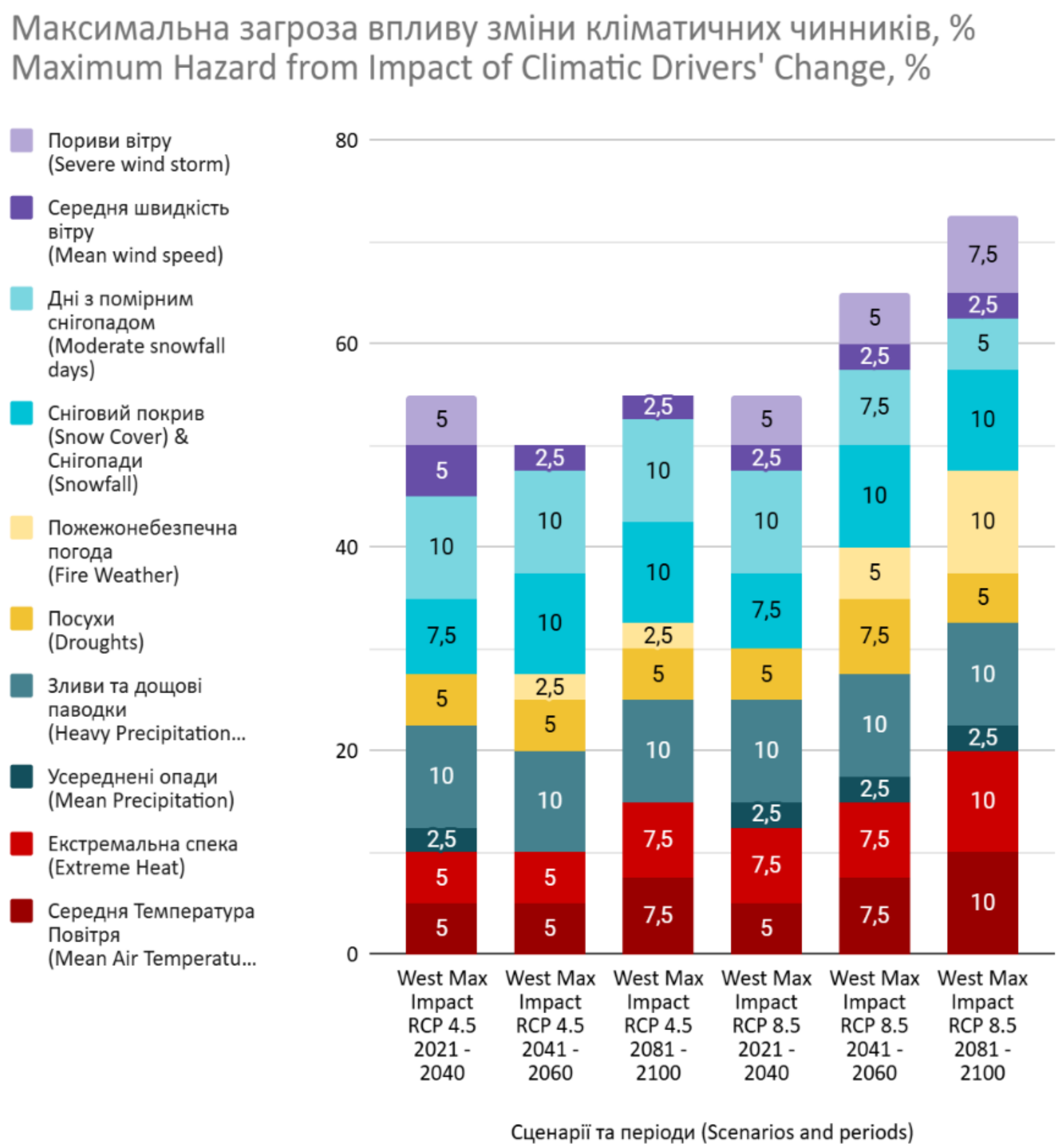

Figure 2.10. – Maximum by category and total threat levels for the Western region by scenario and period until the end of the 21st century relative to the period 1991–2010

On the other hand, fire-dangerous weather poses a very high threat at the end of the century and a high threat in the middle of the century under the high concentration scenario RCP 8.5, although under the moderate concentration scenario RCP 4.5, there is no threat in the current period and a low level from the middle to the end of the century. For indicators of increased wind speed and gusts in the current period, the highest medium-level threat was obtained for both scenarios for gusts and for the moderate scenario for increased wind speed. The threat of increased wind speed becomes low from the middle to the end of the century for the moderate scenario and remains low for all periods under the high concentration scenario, for which the threat of increased wind gusts at the medium level persists throughout the century. Thus, the total threat of change in all categories of climatic impact-drivers in the western region ranges from 50 to 72.5% throughout the 21st century. At the same time, in the current period, the total threat is the same for both scenarios and amounts to 55%, but then decreases to 50% and by the end of the century reaches 55% again for the moderate concentration scenario RCP 4.5, but increases significantly for the high concentration scenario RCP 8.5 to 65% by the middle of the century and to 72.5% by the end.

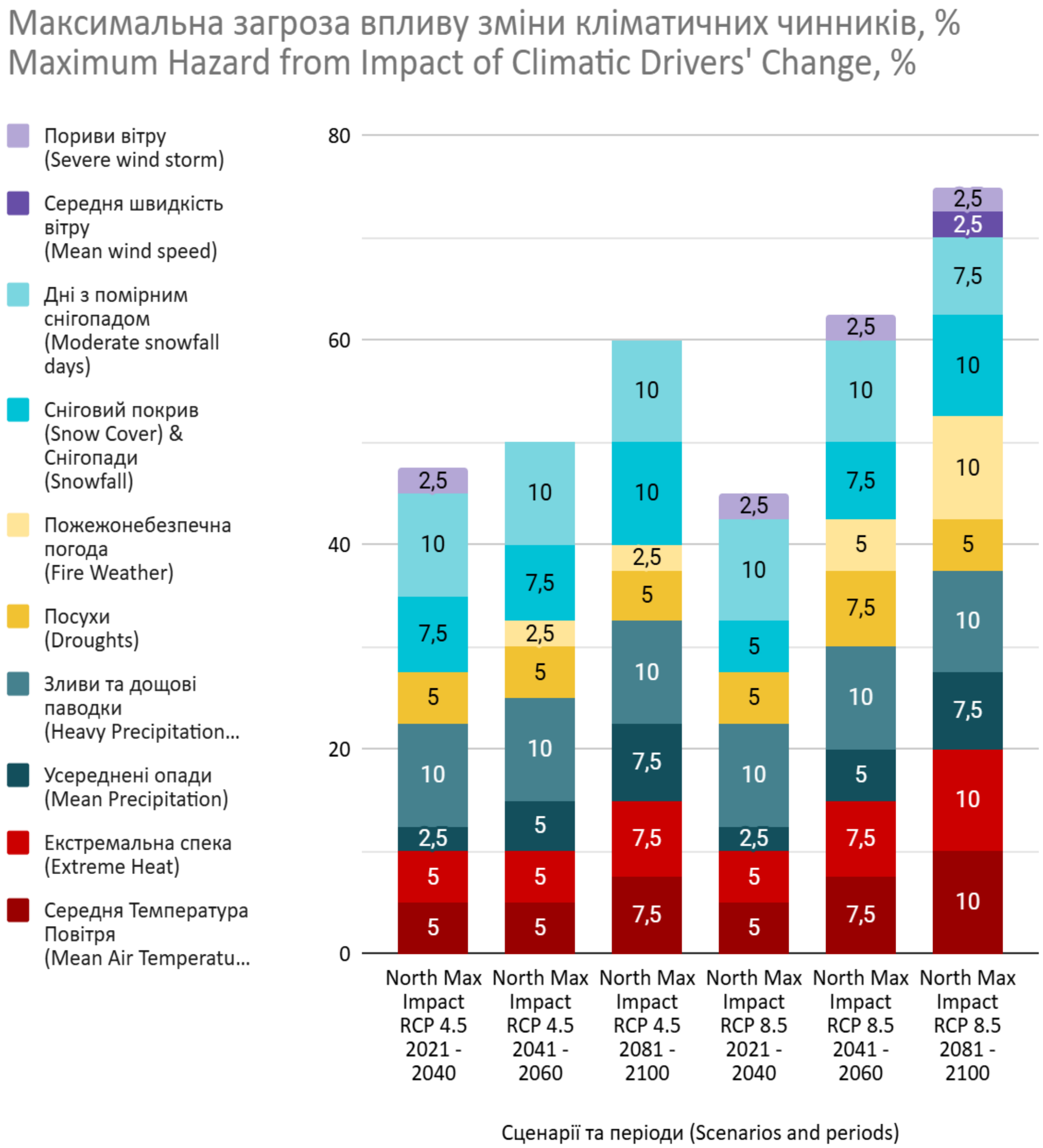

Figure 2.11. – Maximum by category and total threat levels for the Northern Region by scenario and period until the end of the 21st century relative to the period 1991–2010

For the **Northern** region, estimates of maximum threats from changes in climatic impact-drivers are similar to those for the Western region. Thus, throughout the 21st century, for all periods and both scenarios, a very high threat of increased extreme precipitation was obtained, which could cause heavy rains and flash floods (10 points in

Fig. 2.11). Also, for both scenarios, there is a very high threat of an increase in days with snowfall exceeding 10 mm, although under the RCP 8.5 scenario, it decreases to high by the end of the century, apparently due to more rapid warming and less precipitation in the form of snow. This confirms the observed increase in the threat of reduced snowcover and snowfall from high and medium for the moderate and high concentration scenarios, respectively, in the current period to high in the middle and very high by the end of the century for both scenarios. The threat of an increase in mean temperature and extreme heat is very high only at the end of the century under the RCP 8.5 scenario, it is high in previous periods, and for the RCP 4.5 scenario it is only moderate until the middle of the century. Also, for both scenarios, the threat is medium and from an increase in drought, only by the middle of the century under the RCP 8.5 scenario is there a high threat of an increase in this factor, similar to the western region.

Droughts are directly related to a decrease in precipitation, and in the northern region, the threat level of this factor increases from low for the current period, medium in the middle of the century, to high at the end of the century under both scenarios. However, as in the western region, fire-dangerous weather poses a very high threat at the end of the century and a high threat in the middle of the century, with no threat in the current period under the high concentration RCP 8.5 scenario, although for the moderate concentration scenario RCP 4.5, there is also no threat in the current period and a low level from the middle to the end of the century. For indicators of increased wind speed and gusts for the northern region, lower threat levels were obtained overall compared to the western region. Thus, for both scenarios, a low level of threat from increased wind gusts was obtained for the current period.

The low level of threat from wind gusts remains for the RCP 8.5 scenario throughout the century, and at the end, a low level of threat from increased wind speed is also added. Thus, the total threat of change in all categories of climatic impact-drivers in the northern region has a greater range of values than in the western region, ranging from 45% to 75% throughout the 21st century for both scenarios. At the same time, in the current period, the total threat is lower for the RCP 8.5 scenario (45%) and higher (47.5%) for the RCP 4.5 scenario. However, in the future, the rate of increase in threats under the RCP 8.5 scenario will accelerate and, by the middle of the century, will significantly exceed the total threat under the RCP 4.5 scenario: 50% by the middle and 60% by the end of the century, compared to 62.5% and 75% for the high concentration RCP 8.5 scenario by the middle and end of the century, respectively.

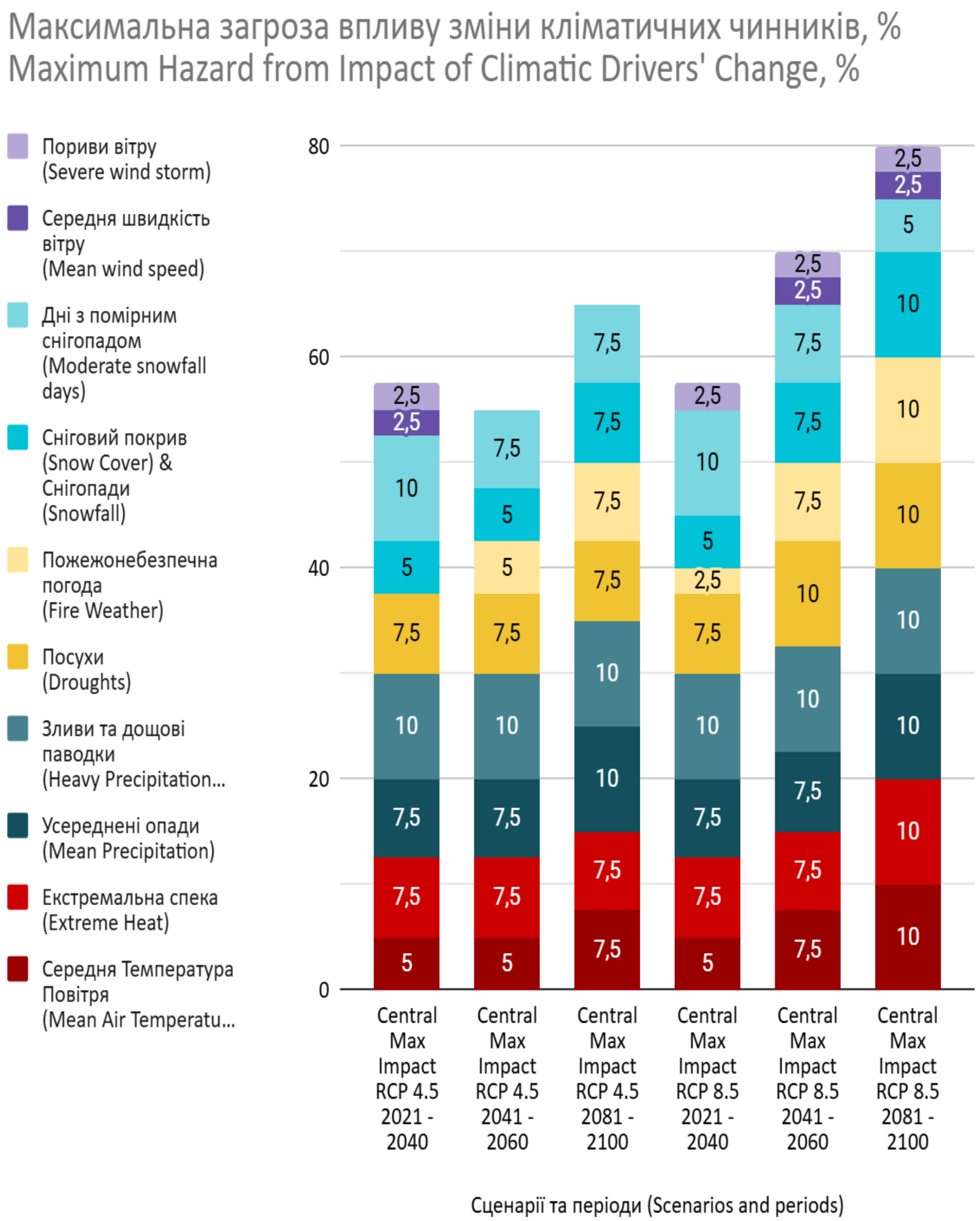

Figure 2.12. – Maximum by category and total threat levels for the Central region according to scenarios and periods until the end of the 21st century relative to the period 1991–2010

For the **Central** region as a whole, similar estimates were obtained for the western and northern regions, but with an increase in threats associated with reduced moisture. At the same time, throughout the 21st century, for all periods and both scenarios, there remains a very high threat of increased extreme precipitation, which can cause heavy rains and flash floods (10 points in Fig. 2.12). At the same time, slightly lower threats from an increase in days with snowfall above 10 mm are obtained in the centre, although for both scenarios a very high threat remains in the current period, with the threat level decreasing to high by the middle and end of the century under the moderate RCP 4.5 scenario. However, under the RCP 8.5 scenario, the threat decreases to medium by the end of the century, apparently due to more rapid warming and less precipitation in the form of snow. This confirms the observed increase in the threat of reduced snowcover and snowfall from moderate for both scenarios in the current period to high by the middle and very high by the end of the century for the RCP 8.5 scenario and moderate and high for RCP 4.5, respectively.

Unlike the western and northern regions, the centre has a high level of threat from increased drought throughout the century for RCP 4.5. There is also a high level of threat in the current period under the RCP 8.5 scenario, but from the middle of the century there is a very high threat of an increase in this CID, unlike the regions mentioned above. Droughts are directly related to a decrease in precipitation, and in the centre, the threat level of this factor increases from high in the current period and in the middle of the century to very high at the end of the century in both scenarios. Similar to the northern and western regions, the distribution of threats from fire-dangerous weather is also obtained in the central region. Thus, a very high threat at the end, high in the middle of the century and low in the current period is obtained under the high concentration scenario RCP 8.5, although for the moderate concentration scenario RCP 4.5, there is no threat in the current period and a medium and high level in the middle and end of the century, respectively.

The threats of an increase in mean air temperature and extreme heat are very high only at the end of the century under the RCP 8.5 scenario, while in previous periods the threat of an increase in heat is high for both scenarios, and for the mean air temperature, the threat is medium for the RCP 4.5 scenario until the middle of the century and for RCP 8.5 only in the current period, increasing to high by the middle of the century. For indicators of increased wind speed and gusts for the central region, intermediate threat levels between western and northern were obtained. Thus, for both scenarios, a low level of threat from increased wind gusts is obtained for the current period, but for the RCP 4.5 scenario, a low level of threat from increased wind speed is also added. The low threat level from wind gusts remains for the RCP 8.5 scenario throughout the century, and from the middle to the end of the century, a low threat level from increased wind speeds is also added. Thus, the total threat of change in all categories of climatic impact-drivers in the central region has the highest value of 80% among all regions, with the exception of the coastal region, where coastal CIDs are added to the total threat of the ten categories of factors presented. In the central region, the total threat is currently the same for both scenarios, as in the western region, but the value is higher - 57.5%, and similarly, by the middle of the century, the threat level decreases to 55% for the RCP 4.5 scenario due to the absence of threats from wind CIDs. However, under the RCP 8.5 scenario, the rate of increase in threats increases significantly and, by the middle of the century, significantly exceeds the total threat under the RCP 4.5 scenario at the end of the century (60%) compared to 70% and 80% for the high concentration RCP 8.5 scenario in the middle and end of the century, respectively.

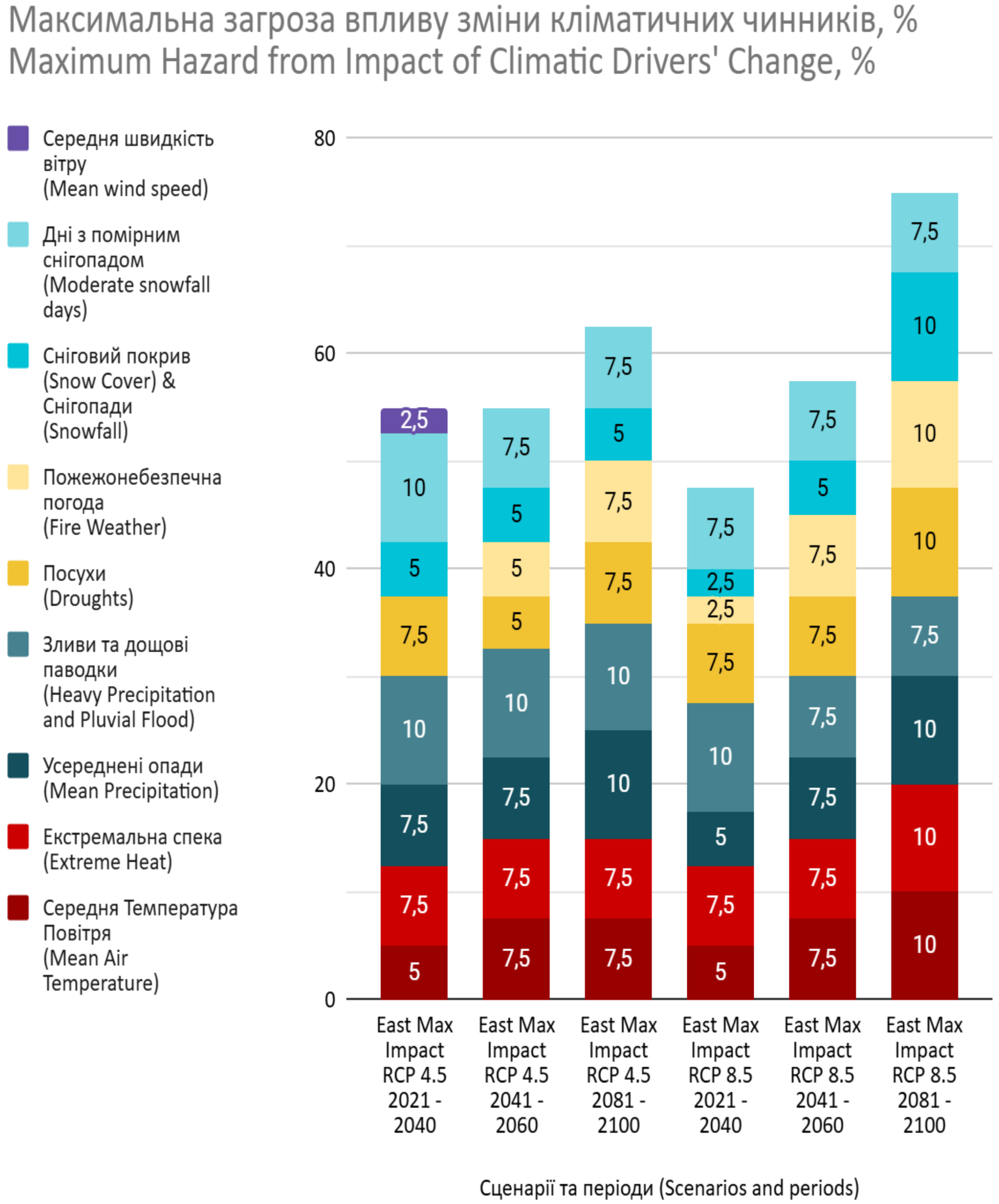

Figure 2.13. – Maximum by category and total threat levels for the Eastern region by scenario and period until the end of the 21st century relative to the period 1991–2010

For the **Eastern** region, the estimates of maximum threats obtained differ slightly from those for the previous regions, since it is for the high- concentration scenario RCP 8.5 that the lowest cumulative value (47.5%) is obtained for the current period, while for the RCP 4.5 scenario, the total threat value for this period is significantly higher, at 55% (Fig. 2.13). This value remains unchanged until the middle of the century, increasing to 62.5% by the end of the century under this moderate concentration scenario. As in other regions, the total threat value increases quite rapidly under the RCP 8.5 scenario over the course of the century: 57.5% by the middle and 75% by the end of the century, when 6 out of 10 CID changes are at a very high level, two of which relate to an increase in the extremity of precipitation, including in the form of snow, at a high level, and two related to an increase in wind speed and gusts, are absent.

In the eastern region, the threat of an increase in mean air temperature and extreme heat is very high only at the end of the century under the RCP 8.5 scenario; in previous periods, the threat of increased heat is high for both scenarios, and for the mean air temperature, the threat is at a medium level for both scenarios only in the current period, increasing to high by the middle of the century. Factors related to reduced moisture for both scenarios contribute significantly to the overall threat in the eastern region. At the same time, throughout the 21st century, for all periods and both scenarios, there remains a very high threat of increased extreme precipitation, which can cause heavy rains and flash floods, and a high threat for RCP 8.5 from the middle of the century onwards.

At the same time, the east also experiences very high levels of threat from an increase in days with snowfall exceeding 10 mm in other periods, which is currently very high for RCP 4.5. Unlike other regions, under the RCP 8.5 scenario, the threat of an increase in this CID remains high throughout the century. At the same time, however, this scenario shows an increase in the threat of a decrease in snowcover and snowfall from low in the current period to medium in the middle and very high by the end of the century. The threat of a decrease in snowcover for the RCP 4.5 scenario remains at a medium level throughout all periods considered. Unlike the western and northern regions, in the east, as well as in the centre, there is a high risk of increased drought at the beginning and end of the century and a medium risk in the middle for RCP 4.5. However, a high level of threat is obtained in the current period and in the middle of the century, increasing to very high by the end of the century for the RCP 8.5 scenario. Droughts are directly related to a decrease in precipitation, and in the east, the threat level of this factor increases similarly to the centre from high (medium for RCP 8.5) in the current period and in the middle of the century to very high at the end of the century for both scenarios.

A distribution of threats from fire-dangerous weather similar to that in the central region is also obtained in the east. Thus, a very high threat at the end, high in the middle of the century and low in the current period is obtained for the scenario of high concentrations RCP 8.5, although for the scenario of moderate concentrations RCP 4.5 there is no threat in the current period and a medium and high level in the middle and end of the century, respectively. For wind indicators for the eastern region, only a low level of threat was obtained in the current period from an increase in wind speed for the RCP 4.5 scenario, and for other periods and scenarios, there are no threats.

Among those considered, the **southern** region has the highest total maximum threats, while in the east and north (as well as the following regions), the highest cumulative value (55%) in the current period was obtained for the high concentration scenario RCP 8.5, while for the RCP 4.5 scenario, the total threat value for this period is significantly higher, at 62.5% (Fig. 2.14).

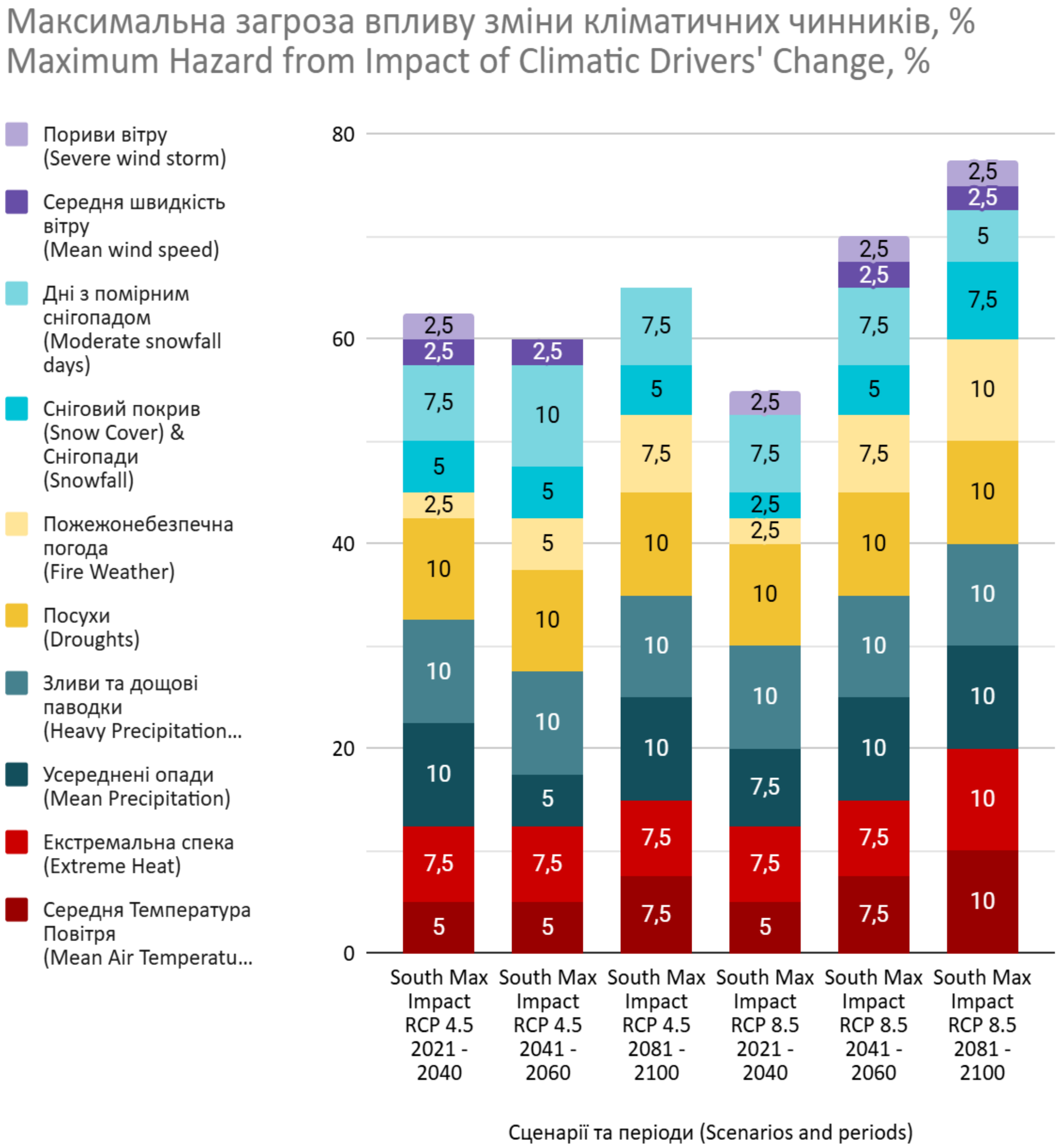

Figure 2.14. – Maximum by category and total threat levels for the Southern region by scenario and period until the end of the 21st century relative to the period 1991–2010

This value decreases slightly to 60% by the middle of the century, with an increase to 65% by the end of the century under this moderate concentration scenario. As in other regions, the total value of threats increases quite rapidly under the RCP 8.5 scenario, especially by the middle of the century, when it reaches 70%, and by the end of the century, when it reaches 77.5%, with 6 out of 10 CID changes at a very high level and the others at a slightly lower level: two related to an increase in the extremity of snowfalls (high level) and a decrease in snowcover (medium), and two more at a low level related to an increase in wind speed and gusts.

In the southern region, two threats remain at a very high level (10 points in Fig. 2.14) throughout the 21st century for all periods and both scenarios: an increase in extreme precipitation, which can cause heavy rains and flash floods, and an increase in droughts. The combination of these two threats could cause cascading risks, especially for sectors such as agriculture and forestry, biodiversity, buildings, disaster risk management, etc.

The threats of rising mean air temperatures and extreme heat are similar to those in the central region and are very high only at the end of the century under the RCP 8.5 scenario. In previous periods, the threat of increased heat is high for both scenarios, while for mean air temperature, the threat is medium for the RCP 4.5 scenario until the middle of the century and for RCP 8.5 only in the current period, increasing to high by the middle of the century. CIDs related to reduced moisture for both scenarios contribute significantly to the overall threat in the southern region. At the same time, in the south, by the middle of the century, RCP 4.5 also shows a very high level of threat from an increase in days with snowfall of more than 10 mm and high threats in other periods. Similar to other regions, with the exception of the eastern regions, under the RCP 8.5 scenario, the threat of an increase in this CID remains high until the middle of the century, and by the end of the century it becomes medium, apparently due to rising temperatures.

At the same time, however, this scenario shows an increase in the threat of a decrease in snowcover and snowfall from low in the current period to medium by the middle of the century and high by the end of the century. The threat of a decrease in snowcover for the RCP 4.5 scenario remains at a medium level throughout all periods considered, as in the east. The very high threat of drought is directly related not only to the reduction in snowcover, but also to the reduction in precipitation. In the south, the threat level of this factor is also very high for two out of three periods for both scenarios. Only in the current period is it high for RCP 8.5 and medium for the middle of the century under the RCP 4.5 scenario.

Droughts and reductions in precipitation and snowcover in the south clearly contribute to an increase in the threat of fire-dangerous weather, which rises from low in the current period for both scenarios to high and very high in the middle and end of the century under the high concentration scenario RCP 8.5, although for the moderate concentration scenario RCP 4.5, slightly lower threats are obtained: medium and high levels for the middle and end of the century, respectively. In the southern region, although the wind indicators show a low level of threat, this is true for almost all periods and for both factors, which together contribute up to 5% to the overall threat in the region. Obviously, the threat of increased wind speeds and gusts indicates proximity to the seas, where these winds are becoming stronger with climate change. Only at the end of the century for the RCP 4.5 scenario are there no threats of increased wind speeds.

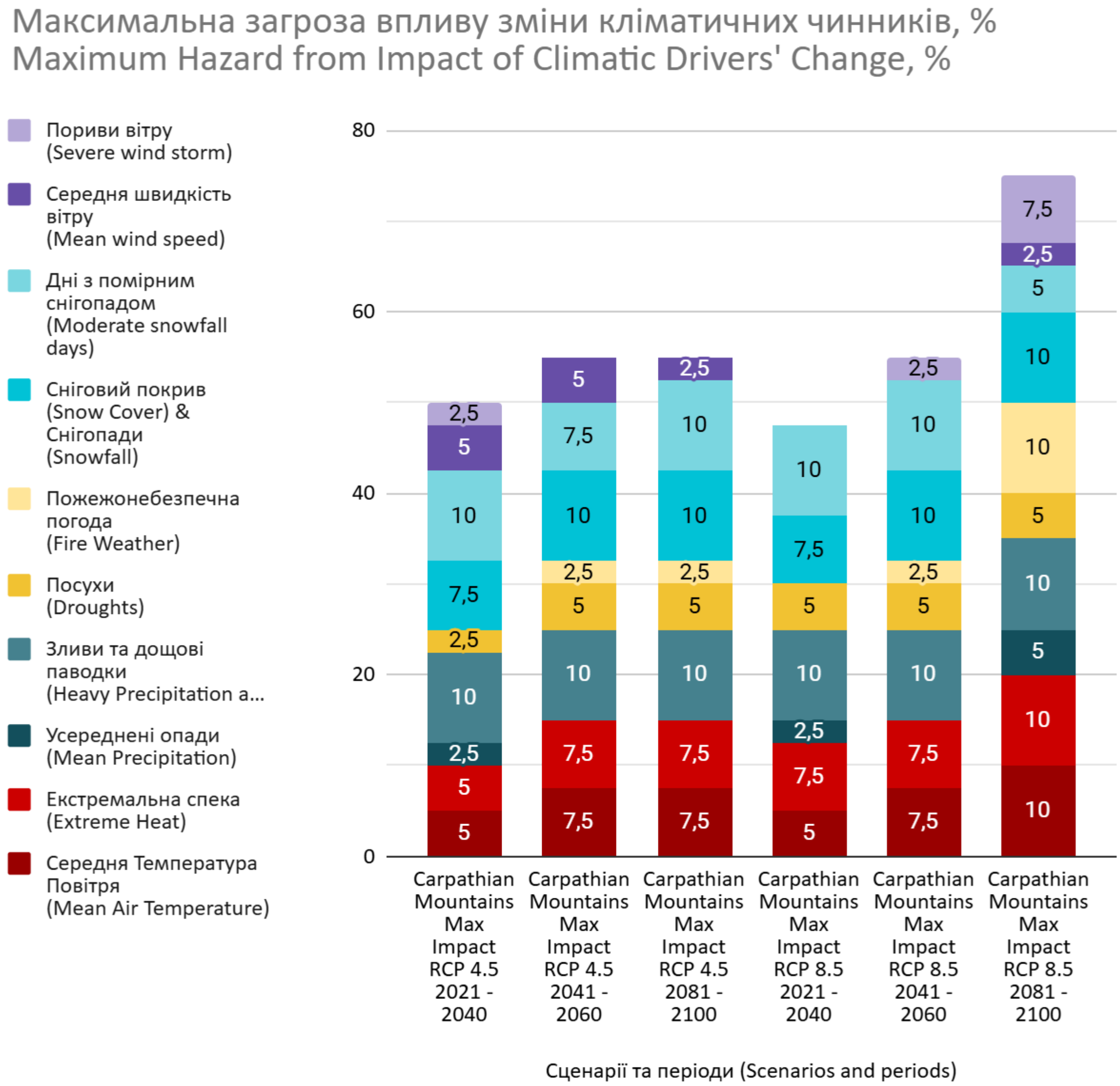

Figure 2.15. – Maximum by category and total threat levels for the Carpathian Mountains by scenario and period until the end of the 21st century relative to the period 1991–2010

Overall, for **the Carpathian Mountains** (Fig. 2.15), a very high level of threat of increased extreme precipitation, which can lead to flash floods, remains in all periods under both scenarios. The threat of an increase in days with moderate snowfalls, which can cause avalanches and other dangerous phenomena in the mountains, ranges from very high in the current period for both scenarios to high in the middle of the century, with a further increase to very high levels under RCP 4.5, and for RCP 8.5, the threat remains very high in the middle of the century and decreases to medium by the end of the century, apparently due to significant warming under this scenario, which reaches a very high level for temperature CIDs. Also, the decrease in snowcover for both scenarios from a high level in the current period increases to very high in the middle and end of the century, which may also be influenced by the increase in extreme heat and air temperature, the threat of which is high from the middle of the century in both scenarios and in the current period for heat under the RCP 8.5 scenario.

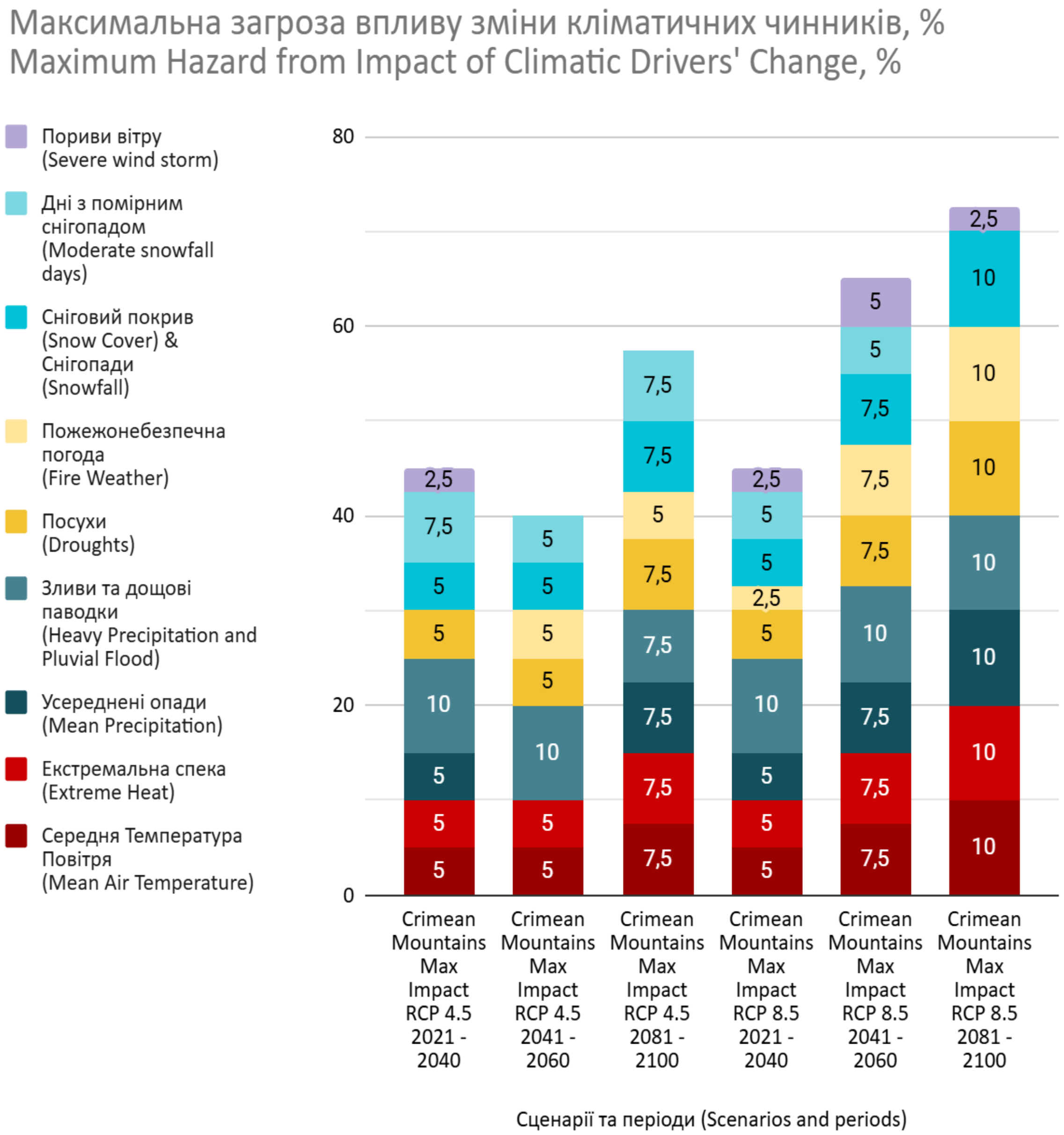

Figure 2.16. – Maximum by category and total threat levels for the Crimean Mountains region by scenario and period until the end of the 21st century relative to the period 1991–2010

Although the threat of reduced precipitation in the Carpathian Mountains for both scenarios is low in the current period, it is absent in the middle of the century and has a medium level at the end of the century under RCP 8.5, an average threat level for increased drought has been obtained for all periods and scenarios, with the exception of the current period, which has a low threat level for RCP 4.5. An increase in wind speed, which has a medium level of threat at the beginning and middle of the century, decreasing to a low level at the end of the century under RCP 4.5, may contribute to increased aridity and fire risk. The RCP 8.5 scenario is characterised by an increase in the threat of wind gusts from a low level in the middle of the century to a high level at the end of the century, i.e. an overall increase in the extremity of weather conditions in the Carpathian Mountains.

Unlike most of the regions already considered, the lowest cumulative threat level (40%) was obtained for the RCP 4.5 scenario for the middle of the century in **the Crimean Mountains** (Fig. 2.16). This value is the lowest among all regions, periods and scenarios and consists of a very high threat of increased extreme precipitation and medium threat levels for six categories: increased mean air temperature and extreme heat, droughts and fire-dangerous weather, and both snow-type categories.

In the current period, for both scenarios, the threat of increased extreme precipitation remains very high, with medium threats of increased mean air temperature and extreme heat, droughts and reduced snowcover, a medium threat of reduced precipitation and a low threat of increased wind gusts. The difference between the scenarios lies in the higher threats of increased moderate snowfall and the absence of a change of fire-dangerous weather for the RCP 4.5 scenario, while for the high concentration RCP 8.5 scenario, these categories correspond to medium and low levels of threats. As in other regions, the total value of threats increases quite rapidly under the RCP 8.5 scenario, especially by the middle of the century, when it rises to 65% due to the fact that the medium threat levels in the previous period increase to a high level, and for wind gusts to medium, while the threat of increased moderate snowfall remains at medium.

For **the Coastal Region** (Fig. 2.17), the threats of an increase in mean air temperature and extreme heat are greater than those obtained in other regions, since very high levels are obtained not only at the end of the century under the RCP 8.5 scenario, but also heat has the maximum threat in this period and under another scenario from the middle of the century.

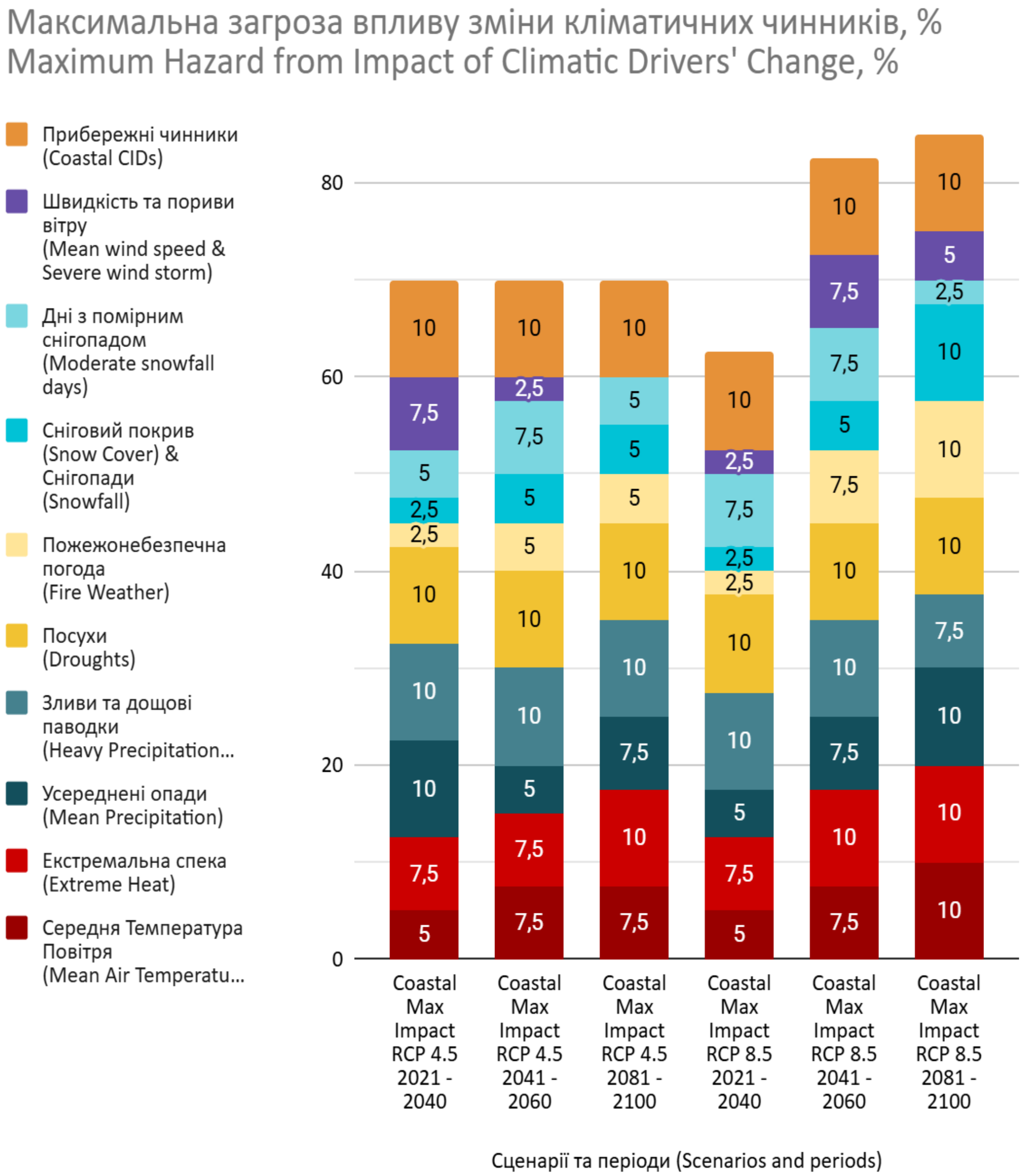

Figure 2.17. – Maximum by category and total threat levels for the Coastal region by scenario and period until the end of the 21st century relative to the period 1991–2010

In other periods, the threat of increased heat is high for both scenarios. Due to the increase in mean air temperature, the threat is medium in the current period and high in the middle of the century for both scenarios, remaining high for RCP 4.5 and increasing to very high for RCP 8.5 by the end of the century. CIDs related to reduced moisture for both scenarios, namely precipitation, including snowfalls and snowcover, contribute significantly to the total threat in the coastal zone. Thus, in both scenarios, there is an increase in the threat of reduced snowcover and precipitation in the form of snow from low in the current period to medium by the middle of the century. The threat of reduced snowcover by the end of the century remains at a medium level for the RCP 4.5 scenario, and reaches a very high level for the RCP 8.5 scenario. Droughts and reductions in precipitation and snowcover in coastal areas clearly contribute to an increase in the threat of fire-dangerous weather, which rises from low in the current period for both scenarios to high and very high in the middle and end of the century under the high concentration RCP 8.5 scenario, while for the moderate concentration scenario RCP 4.5, a medium level is obtained for the middle and end of the century. At the same time, high threats are obtained on the coasts from an increase in days with snowfall of more than 10 mm for the current period and the middle of the century, but low for the end of the century for RCP 8.5 due to apparently significant warming. Under the RCP 4.5 scenario, the threat of an increase in this CID is high for the middle of the century and medium for the other two periods. For the coastal zone, the greatest threats are from an increase in wind speeds. The threat is high for the middle of the century, medium for the end of the century, and low for the current period for the RCP 8.5 scenario. Under the RCP 4.5 scenario, the threat of increased wind speeds and gusts is also high in the current period, but decreases to low in the middle of the century and disappears by the end of the century. In all periods, the threat of sea level rise is highest under both scenarios.

3. ASSESSMENT OF THE VULNERABILITY OF THE CROP PRODUCTION SECTOR TO CLIMATE CHANGE

3.1. Sensitivity of crop production to climate change

Sensitivity is the degree to which a system or object is negatively or positively affected by climate change, and it does NOT depend on its geographical location. In our assessments, we focused on the negative impact of climate change. Therefore, along with the weighting coefficients of sensitivity to climate change, which corresponds specifically to negative effects, the directions of change are indicated, namely increases or decreases, with corresponding up and down arrows (Table 3.1). For example, a reduction in the growing season is considered negative for both crop production and animal husbandry. Therefore, the lengthening of the growing season due to the predicted warming will not have a negative impact on these sectors of agriculture.

According to the experts' estimates presented in Table 3.1, the highest sensitivity coefficient for crop production to droughts (1.3) is expected. In the same category of CIDs, which characterise wet and dry conditions, crop production is highly sensitive to increases in very heavy precipitation and maximum precipitation over 1 and 5 days (0.6, 0.5 and 0.4, respectively). Crop production is highly sensitive to a decrease in precipitation in April and July (0.5 each), less so in October, January and annual precipitation (0.3, 0.2 and 0.1, respectively). Crop production is also quite sensitive to an increase in days with fire-dangerous weather (0.3).

In the heat and cold category, crop production is highly sensitive to increases in maximum daily and extreme air temperatures in summer (0.6 each), tropical nights and mean air temperature in July (0.4 each), but also to an increase in the number of frost and ice days (0.5 and 0.4, respectively). There is less sensitivity to a reduction in the growing season and the temperature of very cold days (0.3 each). In this category, the sensitivity to an increase in temperature in April is 0.2, and the change in the rest of the CID is 0.1.

Among other categories, the sensitivity of crop production to a decrease in snowcover and an increase in wind gusts is also quite high (0.4 each). The change in other CID in the categories of snow, wind and coastal is up to 0.2 (increase in snowfall of more than 10 mm/day).

Table 3.1. Sensitivity of crop production to changes in climatic factors with weighted coefficients aggregated by category

IPCC CID	IPCC CID Category	CID name	**Units**	**Crop production**	
				Assessment	**Amount by category**
HEAT AND COLD	↗ MEAN AIR TEMPERATURE	↗ Annual near surface air temperature	°C	0.0	1.1
		↗ January mean air temperature	°C	0.1	
		↗ April mean air temperature	°C	0.2	
		↗ July man air temperature	°C	0.4	
		↗ October mean air temperature	°C	0.1	
		↘ Growing season length	D/yr	0.3	
	↗ EXTREME HEAT	↗ Mean of maximum daily air temperature in summer	°C	0.6	1.7
		↗ Days with very high and extreme heat	D/yr	0.6	
		↗ Tropical nights	D/yr	0.4	
		↗ Humidex index for the mean maximum air temperatures in summer	U.O.	0.1	
		↗ Cooling Degree Days (CDD))	Degree days/year	0.0	
	↗ COLD WAVES	↘ The temperature of very cold days in the winter months	°C	0.3	0.3
		↗ Heating degree days	Degree days/year	0.0	
	↗ FROST	↗ Frost days	D/yr	0.5	0.9
		↗ Ice days	D/yr	0.4	
WET AND DRY	↘ MEAN PRECIPITATION	↘ Annual precipitation	%	0.1	1.6
		↘ January precipitation	%	0.2	
		↘ April precipitation	%	0.5	
		↘ July precipitation	%	0.5	
		↘ October precipitation	%	0.3	
		↗ Maximum 5-days precipitation	mm	0.4	1.5

	↗ HEAVY PRECIPITATION AND PLUVIAL FLOODS	↗ Maximum 1-day precipitation	mm	0.5	
		↗ Very heavy precipitation annual sums	%	0.6	
	↗ DROUGHT	↗ Maximum duration of drought in 20 years	D/yr	1.3	1.3
	↗ NUMBER OF DAYS WITH FIRE WEATHER FWI >30	↗ Fire weather index > 30	D/yr	0.3	0.3
SNOWFALLAND SNOWCOVER	↘ SNOWFALL AND SNOW COVER	↘ ANNUAL SNOWFALL	mm	0.2	0.6
		↘ NUMBER OF DAYS WITH SNOWCOVER ≥30%	D/yr	0.4	
	↗ NUMBER OF DAYS WITH SNOWFALL ≥ 10 MM PER DAY		D/yr	0.1	0.1
SURFACE WIND SPEED	↗ AVERAGE WIND SPEED		m/s	0.1	0.1
	↗ WIND GUSTS ≥ 10.8 M/S (6 BEAUFORT)		D/yr	0.4	0.4
COASTAL	↗ RELATIVE SEA LEVEL RISE		M	0.1	0.1
	↗ EXTREME SURGE STORM LEVEL (COASTAL FLOOD)		M	0.0	0.0
Sum				**10.0**	**10.0**

The greatest sensitivity of crop production, according to aggregate estimates, is to an increase in extreme heat (1.7), followed by a decrease in mean precipitation (1.6), an increase in heavy rains and pluvial floods (1.5), droughts (1.3), and an increase in mean air temperature (1.1). Less, but still significant sensitivity to increased frosts (0.9) and reduced snowcover with snowfalls (0.6). The sensitivity of the industry to changes in all other categories of CID is low.

3.2. Vulnerability

The vulnerability of an industry (system) is its susceptibility to negative impacts. Vulnerability is proportional to the degree of change in various climatic impact-drivers (CIDs) and elements, including sensitivity or susceptibility to damage and the inability to cope and adapt. According to the glossary in the Second Working Group of the IPCC, **the vulnerability index** is "a metric that characterises the vulnerability of a system. The climate vulnerability index is usually calculated by combining, with or without weighting, several indicators that are assumed to represent vulnerability."

In this study, we calculated vulnerability as the sum of the multiplication of the degrees of impact of each CID on sensitivity to its negative impact. Since the sum of the weighting coefficients of sensitivities to 32 CIDs for all sectors is 10 a.u. (Table 3.1), and the maximum degree of impact is determined by 10 main categories of the IPCC, also within the range of 10 (Figs. 2.10–2.17), vulnerability can be represented as a percentage (%), where 100% means complete degradation or significant damage and losses for the sector (system):

Vulnerability (%) = ∑ (32 CID) ***Degree of CID impact x Sensitivity to CID***

The analysis focuses primarily on the negative reactions of the system to external influences that require certain adaptation measures, as a result of which it is possible to reduce sensitivity to certain CIDs or even switch the entire crop production sector to greenhouse cultivation with full climate control. This will not be able to completely eliminate the impact of climate change, for example due to flooding, lack of drinking water due to drought, etc., but at least significantly reduce losses, although such measures will certainly require significant capital investments.

To assess the vulnerability of crop production to climate change in different regions of Ukraine, corresponding maps were created for the periods 2021–2040, 2041–2060, and 2081–2100 for two scenarios: RCP 4.5 (moderate GHG concentrations) and RCP 8.5 (business as usual, high GHG concentrations) (Fig. 3.1).

Analysis of statistical data on crop production vulnerability obtained in calculations using aggregation of all CIDs (Table 3.2) showed that the highest values of the indicator for Ukraine will be observed at the end of the 21st century: for the RCP 4.5 scenario, within the range of 22% to 46%, and for the RCP 8.5 scenario, from 33% to 59%, depending on the region. In the current period 2021–2040, in both scenarios, the vulnerability values are spatially almost identical and are within the low and medium range of up to 30%. Only in the South, Coast, East and Centre does crop production vulnerability sometimes exceed 30% and become high. For the period 2041–2060, the difference in crop production vulnerability between the two scenarios gradually begins to increase.

Next, we will consider the results obtained by region.

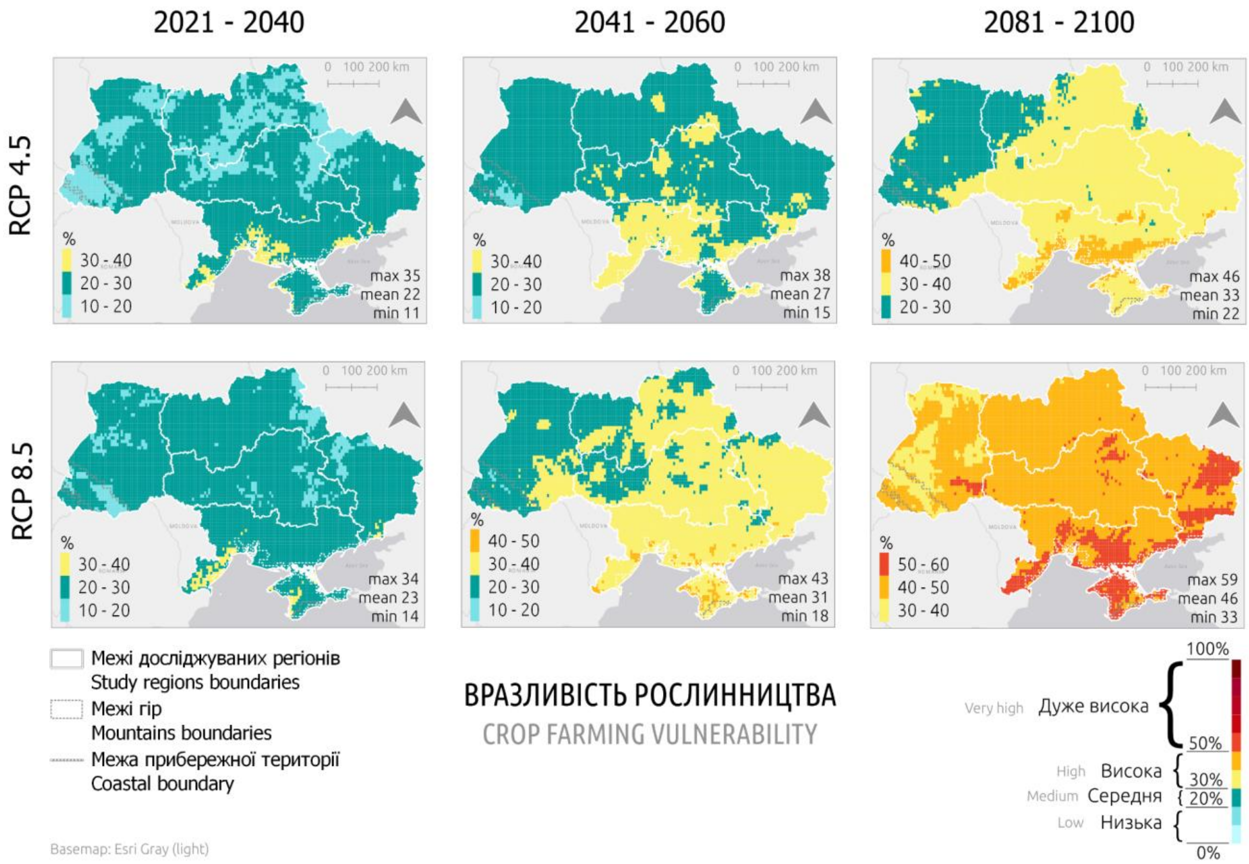

Figure 3.1. Vulnerability of crop farming to changes in all climatic impact-drivers (CID) for scenarios and periods until the end of the 21st century.

Table 3.2. Statistical estimates of crop production vulnerability to climate change by region, scenario and period (%)

Crop production										
Region	**Scenario**	**2021**			**2041–2060**			**2081–2100**		
		min	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**
West	RCP 4.5	13	20	28	17	25	31	22	27	33
	RCP 8.5	15	22	29	21	27	37	34	41	50
North	RCP 4.5	14	20	25	21	26	32	22	31	37
	RCP 8.5	16	23	27	24	30	35	39	45	51
Centre	RCP 4.5	16	21	30	22	28	34	26	33	43
	RCP 8.5	18	22	29	26	31	39	39	47	53
East	RCP 4.5	16	22	31	21	26	34	29	33	43
	RCP 8.5	18	23	31	27	33	40	43	49	54
South	RCP 4.5	19	26	35	21	30	38	29	38	46
	RCP 8.5	19	26	33	26	35	43	41	49	59
Carpathian Mountains	RCP 4.5	11	18	24	15	21	27	22	27	33
	RCP 8.5	14	20	26	18	25	30	33	39	46
Crimean Mountains	RCP 4.5	16	23	28	22	26	30	31	35	41
	RCP 8.5	21	25	29	32	37	43	44	50	58
Coastal	RCP 4.5	21	29	35	24	32	37	31	40	45
	RCP 8.5	21	27	34	33	38	43	44	51	58

3.2.1. South

Among the regions considered, the Southern region has the highest maximum vulnerability values of 59% at the end of the century (Table 3.2), with both the east and north (as well as other regions), the highest concentration scenario RCP 8.5 has the lowest cumulative value (40.25%) in the current period, while under the RCP 4.5 scenario, the vulnerability value in this period is higher and amounts to 42.5% (Appendix A.1.1). The maximum vulnerability value increases slightly to 38% by the middle of the century, rising to 46% by the end of the century under the moderate concentration scenario (Table 3.3). As in other regions, the total vulnerability value increases quite rapidly under the RCP 8.5 scenario, especially by the middle of the century, when it reaches 43%, and by the end of the century, when it reaches 59%, with 6 out of 10 impacts of CID at a very high level and the others at a slightly lower level: two related to an increase in the extremity of snowfalls (high level) and a decrease in snowcover (medium), and two more at a low level, which are associated with an increase in wind speed and gusts (Fig. 2.14).

In the southern region, vulnerability to droughts throughout the 21st century remains very high for all periods and both scenarios (Fig. 3.2). The vulnerability of crop production to increased extreme precipitation, which can cause heavy rainfall and flash floods, heat and mean air temperatures, as well as reduced snowcover, is increasing over time. The combination of all these factors can cause cascading risks in the region, including for crop production.

Vulnerability due to reduced snowcover for the RCP 4.5 scenario remains at a medium level throughout all periods considered, as in the east. The very high contributions to drought vulnerability are directly related not only to reduced snowcover, but also to reduced precipitation. In the south, the vulnerability of the sector to changes in this factor is also very high for two out of three periods for both scenarios. As a result, the maximum vulnerability in the current period is slightly higher for RCP 4.5 than for RCP 8.5: 35% versus 33%. Droughts and reductions in precipitation and snowcover in the south clearly contribute to an increase in the vulnerability of crop production to fire-prone weather, which rises from low in the current period for both scenarios to high and very high in the middle and end of the century under the high concentration scenario RCP 8.5 (Fig. 3.2).

Table 3.3. – Statistical estimates of crop production vulnerability to climate change by scenario and period (%) for the southern region

South			
RCP4.5	**2021–2040**	**2041–2060**	**2081–2100**
Max	35	38	46
mean	26	30	38
min	19	21	29
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	33	43	59
mean	26	35	49
min	19	26	41

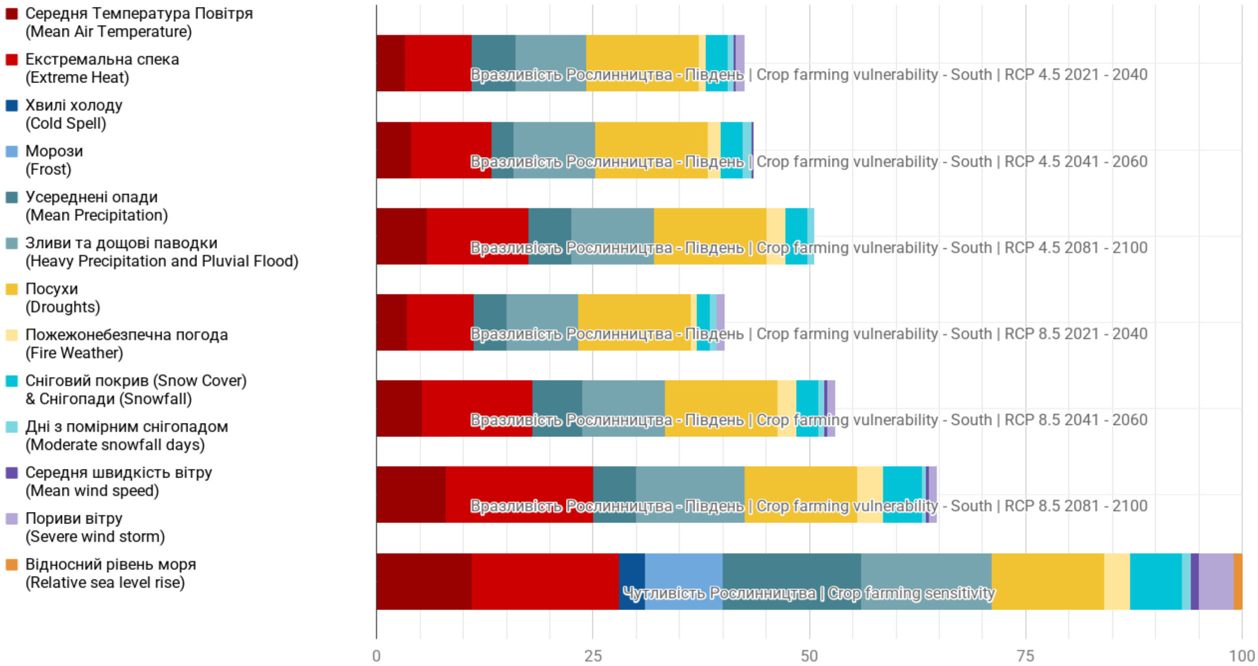

Figure 3.2. – Maximum vulnerability of crop production in the southern region in three periods under two scenarios compared to sensitivity (lower bar) divided into CID categories (colours)

3.2.2. Centre

For the central region as a whole, similar assessments of crop production vulnerability were obtained as for the western and northern regions, but with increased vulnerability associated with reduced moisture. At the same time, throughout the 21st century, for all periods and both scenarios, the contributions to maximum vulnerability from increased extreme precipitation, which can cause heavy rainfall and flash floods, and droughts are increasing (Fig. 3.3). In the centre, contributions to vulnerability increase due to an increase in the number of days with snowfall exceeding 10 mm, but under the RCP 8.5 scenario, they decrease by the end of the century, apparently due to more rapid warming and less precipitation in the form of snow. This confirms the observed increase in vulnerability due to the decrease in snowcover and snowfall (Fig. 3.3).

In the central region, vulnerability is currently almost the same for both scenarios, but the maximum value of 30% is obtained for the RCP 4.5 scenario, which corresponds to the high vulnerability category. By the middle and end of the century, the maximum vulnerability values increase to 34% and 43%, respectively, for the RCP 4.5 scenario due to the absence of threats from wind factors (Fig. 3.3, Table A.1.2). However, under the RCP 8.5 scenario, the rate of increase in vulnerability increases significantly, and by the middle of the century, the statistical values of crop production vulnerability in this region practically correspond to the values under the RCP 4.5 scenario at the end of the century

(Table 3.4). By the end of the century, under the RCP 8.5 scenario , areas with very high vulnerability (up to 53%) appear mainly in the north of the region (Poltava Oblast).

Table 3.4. Statistical estimates of crop production vulnerability to climate change by scenario and period (%) for the central region

Centre			
RCP4.5	**2021**	**2041–2060**	**2081–2100**
max	30	34	43
mean	21	28	33
min	16	22	26
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	29	39	53
mean	22	31	47
min	18	26	39

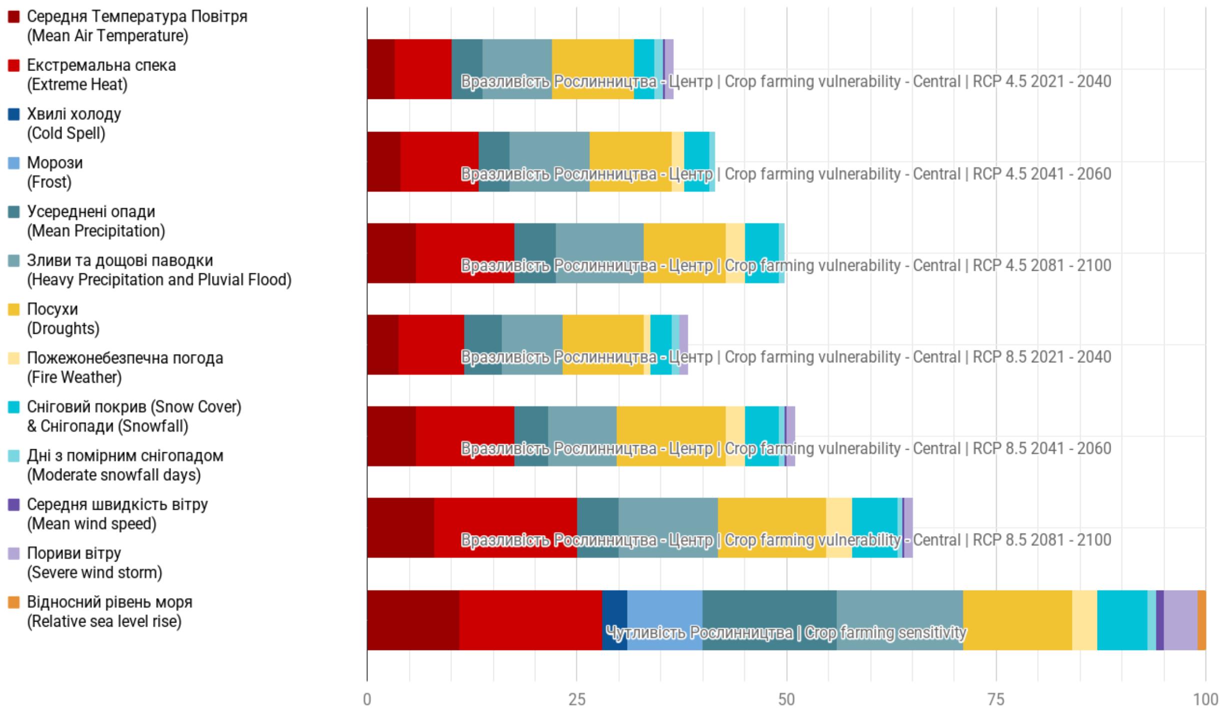

Figure 3.3. – Maximum vulnerability of crop production in the central region in three periods under two scenarios compared to sensitivity (lower bar) divided into CID categories (colours)

3.2.3. West

The crop production sector in the western region throughout the 21st century remains the least vulnerable among all regions and for both scenarios (Fig. 3.1). Even at the end of the century, according to the RCP 4.5 scenario, the average vulnerability of the sector remains at a medium level (27%), as in the Carpathian Mountains, with high vulnerability values only in the south of the western region in the Chernivtsi region and in some areas of Zakarpattia. However, under the high concentration scenario RCP 8.5, even in this region, the vulnerability of crop production at the end of the century increases to high and very high (Table 3.5) in Chernivtsi and in the south of Ternopil and Khmelnytskyi regions (Fig. 3.1).

The greatest contributions to crop production vulnerability in the region come from increased heavy rainfall, as well as heat, aridity and days with snowfall exceeding 10 mm, although under the RCP 8.5 scenario it gradually decreases, apparently due to more rapid warming and less precipitation in the form of snow (Fig. 3.4). This confirms the increase in vulnerability due to reduced snowcover and precipitation in the form of snow for both scenarios. The increase in wind speed and gusts in the current period also makes a significant contribution to both scenarios, but only for the RCP 8.5 scenario does it persist throughout the century and increase to its maximum. Similarly, the vulnerability of crop production increases under this high concentration scenario due to an increase in the number of days with fire-hazardous weather, although for the moderate concentration scenario RCP 4.5, there is no vulnerability in the current period and a low level from the middle to the end of the century.

Table 3.5. Statistical estimates of crop production vulnerability to climate change by scenario and period (%) for the western region

West			
RCP4.5	**2021–2040**	**2041–2060**	**2081–2100**
max	28	31	33
mean	20	25	27
min	13	17	22
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	29	37	50
mean	22	27	41
min	15	21	34

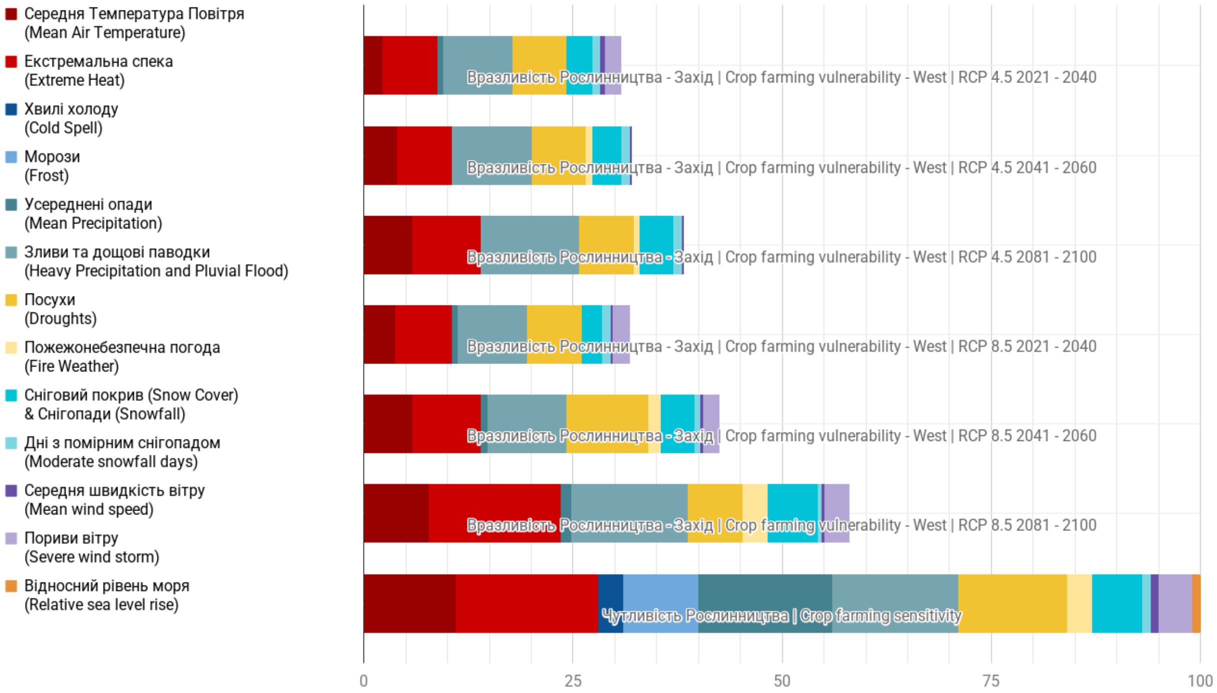

Figure 3.4. – Maximum vulnerability of crop production in the western region in three periods under two scenarios compared to sensitivity (lower bar) divided into CID categories (colours)

3.2.4. East

For the eastern region, the estimates of crop production vulnerability in the current period are mostly medium and almost identical for both scenarios (from 16% to 31%), but begin to differ significantly from the middle of the century and reach very high vulnerability values of 54% by the end of the century under the RCP 8.5 high concentration scenario (Fig. 3.1, Table 3.6).

In the eastern region, crop production vulnerability is mainly caused by droughts, reduced precipitation, increased mean air temperature and extreme heat, as well as increased extreme precipitation, which can cause heavy rains and flash floods. At the same time, in the east, for RCP 4.5, there are also significant contributions to vulnerability from an increase in the number of days with snowfall exceeding 10 mm, and unlike other regions, under the RCP 8.5 scenario, the vulnerability of crop production to this factor remains high over the century. This scenario also shows an increase in vulnerability due to a decrease in snowcover and snowfall. Vulnerability to a decrease in snowcover for the RCP 4.5 scenario remains at an average level throughout all periods considered (Fig. 3.5).

Table 3.6. Statistical estimates of crop production vulnerability to climate change by scenario and period (%) for the eastern region

East			
RCP4.5	**2021–2040**	**2041–2060**	**2081–2100**
max	31	34	43
mean	22	26	33
min	16	21	29
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	31	40	54
mean	23	33	49
min	18	27	43

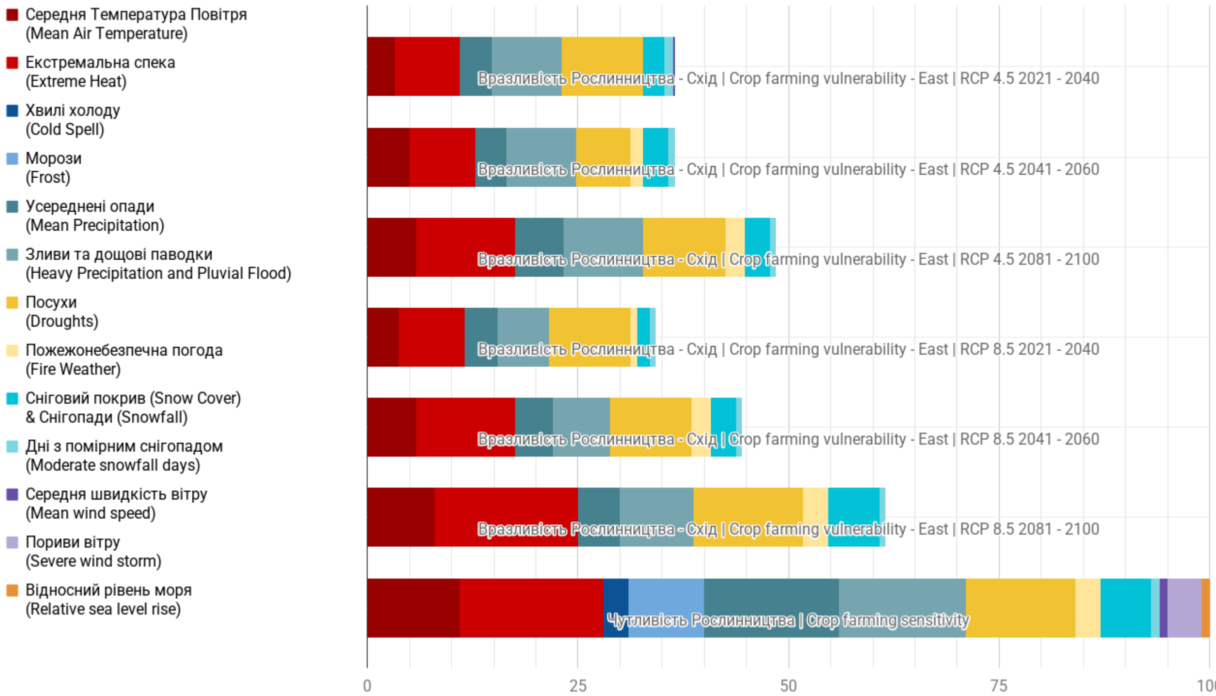

Figure 3.5. – Maximum vulnerability of animal husbandry in the eastern region in three periods under two scenarios compared to sensitivity (lower bar) divided into categories of vulnerability (colours)

3.2.5. North

For the northern region, estimates of maximum vulnerability to changes in climatic impact-drivers are similar to those for the western region. Thus, throughout the 21st century, for all periods and both scenarios, high contributions to vulnerability are obtained from an increase in extreme precipitation, which can cause heavy rains and flash floods (Fig. 3.6). Also, for both scenarios, there are significant contributions to vulnerability from an increase in days with snowfall exceeding 10 mm, although under the RCP 8.5 scenario, it decreases by the end of the century, apparently due to more rapid warming and less precipitation in the form of snow. This confirms the observed increase in vulnerability from the decrease in snowcover and snowfall by the end of the century for both scenarios (Fig. 3.6).

The vulnerability of crop production in the region to rising mean temperatures and extreme heat is only significant at the end of the century under the RCP 8.5 scenario; in previous periods and for the RCP 4.5 scenario, the contributions of this category of CID are smaller. Similarly, vulnerability to increased drought has a significant contribution for both scenarios, and by the middle of the century, it is highest under the RCP 8.5 scenario (Fig. 3.6). The region's vulnerability to fire-dangerous weather increases over the century to a maximum under the high concentration RCP 8.5 scenario, although for the moderate concentration RCP 4.5 scenario, there is also no vulnerability in the current period and a low level from the middle to the end of the century.

The increase in wind speed and gusts in the northern region has a low contribution to vulnerability compared to the western region. Thus, for both scenarios, a low contribution to vulnerability from increased wind gusts is obtained for the current period. The low level of vulnerability to wind gusts remains for the RCP 8.5 scenario throughout the century, and at the end, a low level of vulnerability to increased wind speeds is also added (Fig. 3.6).

Thus, in the current period, the vulnerability of the crop production sector for the RCP 8.5 scenario averages 20% and 23% for the RCP 4.5 scenario (Table 3.7). However, in the future, the rate of increase in vulnerability under the RCP 8.5 scenario will accelerate and, by the middle of the century, will significantly exceed the total vulnerability under the RCP 4.5 scenario: average values of 26% in the middle and 31% at the end of the century, compared to 30% and 45% with a maximum of 51%, which is already a very high level of vulnerability, for the high concentration scenario RCP 8.5 in the middle and end of the century, respectively.

Table 3.7. Statistical estimates of crop production vulnerability to climate change by scenario and period (%) for the northern region

North			
RCP4.5	**2021**	**2041–2060**	**2081–2100**
max	25	32	37
mean	20	26	31
min	14	21	22
RCP8.5	**2021–2040**	**2041–2060**	**2081 – 2100**
max	27	35	51
mean	23	30	45
min	16	24	39

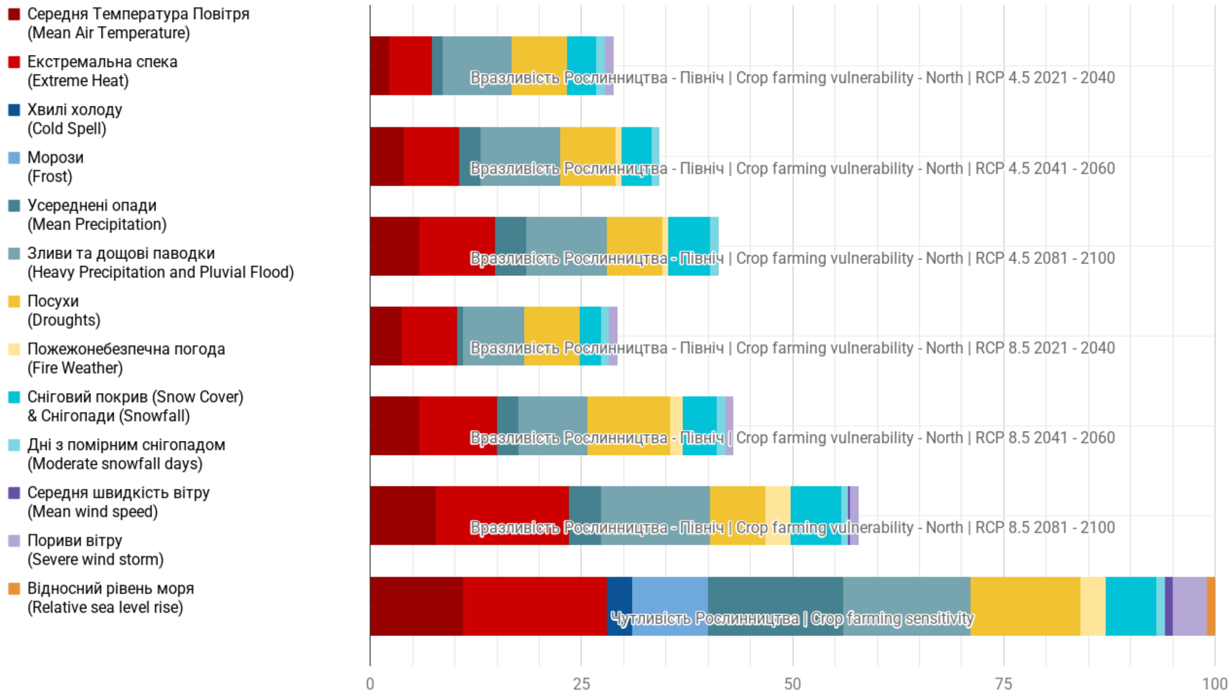

Figure 3.6. – Maximum vulnerability of crop production in the northern region in three periods under two scenarios compared to sensitivity (lower bar) divided into CID categories (colours)

3.2.6. Carpathian Mountains

The Carpathian Mountains region is located in the middle of the western region, but has an altitude of over 400 metres above sea level, and there are 252 RCM grid nodes on its territory (Fig. 2.9). The vulnerability values obtained for the current period range from 11% to 24% for both scenarios, which corresponds to the lowest vulnerability of the industry among all regions (Table 3.2).

By the middle of the century, the vulnerability levels in both scenarios are almost the same, but the differences between the moderate and high concentration scenarios are greater in terms of vulnerability from increased moderate snowfall and higher wind speeds under RCP 4.5 versus higher heat and increased wind gusts under RCP 8.5 (Fig. 3.7).

By the end of the century, with climate change, the vulnerability of crop production is also increasing in both scenarios, but will remain the lowest within Ukraine: from 22% to 33% under RCP 4.5 and from 33% to 46% under RCP 8.5, i.e. it will not reach a very high level (Table 3.8). The share of the impact of increased average wind speed in the vulnerability decreases, but the share due to increased moderate snowfall increases. By the end of the century, under the RCP 8.5 scenario, the vulnerability of the crop production sector increases to medium, with a maximum value of 46%, which already indicates high vulnerability. It consists of vulnerabilities from all categories of climatic impact-drivers, of which the largest contribution is expected from increased heat and extreme precipitation, and less from increased mean temperature, droughts and snowfalls exceeding 10 mm/day. However, an increase in the number of days with fire-dangerous weather and wind gusts, as well as a decrease in precipitation and snowcover, also contribute significantly to overall vulnerability (Fig. 3.7).

Table 3.8. Statistical estimates of crop production vulnerability to climate change by scenario and period (%) for the Carpathian Mountains region

Carpathians			
RCP4.5	**2021–2040**	**2041–2060**	**2081 – 2100**
max	24	27	33
mean	18	21	27
min	11	15	22
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	26	30	46
mean	20	25	39
min	14	18	33

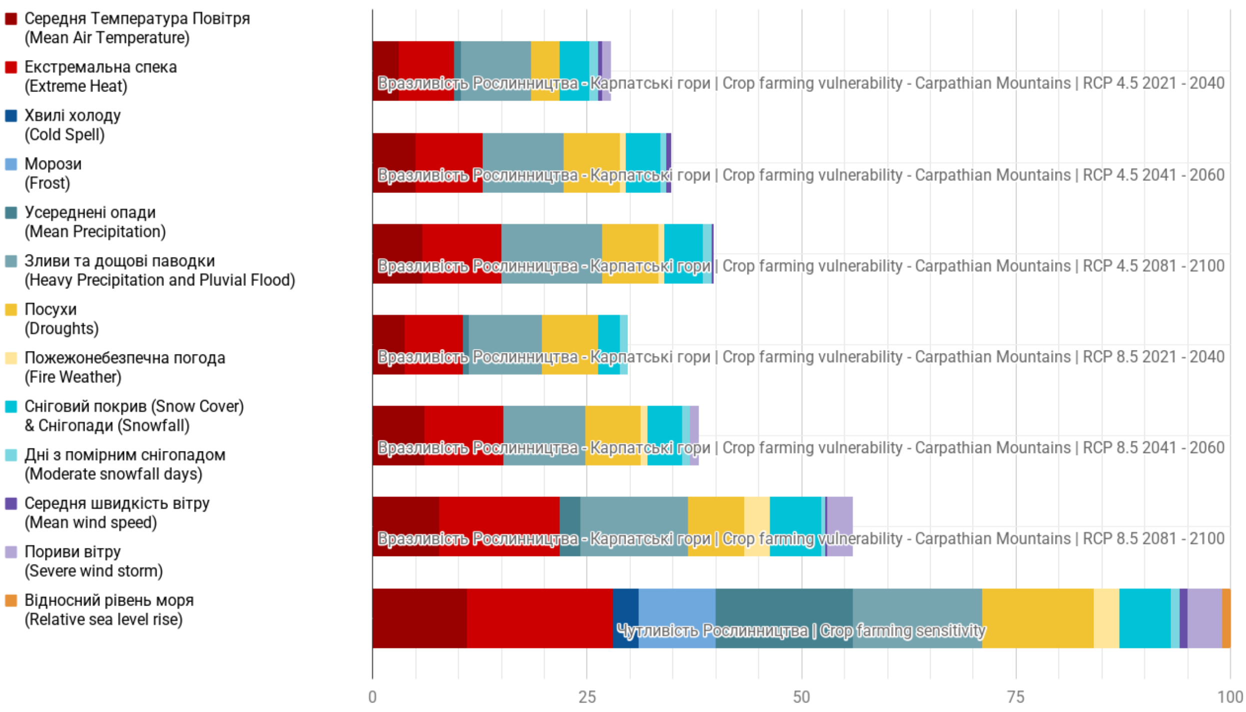

Figure 3.7. – Maximum vulnerability of crop productio in the Carpathian Mountains in three periods under two scenarios compared to sensitivity (lower bar) divided into categories of vulnerability (colours)

3.2.7. Crimean Mountains

The Crimean Mountains region is directly adjacent to the coastal zone on the southern shore of Crimea. It is the smallest of the regions considered and contains only 22 RCM grid nodes with an altitude of more than 400 m above sea level (Fig. 2.9).

In the current period, almost identical values of the total maximum vulnerability in the region were obtained: from 16% to 28% and from 21% to 29% for both scenarios (Table 3.9). At the same time, only the minimum vulnerability value in the region of 16% under the RCP 4.5 scenario remains in the low category, while all other statistical values are in the medium vulnerability category, up to a maximum of 28% and 29% under the moderate and high GHG concentration scenarios, respectively (Table 3.9).

Table 3.9. Statistical estimates of crop production vulnerability to climate change by scenario and period (%) for the Crimean Mountains region

Crimean Mountains			
RCP4.5	**2021 – 2040**	**2041–2060**	**2081–2100**
max	28	30	41
mean	23	26	35
min	16	22	31
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	29	43	58
mean	25	37	50
min	21	32	44

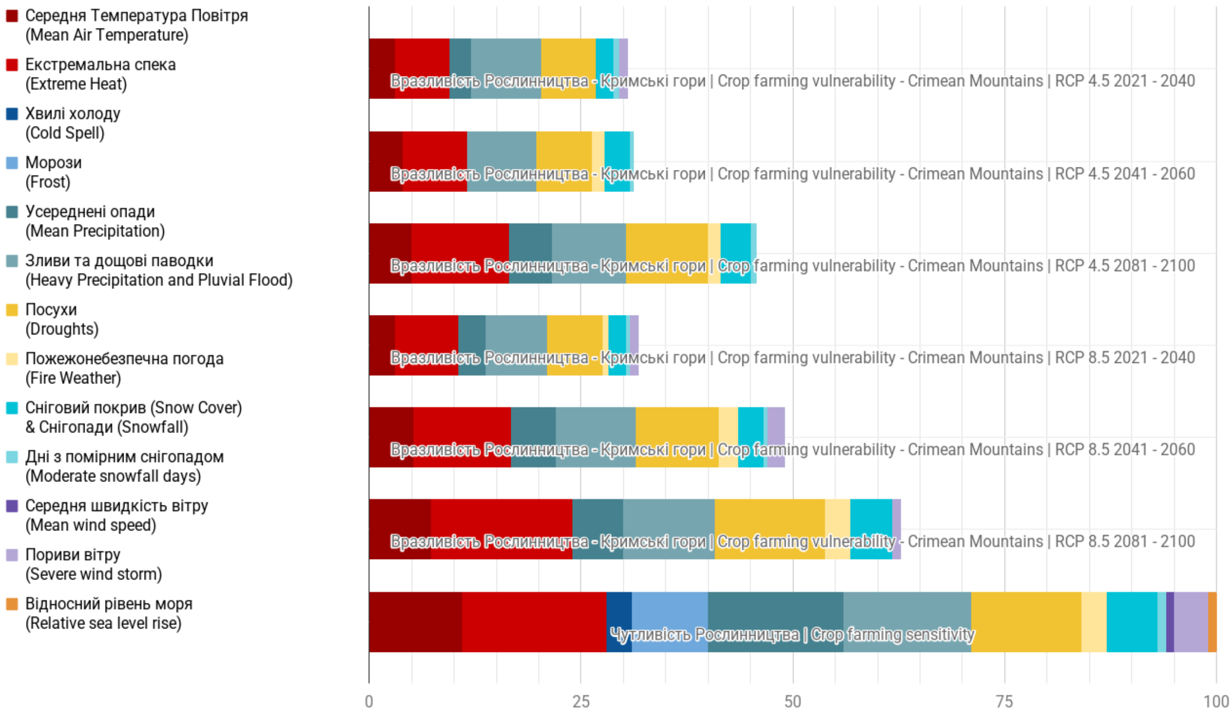

Figure 3.8. – Maximum vulnerability of crop production in the Crimean Mountains in three periods under two scenarios compared to sensitivity (lower bar) divided into CID categories (colours)

By the middle of the century, vulnerability under the high concentration scenario RCP 8.5 exceeds that under the moderate concentration scenario RCP 4.5 (by 11% on average) among all regions (Table 3.2) and reaches a high level of up to 43%.

By the end of the century, vulnerability under the RCP 8.5 scenario reaches a maximum of 58% in the Crimean Mountains, with an average value of 50% also in the very high category, and a minimum of 44%, which exceeds the maximum of 41%, i.e. a high level of vulnerability for the sector, for the RCP 4.5 scenario, for which the indicator in the Crimean Mountains is within the range of 31% (Table 3.9). The difference in vulnerability values between the scenarios is mainly due to greater contributions from heat and aridity under the RCP 8.5 scenario in this region.

3.2.8. Coastal

Among the regions considered, slightly modified methodological approaches were used for the coastal zone, since the number of categories of climatic impact-drivers had to be the same in order to harmonise the assessment with other geographical regions. Therefore, for this region, two wind CIDs were combined into one and two coastal CIDs were also combined into one by determining the maximum threat not only across the region but also among pairs of these CIDs. It is evident that for this coastal zone, the maximum threat from an increase in coastal CIDs (sea level and storm surges) will be very high in all periods (10 points in Fig. 2.15), which could obviously affect the vulnerability of the industry in the coastal region. However, since the sensitivity of crop production to changes in coastal factors is set at 0.1 for sea level rise (Table 3.1), the contribution to the vulnerability of the industry from changes in these CIDs is minimal in all periods.

Overall, for the RCP 4.5 scenario, the vulnerability value consists of many factors, of which, in addition to coastal CIDs, high levels of threats from increased extreme precipitation, which can cause heavy rains and flash floods, and increased droughts, as in the neighbouring southern region, for which it was noted that the combination of three very high threats could cause cascading risks for crop production.

As in other regions, among the vulnerability assessments considered, the value for the current period obtained for the high concentration scenario RCP 8.5 is 34%, which is lower, although close, to the estimates obtained for the RCP 4.5 scenario (Table 3.10).

Table 3.10. Statistical estimates of crop production vulnerability to climate change by scenario and period (%) for the coastal region

Coast			
RCP4.5	**2021**	**2041**	**2081–2100**
max	35	37	45
mean	29	32	40
min	21	24	31
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	34	43	58
mean	27	38	51

min	21	33	44

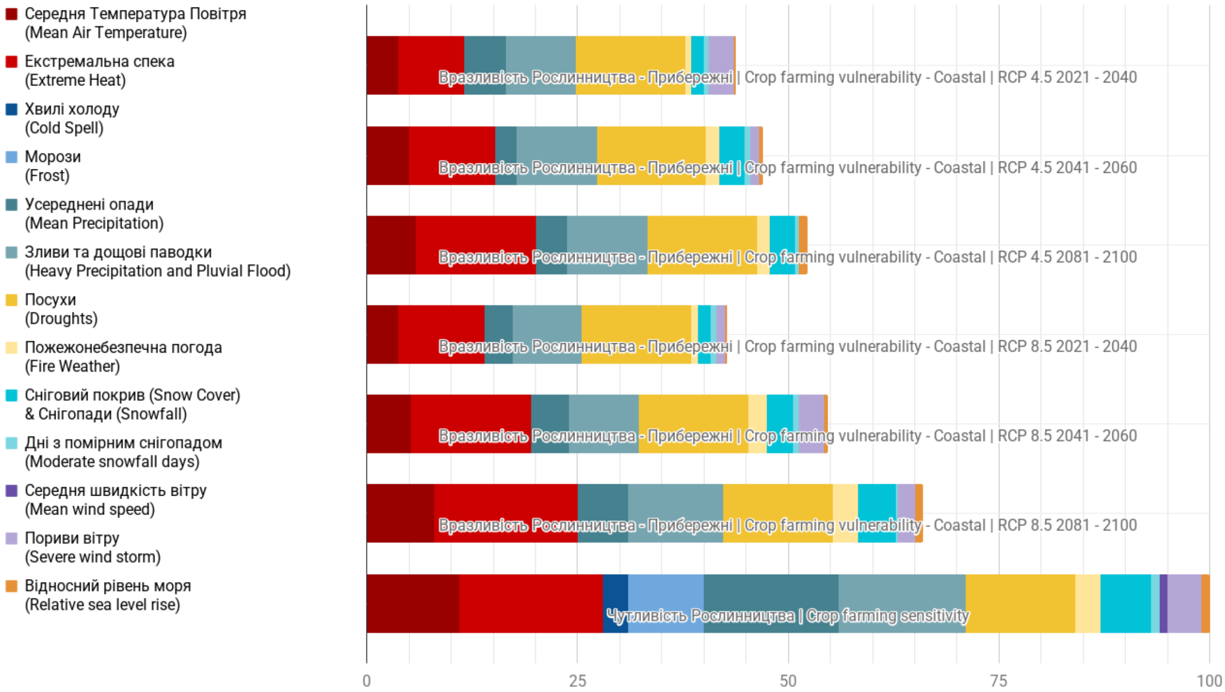

Figure 3.9. – Maximum vulnerability of crop production in the coastal region in three periods under two scenarios compared to sensitivity (lower bar) divided into CID categories (colours)

As in other regions, vulnerability increases quite rapidly under the RCP 8.5 scenario, especially by the middle of the century, when it rises to an average of 38% and a maximum of 43%, and by the end of the century reaches a maximum of 58%, with 7 out of 10 threats at a very high level (Fig. 2.15), while the others are slightly lower: a high level of threat from increased precipitation extremes, but low for moderate snowfall, and a medium level of threat from increased wind speed and gusts.

4. ASSESSMENT OF THE VULNERABILITY OF THE ANIMAL HUSBANDRY SECTOR TO CLIMATE CHANGE

4.1. Sensitivity of animal husbandry to climate change

It should be noted that the weight coefficients of sensitivity of animal husbandry obtained do NOT depend on the geographical region of location, but represent only the response of the industry under study to changes in environmental parameters, expressed in numerical terms (Table 4.1). Studies published by the FAO show that animal husbandry is most affected by high air temperatures, changes in humidity and thermal radiation indicators.

An expert assessment of the sensitivity of animal husbandry to climate change showed that the greatest impact on the industry is the increase in the duration of droughts. The highest weighting coefficient of 1.1 has been assigned to this CID. It is known that droughts are atmospheric phenomena accompanied by prolonged periods of high air temperatures, low humidity, and lack of precipitation, which will negatively affect both the condition of livestock and the yield of forage crops, as well as the quantity and availability of drinking water.

The next group of criteria to which livestock farming is highly sensitive is thermal regime indicators. The highest weight coefficients here are 0.6 for climate indices such as the number of days with very strong and extreme heat. An increase in this indicator will obviously indicate a period when the condition of animals may deteriorate, their productivity may decline, and the condition of forage land and natural pastures may deteriorate with a decrease in their productivity. The industry is also highly sensitive (0.6) to increases in the maximum daily temperature during the summer, which will generally indicate an increased temperature background with the negative consequences mentioned above. Such a CID as tropical nights is defined as the number of days when the minimum (mainly night-time) air temperature is above 20°C. The sensitivity of the industry to this indicator is also 0.6. If the value of the indicator increases, this will lead to high night-time temperatures making it impossible for livestock and forage crops to recover physiologically after daytime heat stress. Sensitivity to the decrease in temperature on very cold days in the winter months (cold spells) is also high (0.6). An increase in the number of such periods may lead to an increase in the cost of keeping livestock indoors and to a general deterioration in the condition of the animals.

Slightly lower (0.5) is the sensitivity of the industry to changes in indices such as a reduction in the length of the growing season and an increase in the Humidex index, which is based on average maximum temperatures in the summer months and air humidity indicators, as well as heating degree-days. Current climate change trends indicate that the growing season is likely to increase, which may have a positive impact on the industry due to the possibility of improving the feed base by growing a second crop of fodder crops. The Humidex index is also likely to increase, which will have an adverse effect on the industry, as will all changes caused by rising summer temperatures and a corresponding decrease in relative air humidity. The heating degree-day index is likely to decrease, which will improve conditions for keeping livestock indoors in winter. Animal husbandry is moderately sensitive to increases in mean air temperatures (from 0.1 to 0.4). The highest sensitivity (0.4) is to increases in the mean temperature in July.

The sensitivity of the industry to the amount and pattern of precipitation is also medium. The highest weight coefficient of sensitivity (0.5) is for the index of maximum precipitation over 5 days. Significant amounts of precipitation falling in a relatively short period of time are often torrential and can negatively affect the condition of forage lands, causing soil erosion, damage to plantings, and hindering grazing on natural pastures.

In relation to the decrease of average monthly precipitation values, the industry has sensitivity indicators of 0.1–0.4. The greatest impact will be caused by a decrease in precipitation in April and July (0.4) and slightly less in October (0.3). A decrease in precipitation in the spring and summer will obviously create conditions for a reduction in the harvest of forage crops and feed stocks, which will negatively affect the development of the industry.

We note a moderate sensitivity (0.3) to precipitation patterns, represented by indices such as maximum daily precipitation and annual very heavy precipitation. The industry is less sensitive to wind CIDs (0.1–0.2) and the presence of snowcover and snowfall changes (0.1–0.2).

According to aggregate estimates (last column of Table 4.1), animal husbandry is most sensitive to an increase in extreme heat (2.3). The industry is also quite sensitive to an increase in mean air temperature (1.7) and a decrease in mean precipitation (1.4). Sensitivity values are also high at 1.1 for an increase in heavy rains and pluvial floods, droughts, as well as cold spells and, accordingly, degree-days of the heating period. The medium sensitivity of animal husbandry to an increase in frosts (0.4), and to changes in all other categories of CID, the sensitivity of the industry is low or absent (coastal).

Table 4.1. Sensitivity of animal husbandry to changes in climatic impact-drivers (CID) with weighted coefficients aggregated by category

IPCC CID	IPCC CID Category	CID name	Units	Animal husbandry	
				Assessment	Amount per category
HEAT AND COLD	↗ MEAN AIR TEMPERATURE	↗ Annual near surface air temperature	°C	0.1	1.7
		↗ January mean air temperature	°C	0.2	
		↗ April mean air temperature	°	0.3	
		↗ July man air temperature	°	0.4	
		↗ October mean air temperature	°	0.2	
		↘ Growing season length	d/y	0.5	
	↗ EXTREME HEAT	↗ Mean of maximum daily air temperature in summer	°C	0.6	2.3
		↗ Days with very high and extreme heat	d/y	0.6	
		↗ Tropical nights	d/y	0.6	
		↗ Humidex index for the mean maximum air temperatures in summer	index	0.5	
		↗ Cooling Degree Days (CDD))	dd/y	0.0	
	↗ COLD WAVES	↘ The temperature of very cold days in the winter months	°C	0.6	1.1
		↗ Heating degree days	dd/y	0.5	
	↗ FROST	↗ Frost days	d/y	0.2	0.4
		↗ Ice days	d/y	0.2	
WET AND DRY	↘ MEAN PRECIPITATION	↘ Annual precipitation	%	1.1	2.2
		↘ January precipitation	%	0.1	
		↘ April precipitation	%	0.2	
		↘ July precipitation	%	0.4	
		↘ October precipitation	%	0.4	
	↗ HEAVY PRECIPITATION AND PLUVIAL FLOODS	↗ Maximum 5-days precipitation	mm	0.3	1.1
		↗ Maximum 1-day precipitation	mm	0.5	
		↗ Very heavy precipitation annual sums	%	0.3	

	↗ DROUGHT	↗ Maximum duration of drought in 20 years	d/y	0.3	0.3
	↗ NUMBER OF DAYS WITH FIRE WEATHER FWI >30	↗ Fire hazard index > 30	d/y	0.3	0.3
SNOWFALLAND SNOWCOVER	↘ SNOWFALL AND SNOW COVER	↘ ANNUAL SNOWFALL	mm	0.1	0.2
		↘ NUMBER OF DAYS WITH SNOWCOVER ≥30%	d/y	0.1	
	↗ NUMBER OF DAYS WITH SNOWFALL ≥ 10 MM PER DAY		d/y	0.1	0.1
SURFACE WIND SPEED	↗ AVERAGE WIND SPEED		m/s	0.1	0.1
	↗ WIND GUSTS ≥ 10.8 M/S (6 BEAUFORT)		d/y	0.2	0.2
COASTAL	↗ RELATIVE SEA LEVEL RISE		m	0.0	0.0
	↗ EXTREME SURGE STORM LEVEL (COASTAL FLOOD)		m	0.0	0.0
Total				10.0	10.0

4.2. Vulnerability

The vulnerability of a sector (system) is its susceptibility to negative impacts. Vulnerability is proportional to the degree of change in various climatic impact-drivers (CIDs) and elements, including sensitivity or susceptibility to damage, and the lack of capacity to cope and adapt. According to the glossary in the Second Working Group of the IPCC, **the vulnerability index** is "a metric that characterises the vulnerability of a system. The climate vulnerability index is usually calculated by combining, with or without weighting, several indicators that are assumed to represent vulnerability."

In this study, we calculated vulnerability as the sum of the multiplication of the degrees of impact of each CSE on sensitivity to its negative impact. Since the sum of the weighting coefficients of sensitivities to 32 CIDs for all sectors is 10 conventional units (Table 4.1), and the maximum degree of impact of CIDs is determined by 10 main categories of IPCC also within 10 (Fig. 2.10 – 2.17), vulnerability can be represented as a percentage (%), where 100% means complete or significant damage and losses to the sector (system):

Vulnerability (%) = ∑ (32 CIDs) ***Degree of CID impact x Sensitivity to CID***

The analysis focuses primarily on the negative reactions of the system to external influences, which, due to the absence/incompleteness/impossibility of adaptation, can lead to its deterioration or degradation. The degree of vulnerability is quantitatively assessed using weighting coefficients of the sensitivity of the system (sector) to the intensity of external factors, in this case to climatic impact-drivers (CID). The degree of CIDs impact is shown in Table 2.2.

Next, we will consider the obtained assessments of the vulnerability of the animal husbandry sector to climate change by region, using maps (Fig. 4.1) and statistical characteristics (Table 4.2) for three periods (2021–2040, 2041–2060 and 2081–2100) and two representative concentration pathways (RCP) scenarios, RCP 4.5 and RCP 8.5.

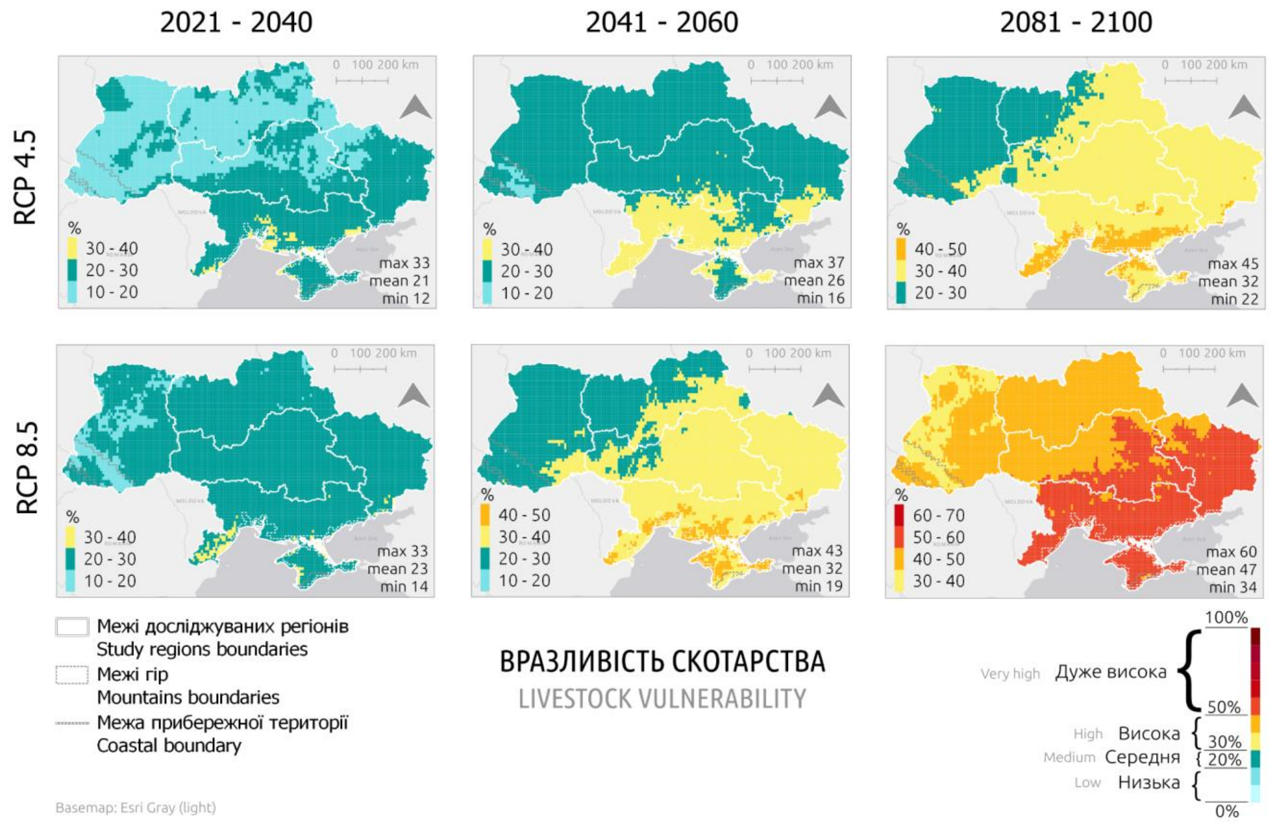

Figure 4.1. – Vulnerability of animal husbandry to changes in all climatic impact-drivers (CID) for scenarios and periods until the end of the 21st century.

Table 4.2. Statistical estimates of the vulnerability of animal husbandry to climate change by region, scenario and period (%)

Animal husbandry										
Region	**Scenario**	**2021–2040**			**2041–2060**			**2081–2100**		
		mean	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**	
West	RCP 4.5	14	19	24	18	24	28	23	26	32
	RCP 8.5	16	21	28	22	26	35	35	41	49
North	RCP 4.5	15	18	23	21	25	29	23	30	35
	RCP 8.5	18	23	25	23	29	34	39	45	50
Centre	RCP 4.5	16	20	28	23	27	33	25	33	41
	RCP 8.5	20	23	29	26	32	40	40	49	55
East	RCP 4.5	17	21	29	23	26	33	30	35	43
	RCP 8.5	20	24	30	29	35	42	46	51	57
South	RCP 4.5	20	26	32	24	31	37	32	38	44
	RCP 8.5	21	26	32	30	37	43	45	53	60
Carpathians	RCP 4.5	12	16	21	16	20	25	22	26	31
	RCP 8.5	14	19	24	19	24	29	34	39	45
Crimean Mountains	RCP 4.5	17	22	25	24	26	29	31	35	40
	RCP 8.5	21	24	26	32	36	42	47	52	58
Coastal areas	RCP 4.5	20	28	33	25	32	37	30	40	45
	RCP 8.5	21	28	33	32	40	43	49	54	58

4.2.1. South

Numerical calculations of animal husbandry vulnerability indicators to climate change in the current period 2021–2040 show approximately the same medium levels of the industry's vulnerability to climate change in both scenarios (Table 4.3). Only in a few small areas in the western part of Mykolaiv Oblast and the north-eastern part of Odesa Oblast, the south-eastern part of Zaporizhzhia Oblast for RCP 4.5, and the south-western part of Odesa Oblast and the western part of the Autonomous Republic of Crimea for RCP 8.5 (Fig. 4.1), the indicators move into the high vulnerability category with a maximum value of 32% (Table 4.3).

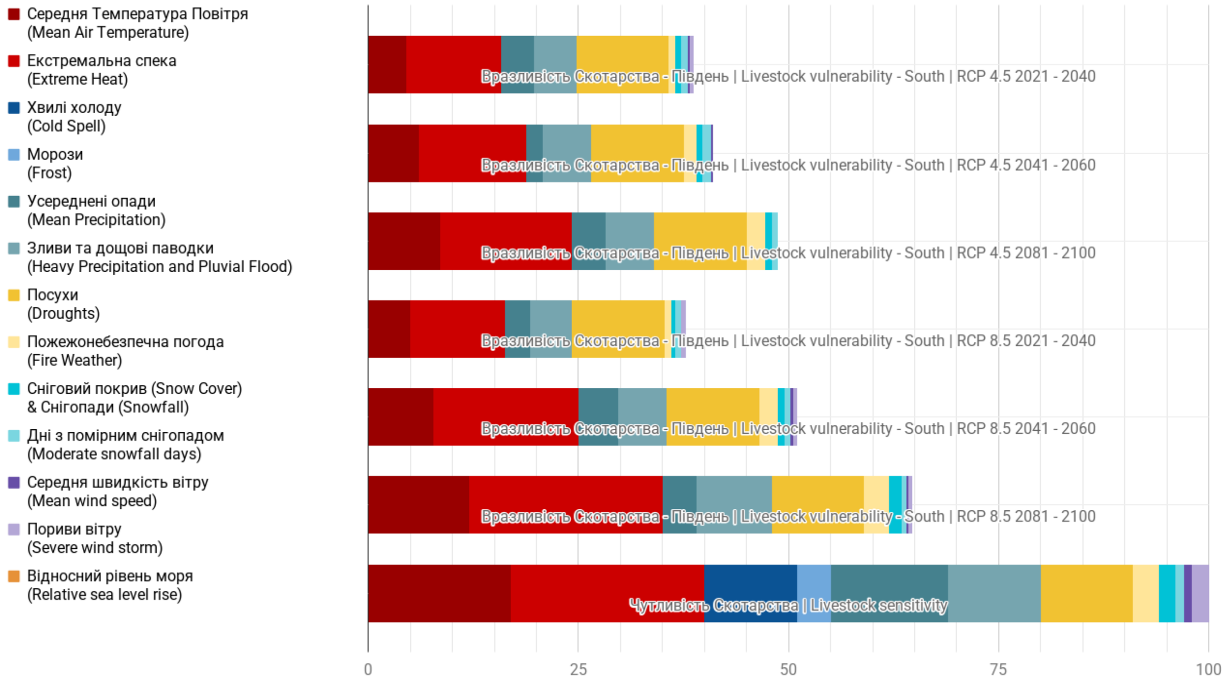

Figure 4.2. – Maximum vulnerability of animal husbandry in the southern region in three periods under two scenarios compared to sensitivity (lower bar) divided into categories of vulnerability (colours)

The vulnerability of animal husbandry to such changes is assessed as high in both scenarios. The difference is that in the RCP 4.5 scenario, vulnerability is high in most of the territory, but in the north of Zaporizhzhia Oblast and in central Crimea, it is assessed as medium (Fig. 4.1). Under the RCP 8.5 scenario, the vulnerability of animal husbandry is high throughout the southern region, with an increase in indicators in the south of Mykolaiv Oblast, the south-west and south of Odesa Oblast, as well as in the centre and west of Crimea. The maximum values for the scenarios are 37% and 43%, respectively.

In the distant future (2081–2100), the difference in animal husbandry vulnerability indicators between scenarios becomes significant. In the case of RCP 4.5, the vulnerability of the industry will remain medium with a slight increase in estimated values, while in the more severe RCP 8.5 scenario, vulnerability will be very high with a relatively uniform distribution of estimated values across the region. For this period***, the region has the highest vulnerability levels in Ukraine for both scenarios – 44% and 60%, respectively*** (Tables 4.2 and 4.3)**.**

Table 4.3. Statistical vulnerability of animal husbandry to climate change by scenario and period (%) for the southern region

South			
RCP4.5	**2021**	**2041–2060**	**2081–2100**
max	32	37	44
mean	26	31	38
min	20	24	32
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	32	43	60
mean	26	37	53
min	21	30	45

4.2.2. Centre

In the current climate period 2021–2040, low (north-western and north-eastern regions) and medium vulnerability levels for the animal husbandry sector were obtained for the central region for the RCP 4.5 scenario. For the RCP 8.5 scenario, a uniform distribution of vulnerability of the sector as medium was obtained (Table 4.4).

By the middle of the century, in the period 2041–2060, vulnerability increases, and differences between scenarios become apparent. While for RCP 4.5, vulnerability increases to a medium level with occasional high levels for virtually all central regions, for the RCP 8.5 scenario, the indicators point to a potentially high vulnerability, with the exception of certain areas of the Vinnytsia region, where vulnerability will remain at a medium level. The maximum values for this period are 33% and 40%, respectively (Fig. 4.1, Table 4.4).

In the distant future (2081–2100), when significant changes in the thermal and moisture regimes are expected, the vulnerability of the industry to these changes will increase (Fig. 4.3). In the case of the RCP 4.5 scenario, a practically uniform distribution of high vulnerability was obtained, with isolated point values of medium vulnerability in the west of the Vinnytsia region (Fig. 4.1). For the RCP 8.5 scenario, high vulnerability was obtained in the west of the region (Vinnytsia, Cherkasy, and western Poltava regions), and very high vulnerability in the south-east. The maximum vulnerability levels for this period under both scenarios are 41% and 55%, respectively (Table 4.4).

Table 4.4. Statistical estimates of animal husbandry vulnerability to climate change by scenario and period (%) for the central region

Centre			
RCP4.5	**2021–2040**	**2041–2060**	**2081–2100**
Max	28	33	41
Mean	20	27	33
Min	16	23	25
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
Max	29	40	55
Mean	23	32	49
Min	20	26	40

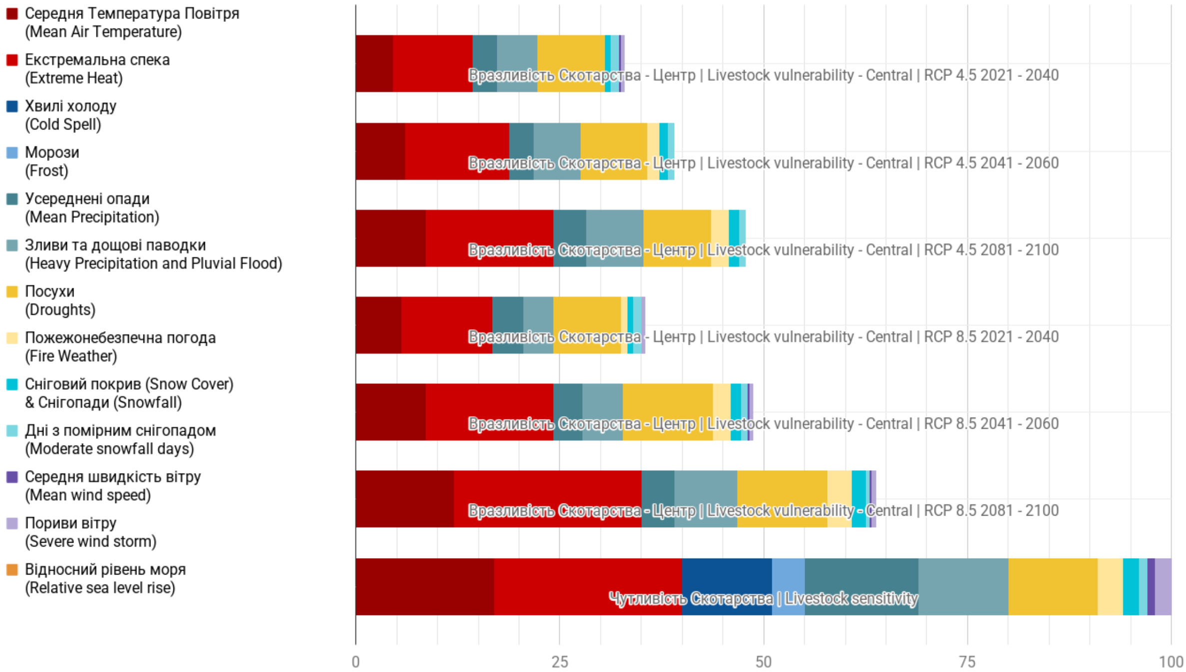

Figure 4.3. – Maximum vulnerability of animal husbandry in the central region in three periods under two scenarios compared to sensitivity (lower bar) divided into categories of vulnerability (colours)

4.2.3 West

It should be noted that this region is the most prosperous in Ukraine in terms of the state and prospects of animal husbandry in the context of climate change (Fig. 4.4). In the current period, we have predominantly low vulnerability for RCP 4.5 and predominantly medium vulnerability with local areas of low vulnerability for RCP 8.5 (Fig. 4.1).

By the middle of the century, in the period 2041–2060, both scenarios show medium vulnerability levels for the industry in the region (Table 4.5). The only difference is that in the south-east of the Khmelnytskyi region, under the RCP 8.5 scenario, there are areas with high vulnerability of the sector (Fig. 4.1). As a result, the maximum vulnerability indicators are obtained there: 28% and 35% according to the scenario, respectively.

Table 4.5. Statistical estimates of the vulnerability of animal husbandry to climate change by scenario and period (%) for the western region

West			
RCP4.5	**2021 – 2040**	**2041–2060**	**2081–2100**
max	24	28	32
mean	19	24	26
min	14	18	23
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	28	35	49
mean	21	26	41
min	16	22	35

In the distant future (2081–2100), according to the RCP 4.5 scenario, virtually the entire region will remain at medium vulnerability levels (except for a small area in the south-east). Within the flat part of the western region of Ukraine (except for the Carpathians), this is the only contiguous region with such relatively low vulnerability indicators for the sector during this period. The maximum value of the indicator is 32%. For the RCP 8.5 scenario, the vulnerability of the sector to climate change is assessed as high, with a maximum indicator of 49%.

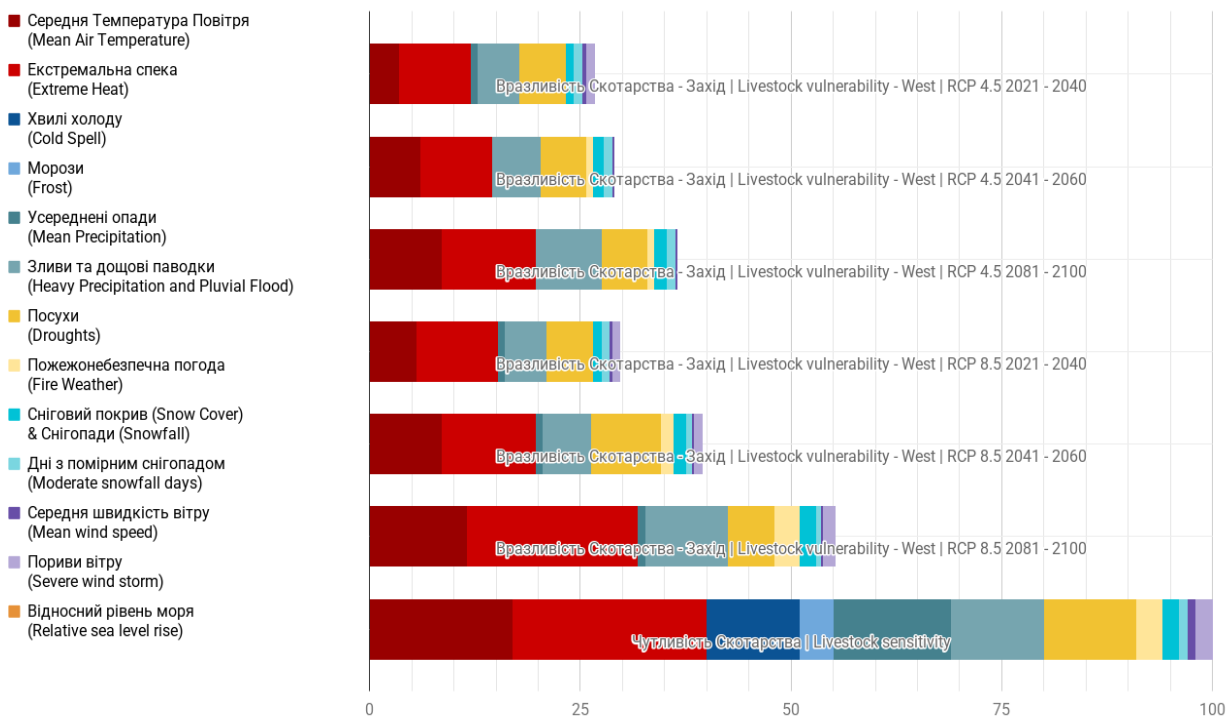

Figure 4.4. – Maximum vulnerability of animal husbandry in the western region in three periods under two scenarios compared to sensitivity (lower bar) divided into CID categories (colours)

4.2.4. East

In eastern Ukraine, as in the south, significant changes in temperature and precipitation patterns are expected, and therefore there is a high probability of a significant change in the vulnerability of animal husbandry to climate change (Fig. 4.5). In the current period 2021–2040, both scenarios show average vulnerability indicators. The difference is that for the RCP 4.5 scenario, there are isolated areas in the north of the region with low vulnerability ratings, and for RCP 8.5, there are also isolated points in the south-east with medium vulnerability levels (Fig. 4.1).

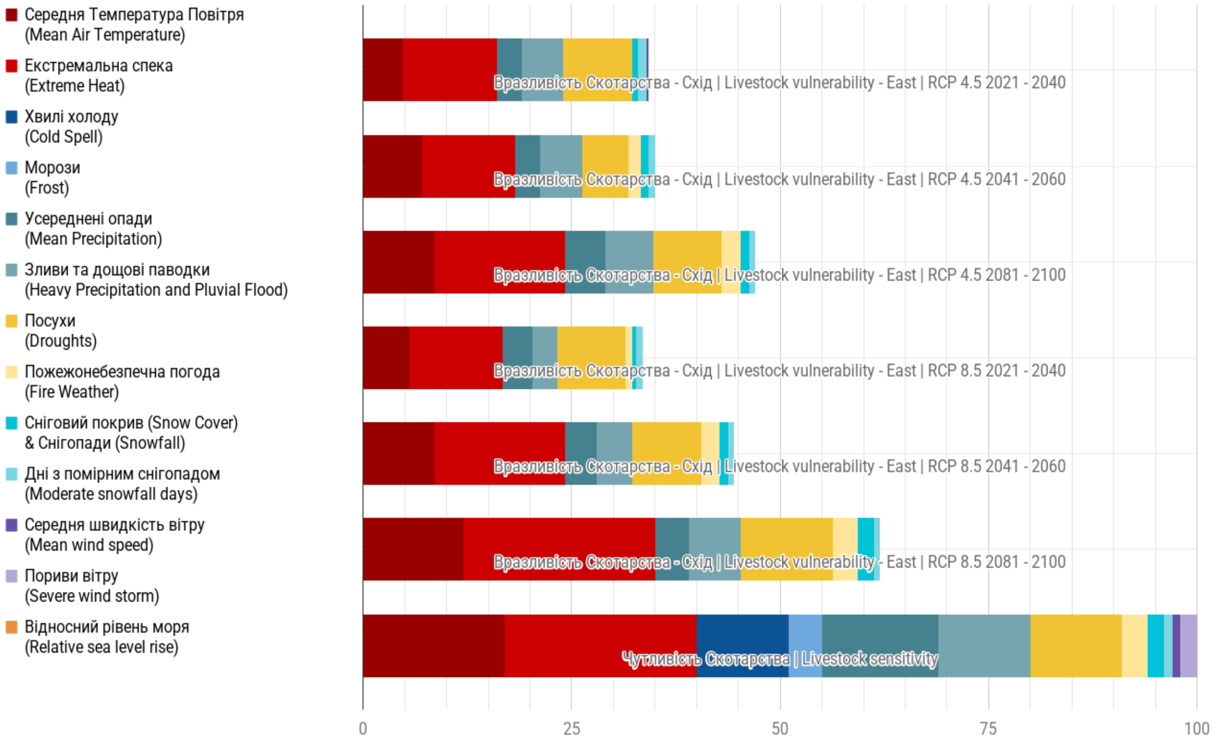

Figure 4.5. – Maximum vulnerability of animal husbandry in the eastern region in three periods under two scenarios compared to sensitivity (lower bar) divided into CID categories (colours)

By the middle of the century, in the period 2041–2060 (Table 4.6), a significant difference is expected if one or the other scenario is implemented. For RCP 4.5, the vulnerability of the industry will remain practically at the previous level (medium), with the exception of the south of Donetsk Oblast, where vulnerability level will increase to high (Fig. 4.5). However, for RCP 8.5, the vulnerability of animal husbandry will increase to high.

In the distant future of 2081–2100 (Table 4.6), in the eastern region, as in the southern region, the vulnerability level of animal husbandry will increase according to calculations for RCP 4.5 to high, and for RCP 8.5 to very high. The maximum values obtained are 43% and 57% according to the scenarios, respectively.

Table 4.6. Statistical estimates of animal husbandry vulnerability to climate change by scenario and period (%) for the eastern region

East			
RCP4.5	**2021 – 2040**	**2041–2060**	**2081–2100**
max	29	33	43
mean	21	26	35
min	17	23	30
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	30	42	57
mean	24	35	51
min	20	29	46

4.2.5. North

In terms of the vulnerability of animal husbandry to climate change and the prospects for change in this indicator, the northern region of Ukraine is close to the scenario expected in the central region (Table 4.7). In the current period, for the RCP 4.5 scenario, the level of vulnerability is assessed as low, with the inclusion of certain areas in the north and north-east of the Chernihiv and Sumy regions, where medium level of vulnerability was obtained (Fig. 4.1). For RCP 8.5, a more even distribution of indicators related to the gradation of medium vulnerability values is obtained, with only a few isolated indicators of low vulnerability.

Table 4.7. Statistical estimates of the vulnerability of animal husbandry to climate change by scenario and period (%) for the northern region

North			
RCP4.5	**2021**	**2041–2060**	**2081–2100**
max	23	29	35
mean	18	25	30
min	15	21	23
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	25	34	50
mean	23	29	45
min	18	23	39

By the middle of the century, in the period 2041–2060, the industry's response to climate change is expected to be more pronounced (Fig. 4.6). Under the RCP 4.5 scenario, the vulnerability of animal husbandry is expected to be at medium levels, with a uniform distribution, while under RCP 8.5, such medium vulnerability levels will remain only in most of the Zhytomyr region (except for the south-east), in the north of the Kyiv region and in the north-east of the Chernihiv region (Fig. 4.1). The maximum indicators are 29% and 34% according to the scenario (Table 4.7).

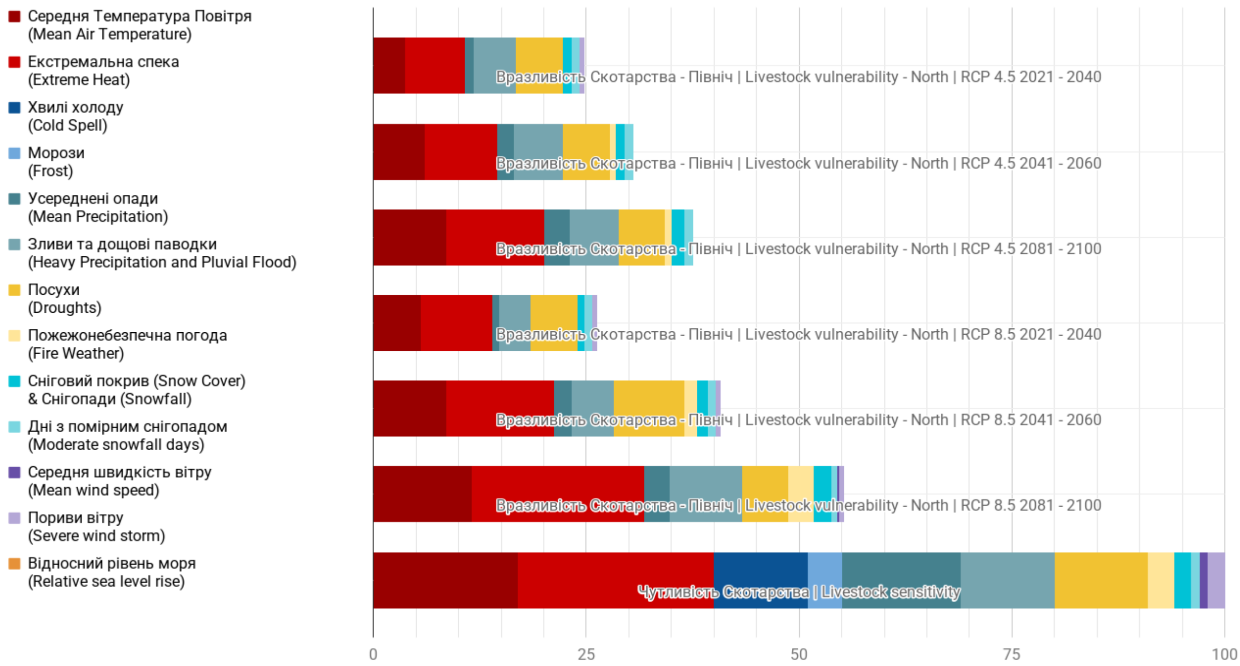

Figure 4.6. – Maximum vulnerability of animal husbandry in the northern region in three periods under two scenarios compared to sensitivity (lower bar) with division into CID categories (colours)

In the distant future, in the period 2081–2100, under a moderate climate change scenario, the vulnerability of the sector is expected to be predominantly high (Table 4.7), with the exception of the north-western part of Zhytomyr Oblast and small areas of north-western Kyiv Oblast, where medium vulnerability to climate change will remain (Fig. 4.1). Under the RCP 8.5 scenario, a significant increase in air temperature is expected during this period, as well as a whole range of natural phenomena associated with high temperatures. This will lead to an increase in the vulnerability of the sector to high levels with a relatively even distribution across the region. The maximum values are 35% and 50% according to the scenarios (Table 4.7).

4.2.6. Carpathian Mountains

In the current period of 2021–2040, the region has the lowest indicators of animal husbandry vulnerability to climate change in Ukraine (Table 4.8). In other words, despite the rather strong anthropogenic impact on the ecosystem of the Ukrainian Carpathians and global and regional climate change, the natural conditions for the development of the animal husbandry sector here remain the least vulnerable (Fig. 4.1). For RCP 4.5, the vulnerability of the industry to climate change is low, with a maximum value of 21%, which already corresponds to medium vulnerability. For the RCP 8.5 scenario, the level of vulnerability in the mountains also remains low, but in the Transcarpathian part it increases to medium, with a maximum value of 24%.

Table 4.8. Statistical estimates of the vulnerability of animal husbandry to climate change by scenario and period (%) for the Carpathian Mountains region

Carpathians			
RCP4.5	**2021 – 2040**	**2041 – 2060**	**2081–2100**
max	21	25	31
mean	16	20	26
min	12	16	22
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	24	29	45
mean	19	24	39
min	14	19	34

By the middle of the century, in the period 2041–2060, more favourable conditions for the industry will remain in the region, with vulnerability to climate change under a moderate scenario remaining low (centre of the region) or medium, with a maximum value of 25%. Under the RCP 8.5 scenario, vulnerability indicators increase to medium values, with a maximum value of 29%.

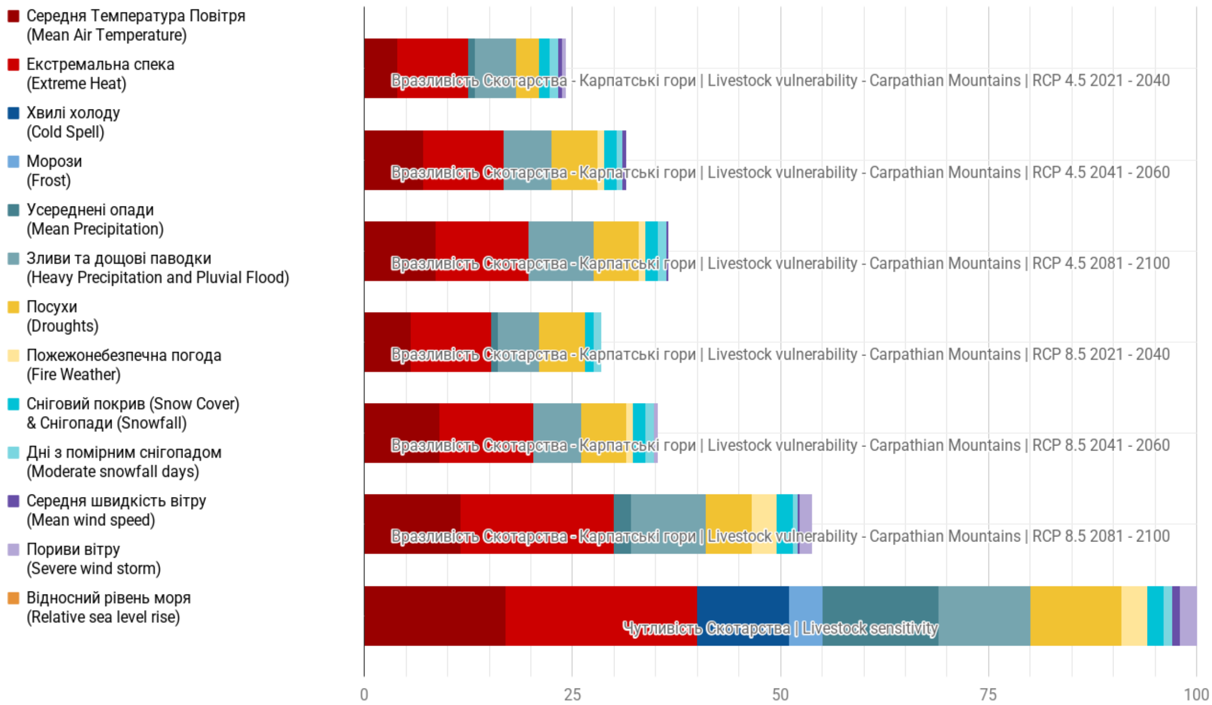

Figure 4.7. – Maximum vulnerability of animal husbandry in the Carpathian Mountains in three periods under two scenarios compared to sensitivity (lower bar) divided into categories (colours)

In the distant future of 2081–2100, under the RCP 4.5 scenario, the vulnerability of the animal husbandry sector under the moderate scenario increases slightly to the medium level across the region. However, attention should be paid to the sharp changes in vulnerability indicators in the case of the RCP 8.5 scenario. Vulnerability indicators increase to high levels, with a maximum of 45%. This fact confirms the significant differences in the change in the thermal regime in the region under the RCP 4.5 and RCP 8.5 scenarios for this period, as obtained in the modelling.

4.2.7. Crimean Mountains

In the current period (Table 4.9), animal husbandry has a predominantly medium degree of vulnerability (22% and 24%) to climate change, with only under the RCP 4.5 scenario the minimum value falls into the low vulnerability category (17%). In fact, the vulnerability of the industry in the Crimean Mountains is lower than or comparable to for this period with the Southern region, where 20–32% was obtained for RCP 4.5 and 21–32% for RCP 8.5.

By the middle of the century, in the period 2041–2060, a certain difference in climate change in the region is expected for each of the scenarios, with more intense changes for RCP 8.5 (Fig. 4.8). Hence, there is a difference in vulnerability for animal husbandry, which will have a maximum of 29% for the moderate scenario and a maximum of 42% for the more severe scenario, corresponding to the high vulnerability of the industry.

At the end of the century, the difference between the scenarios increases, with vulnerability rising to high (maximum – 40%) for RCP 4.5 and to very high with an average value of 52% and a maximum of 58% for RCP 8.5 (Table 4.9).

Table 4.9. Statistical estimates (minimum, average and maximum values) of the vulnerability of animal husbandry to climate change by scenario and period (%) for the Crimean Mountains region

Crimean Mountains			
RCP4.5	**2021–2040**	**2041–2060**	**2081–2100**
max	25	29	40
mean	22	26	35
min	17	24	31
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	26	42	58
mean	24	36	52
min	21	32	47

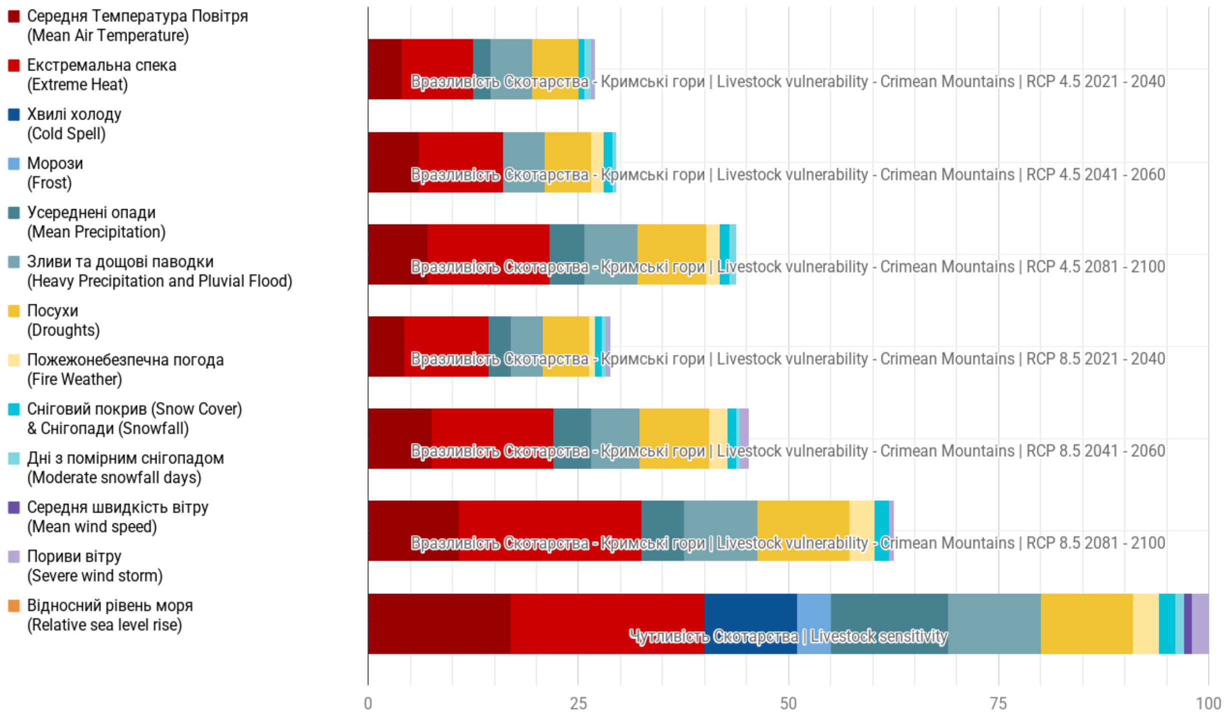

Figure 4.8. – Maximum vulnerability of animal husbandry in the Crimean mountains in three periods under two scenarios compared to sensitivity (lower bar) divided into categories of vulnerability (colours)

4.2.8. Coastal

For the Coastal region, the change in animal husbandry vulnerability indicators (Fig. 4.1) is also close to the indicators of the neighbouring Southern region due to the proximity of their geographical location, and while in the current period the coastal areas have slightly higher and practically equal vulnerability levels ranging from 20–21% to a maximum of 33% in both scenarios (Table 4.10), by the middle of the century the vulnerability indicators are comparable to those for the Southern region, and by the end of the century, in the period 2081–2100, the maximum vulnerability values for RCP 8.5 are slightly lower for coastal regions: 58% versus 60% for the South (Table 4.2).

Table 4.10. Statistical estimates (minimum, average and maximum values) of the vulnerability of animal husbandry to climate change by scenario and period (%) for the coastal region

Coastal region			
RCP4.5	**2021–2040**	**2041–2060**	**2081–2100**
max	33	37	45
mean	28	32	40
min	20	25	30
RCP8.5	**2021–2040**	**2041–2060**	**2081–2100**
max	33	43	58
mean	28	40	54
min	21	32	49

Despite the fact that the threat of sea level rise and increased storm surge height in this region is the highest (Fig. 2.15), but since the animal husbandry sector is not sensitive to these coastal CIDs (Table 4.1), as it is believed that animals can be driven away from the coast, the contribution to vulnerability will be zero (Fig. 4.9).

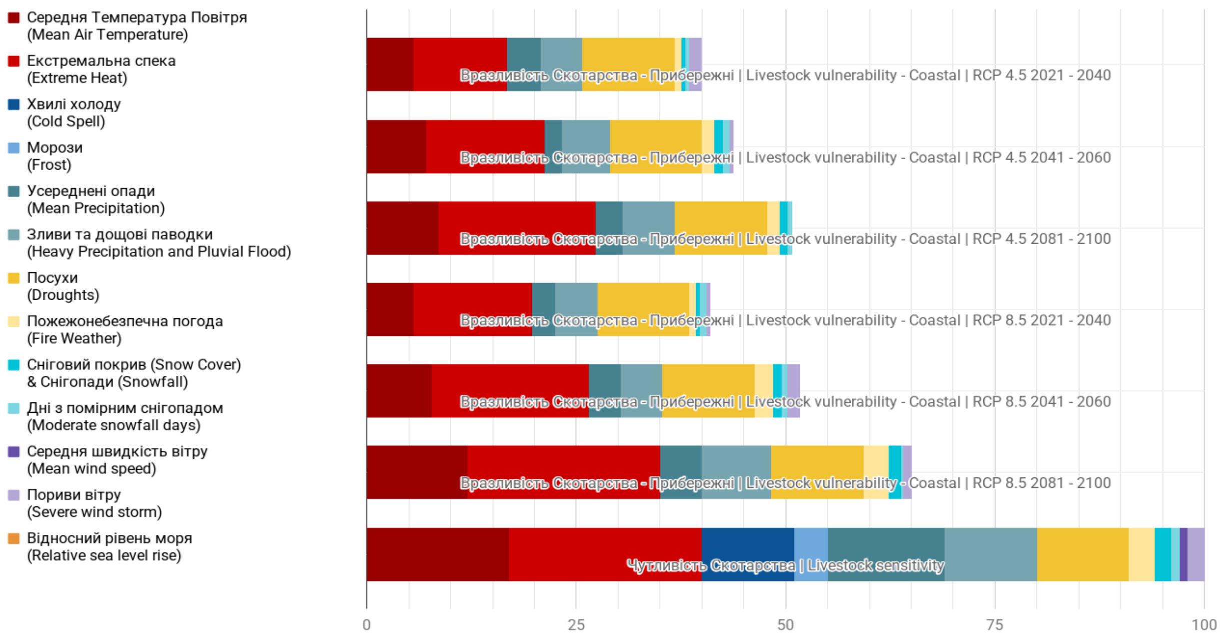

Figure 4.9. – Maximum vulnerability of animal husbandry in the coastal region in three periods under two scenarios compared to sensitivity (lower bar) divided into CID categories (colours)

5. CLIMATE CHANGE RISKS FOR AGRICULTURE

5.1. Methodology for determining climate risks

To assess the risks of climate change for agriculture, the concepts and definitions set out in the "Methodological recommendations for assessing the risks and vulnerability of socio-economic sectors and natural components to climate change" approved by Order of the Ministry of Environmental Protection and Natural Resources of Ukraine No. 386 of 03.06.2023, with some updates and additions to take into account the concepts that appeared in the latest IPCC report in 2021-2023. This updated methodology was tested during the implementation of the EU APENA 3 project and continues to be used to assess climate risks and vulnerabilities of economic sectors and individual systems and territories.

Given that the risk of a particular event is probabilistic and therefore specific to different **hazards,** the risk of **climate change** can only arise when an industry (system) is *sensitive to* and *affected by* **a change in a climate indicator**, and *is* also *exposed*, i.e. located in the area affected by the hazard. The exclusion of one of *the* listed *conditions,* as well as **the absence of the threat of climate change,** reduces the risk to zero. Therefore, the risk is calculated as the product of all the listed prerequisites:

$$\textit{Risk} = \textit{Hazard} \times \textit{Exposure} \times \textit{Sensitivity} \quad (1)$$

$$\textit{Hazard} = \textit{Maximum change in CID} \times \textit{Probability}, \quad (2)$$

where:

Maximum change in CID – proportional to *the impact* of the change in the factor and determined in each category among all climatic impact-drivers and takes values from 0 to 1, where 0 – insignificant, 0.25 – low, 0.5 – medium, 0.75 – high, 1 – very high (Table 2.2);

The probability of an event occurring is assigned a conditional value of 5 (95% probability) at the current node of the climate model grid and 4 (75% probability) for the node adjacent to the current one. Since the probability of an event occurring is high and the location of the event is difficult to determine, the algorithm allows for the local nature of changes in CIDs to be taken into account and, in general, smooths out fluctuations, especially for extreme events. In this methodological approach, it is assumed that if an extreme event is found in a specific node in the calculations based on an ensemble of climate models with bias correction, then the probability of the occurrence of this event is ≥95%, but its territorial location in RCM projections has a lower probability, and therefore the assumption is made that the event may occur in a neighbouring node, but with a lower probability of 75%, for which we use a reduced coefficient (4) in the identified hazards;

Exposure (= 1) – we assume that the agricultural sector is potentially affected by risks throughout Ukraine, i.e. in every node of the geographical grid;

Sensitivity – the values of sensitivity to changes in CIDs range from 0 to a maximum of 2.3 as a result of combining weight coefficients by CID categories established by the IPCC (see sections 3.1 and 4.1, Tables 3.1 and 4.1):

1) increase in mean temperature (includes 5 CIDs: mean air temperatures for the year, January, April, July and October);

2) increase in extreme heat (includes the following CIDs: average maximum daily air temperature for the summer months, number of days with very strong and extreme heat, tropical nights, days with a Humidex index above 30, cooling degree-days);

3) increase in frosts (includes: cold spells and days with frost);

4) decrease in mean precipitation (includes: mean precipitation for the year, January, April, July and October);

5) increase in droughts and fire-dangerous weather (includes indicators of maximum duration of rainless period and number of days with fire weather index >30 per year);

6) increase in extreme precipitation (includes indicators: annual amount of very heavy precipitation, amount of precipitation per day and per 5 days);

7) decrease in snowcover and snowfall (includes: annual precipitation in the form of snow and number of days with snowcover ≥ 30%);

8) increase in snowfall with an intensity of more than 10 mm per day (number of days with snow ≥ 10 mm per day);

9) increase in wind speed and gusts (includes: average wind speeds and number of days with wind gusts ≥ 10.8 m/s);

10) rise in mean sea level and increase in storm surge height (coastal factors).

Risks for the main sectors of agriculture – crop production and animal husbandry – were calculated and analysed for the nearest period 2021–2040 and for the middle of the century 2041–2060. That is, for the periods that are most critical for development and consideration of adaptation to climate change in Ukraine. At the same time, projections for the two scenarios considered were taken into account, and the maximum impact among them was determined for the risks.

It should be noted that for each of the factors included in the listed categories of climate change, the sensitivity of the industry and the total degree of impact were determined depending on regional and temporal changes in climate change, i.e. vulnerability (see sections 3 and 4 above).

Thus, the risk calculation algorithm consists of the following steps:

1. Determination of the maximum *impact* value, which is proportional to the maximum change at each point among the CIDs in the category for each of the periods 2021–2040 and 2041–2060 of each RCP 4.5 and RCP 8.5 scenario. The results of this step are essentially presented in subsection 2.10 for those subcategories where there was more than one factor. As an example, the maximum impact levels obtained in the category of increased extreme precipitation for the Ivano-Frankivsk region (Fig. 5.1) are given, where there are sharp transitions between different natural zones – mountains and valleys, and, accordingly, between the values of the indicators.

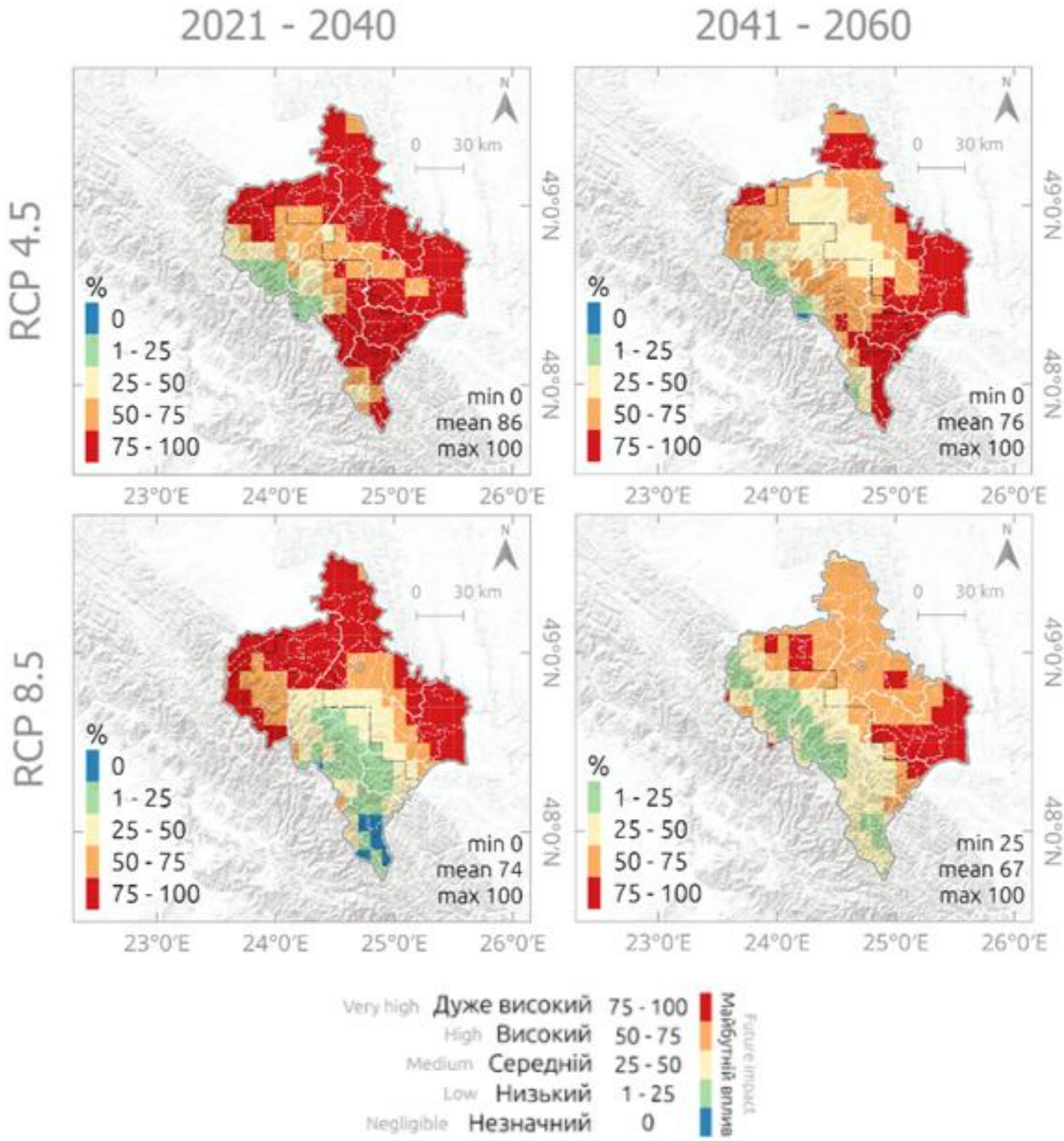

Figure 5.1. – Example of the results of calculating the maximum degree of impact on specific factors (red – very high impact, orange – high, yellow – medium, green – low, blue – insignificant)

2. For the result of the first step, find the maximum impact value for the nearest and average periods under two scenarios at each node of the coordinate grid (Fig. 5.2), i.e., align and search for the maximum impact, which will be ***the maximum impact*** from formula (2).

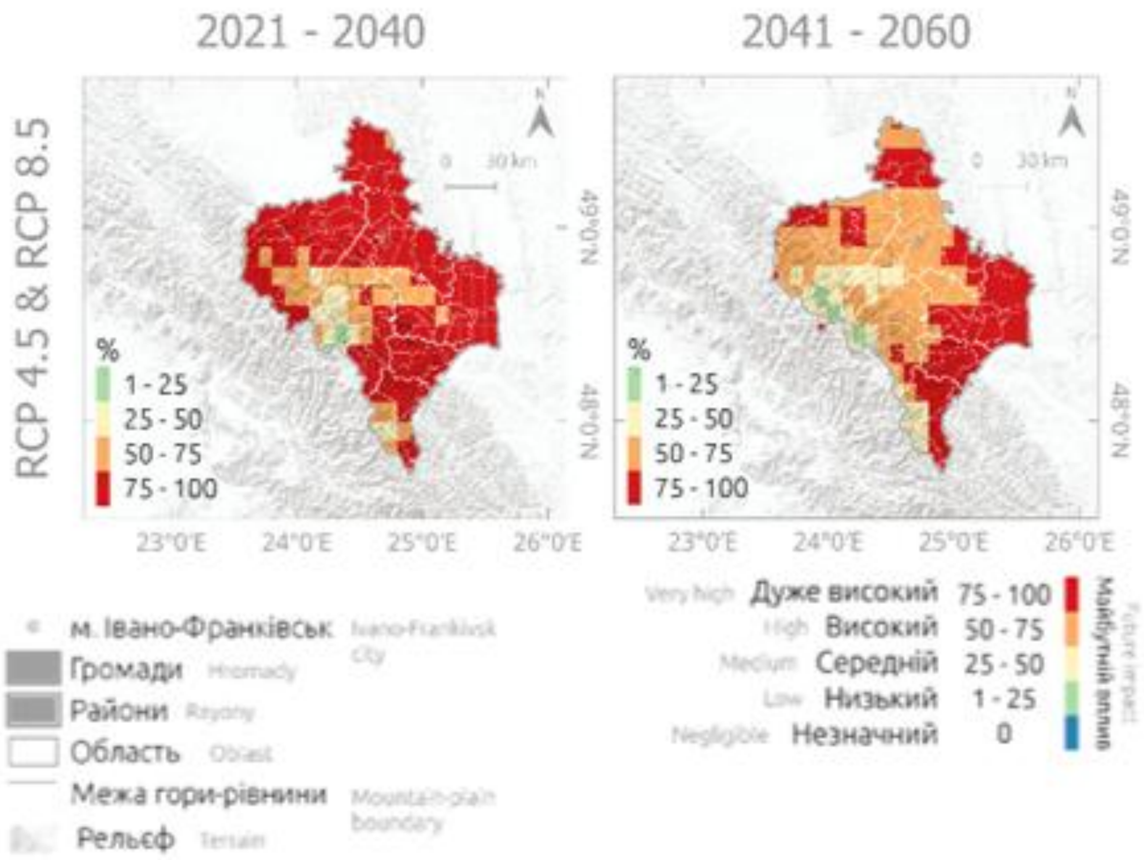

Figure 5.2. – Example of the result of calculating the maximum impact value for both scenarios of the specified factors

3. Calculate *the hazard* using formula (2):

a. Multiply the obtained values of the maximum impact in each of the nodes by a conditional value of 5 for the maximum probability of an event occurring.

b. Going through each node ("current"), determine the nodes adjacent to it (no more than eight) and perform a recalculation (Fig. 5.3): compare the value of the obtained threat in the adjacent node with the value in the current one, which is multiplied by 4 (the probability of the event is less than 75%). Leave the maximum of the two hazard values obtained for the adjacent node (Fig. 5.4):

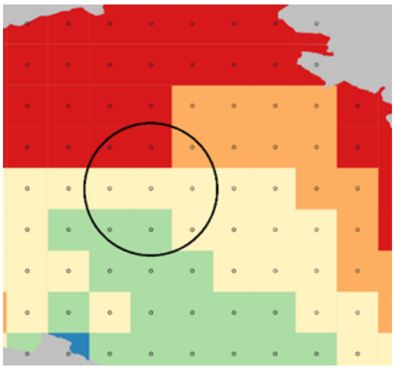

Figure 5.3. – Visualisation for determining adjacent nodes and the maximum hazard in them

If ***(Impact in the adjacent node x 5) < (Impact in the current node x 4)****, then (Hazard in the Adjacent Node) = (Hazard in the Current Node x 4)*

If this condition is not met, the value of Hazard in Adjacent Node remains unchanged

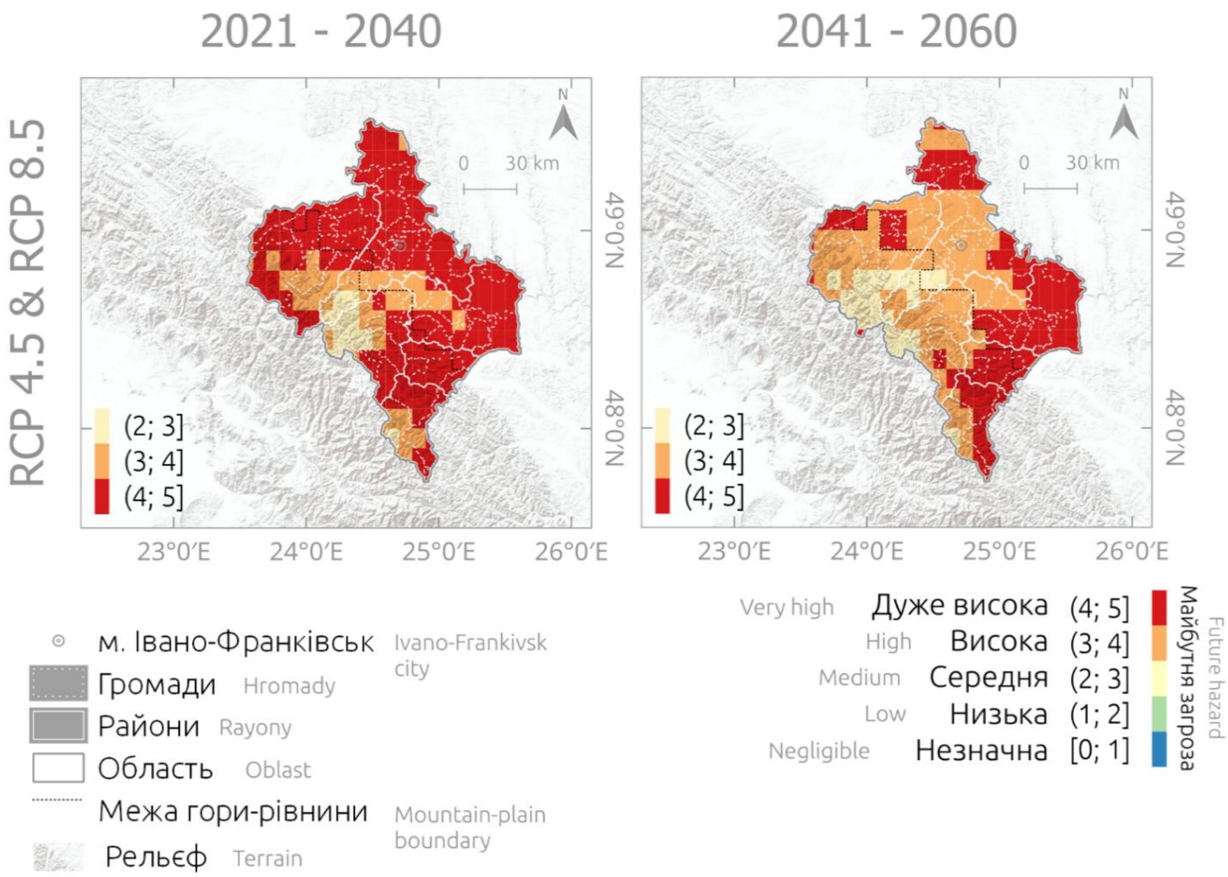

Figure 5.4. – Example of the result of calculating the degree of hazard from identified CIDs

4. To obtain the risk value in the node for each category, multiply the *hazard* value by the sum of the sensitivities of the economic sector for that category. As a result of the algorithm, *the risk* can take values from 0 to 20, which are classified according to the

following gradations (Fig. 5.5) ***[0 – 1] – negligible, [1 – 3] – low, [3 – 6] – medium, [6 – 10] – high, [10 – 20] – very high.***

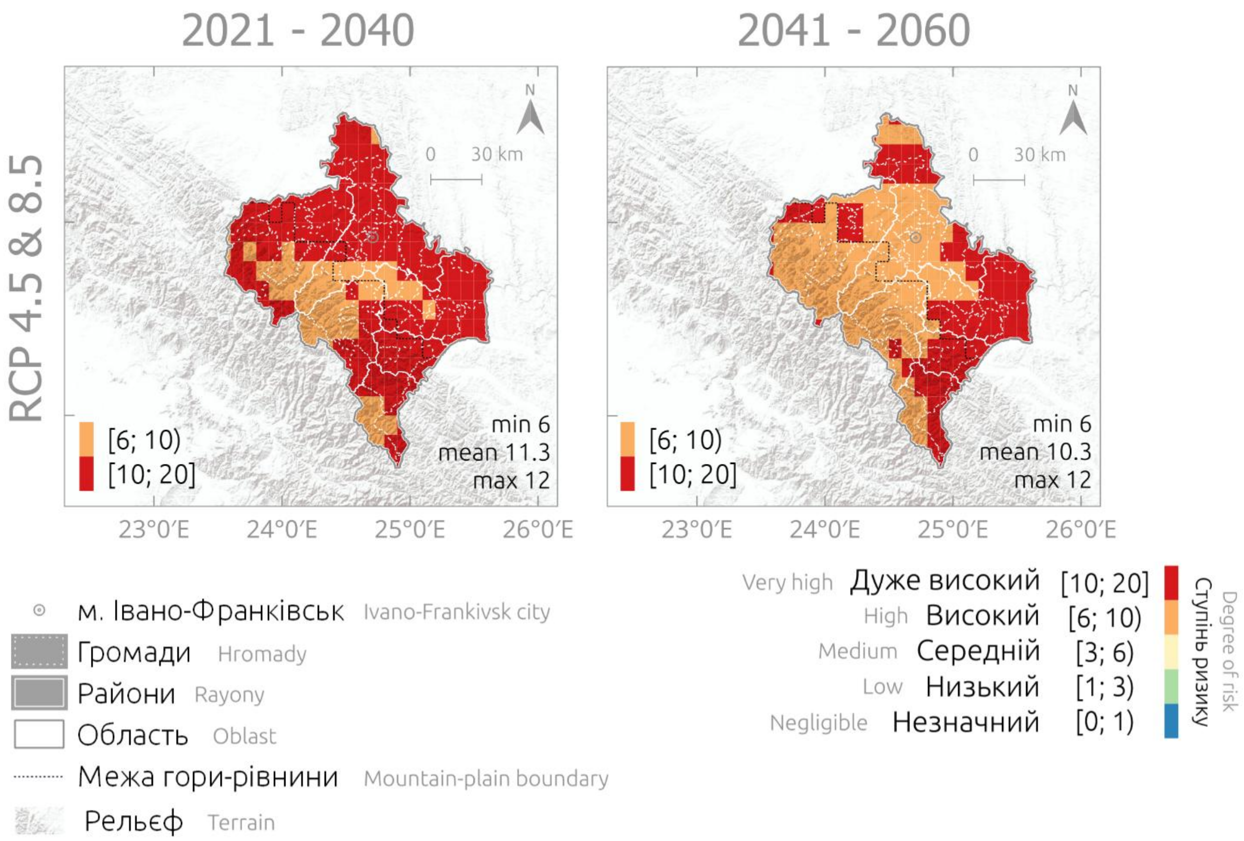

Figure 5.5. – Example of the result of calculating the risk from certain hazard

Thus, the risks from changes in climatic impact-drivers that had a negative impact on the agricultural sector, namely crop production and animal husbandry, were calculated. Let us move on to the analysis of the calculated risks for both sectors in Ukraine from climate change in the current (2021–2040) and future (2041–2060) periods by type of hazard.

5.2. Climate risk assessments for crop production

5.2.1. Mean air temperature

In the near future, 2021–2040, crop production in Ukraine will be at low risk due to an increase in mean air temperature. The risk will be within the range of 2.2–2.8 points in all regions of the country (Table 5.1). As a rule, the mean air temperature affects the sum of effective temperatures accumulated during the growing season. Taking into account recent studies that have shown an increase in the mean temperature in the near future within 0.5ºC per decade, the increase in these sums will be insignificant. All this will not significantly affect the expansion of the species composition of cereals and oilseeds. Also, there may be a minor impact of the increase in mean temperature on the development of winter crops, especially in the autumn period, which may affect plant hardening.

By the middle of the century, 2041–2060, the risk of an increase in the mean temperature compared to the previous period will increase to 4.1 points, which is classified as medium. Moreover, this risk is uniform throughout Ukraine (Fig. 5.6). This may affect the species composition of cereal crops and reduce the area under crops such as barley and rye, which do not require significant heat. Another problem associated with the risk of rising temperatures is the hardening of winter crops in the autumn period.

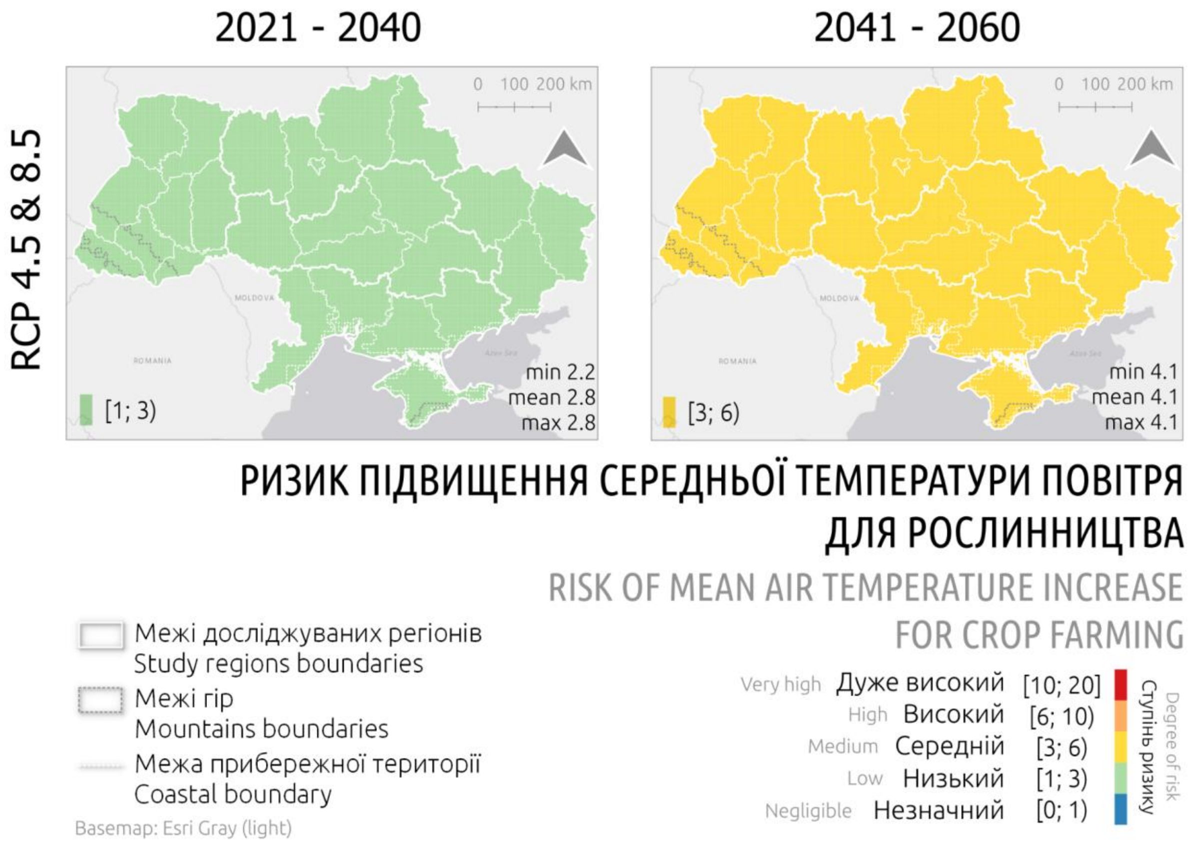

Figure 5.6 – Distribution of the risk of an increase in mean air temperature for crop production in Ukraine

Due to high temperatures, this process will be slow and crops may suffer significant damage during the winter or as a result of a sharp cold snap. Another negative consequence of this risk will be a reduction in the interphase periods for plants, which may affect their productivity and crop quality.

An increase in mean air temperature increases the potential losses of crop production from many pests and diseases, as this can lead to their early appearance, better overwintering and survival in summer. The increase in temperature is expected to affect the geographical range of certain insect species and diseases for different crop-growing regions in Ukraine. The change in mean air temperature may also be a factor in the expansion of migration from south to north of ergonomic and invasive weeds, which will affect crop production development.

Table 5.1. Statistical characteristics of the risk of mean air temperature increase for crop production by region

Mean air temperature						
Region	**2021–2040**			**2041–2060**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	2.2	2.7	2.8	4.1	4.1	4.1
North	2.2	2.7	2.8	4.1	4.1	4.1
Centre	2.2	2.7	2.8	4.1	4.1	4.1
East	2.2	2.7	2.8	4.1	4.1	4.1
South	2.2	2.7	2.8	4.1	4.1	4.1
Carpathian Mountains	2.2	2.7	2.8	4.1	4.1	4.1
Crimean Mountains	2.8	2.8	2.8	4.1	4.1	4.1
Coastal	2.2	2.7	2.8	4.1	4.1	4.1

5.2.2. Extreme heat

Another risk factor for crop production in Ukraine is the increase in extreme heat, with the risk expected to range from 4.3 to 6.4 points, with an average of 5 points, in the near future (2021–2040) according to the combined indicators of two RCP scenarios (Fig. 5.7). Accordingly, the western, eastern and northern territories of Ukraine will be in the medium risk zone with a value ranging from 4.3 to 5.5 points (Table 5.2). The southern, eastern and south-eastern parts of Ukraine will be in the high risk zone ranging from 6.1 to 6.4 points. The coastal areas of the Black and Azov Seas will be in the medium risk zone. By the middle of the century, 2041–2060, crop production will be at a predominantly high risk of extreme heat with values ranging from 4.3 to 8.5 points. Geographically, only the northern and north-western parts of Ukraine will be in the medium risk zone with average values of 5.0 and 5.3 points, while the rest of the country will be in the high risk zone with average values ranging from 6.2 to 6.5 points. The latest calculations show that the increase in the number of hot days by the middle of the century will be 15–20, which will account for 10–15% of the total number of days required for full ripening, for example, of spring crops.

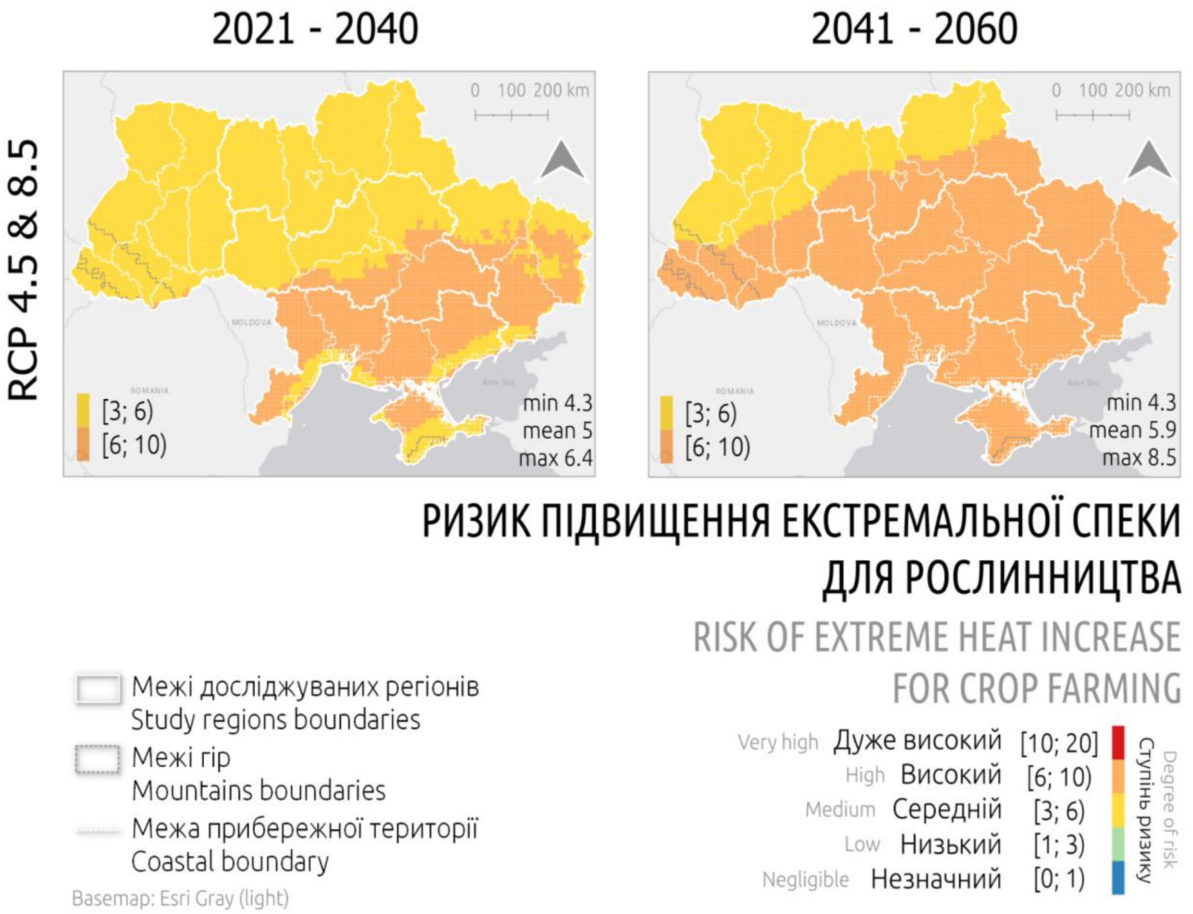

Figure 5.7. – Distribution of risk from extreme heat for crop production in Ukraine

The risk of extreme heat is particularly dangerous for plant development when they are in critical stages of development. For example, when corn crops are going through the main physiological stages of development (flowering, pollination), an increase in temperature to 30–35°C significantly reduces the viability of corn pollen, grain size and, ultimately, yield. For soybean crops, extreme temperatures reduce the number of pods formed and, accordingly, productivity, while for sunflower crops, grain weight decreases by up to 10% at temperatures >35 °C, as does oil content. Thus, the risk of extreme heat has a clear negative impact on the development and yield of agricultural crops, regardless of their type.

Table 5.2. Distribution of the risk of extreme heat for crop production by region

Extreme heat						
Region	2021 – 2040			2041–2060		
	min	mean	max	min	mean	max
West	4.3	4.3	6.4	4.3	5.0	6.4
North	4.3	4.3	4.3	4.3	5.3	6.4
Centre	4.3	4.7	6.4	6.4	6.4	6.4

East	4.3	5.4	6.4	6.4	6.4	6.4
South	4.3	6.1	6.4	6.4	6.4	6.4
Carpathian Mountains	4.3	4.3	6.4	4.3	6.2	6.4
Crimean Mountains	4.3	4.3	4.3	6.4	6.4	6.4
Coastal	4.3	5.5	6.4	6.4	6.5	8.5

5.2.3. Frost

There is no risk of increased frosts for crop production under the two RCP scenarios in the near future and in the middle of the century, as the scenarios do not predict a decrease in temperature (Fig. 5.8 and Table 5.3).

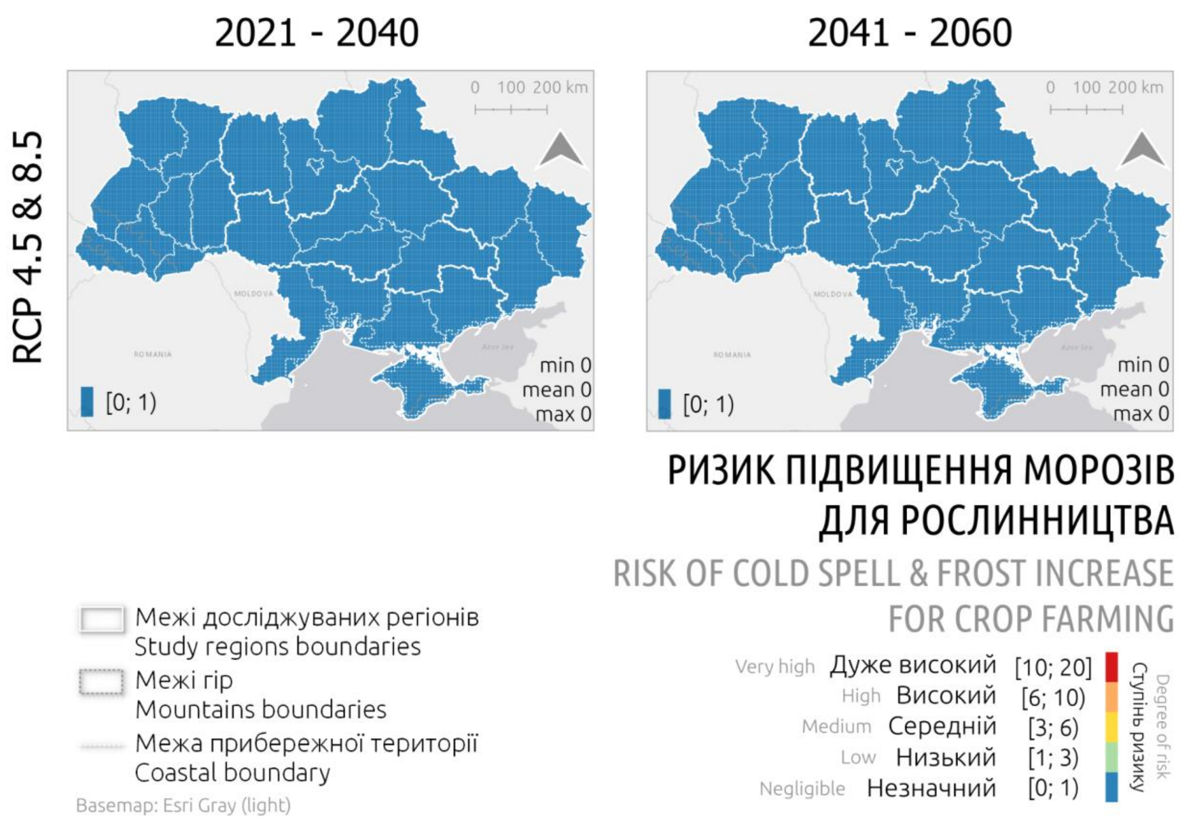

Figure 5.8. – Distribution of risks from an increase in the number of frost events for crop production in Ukraine

Table 5.3. Statistical characteristics of the risk of an increase in the number of frost events for crop production by region

Frosts						
Region	**2021**			**2041–2060**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	0.0	0.0	0.0	0.0	0.0	0.0
North	0.0	0.0	0.0	0.0	0.0	0.0
Centre	0.0	0.0	0.0	0.0	0.0	0.0
East	0.0	0.0	0.0	0.0	0.0	0.0
South	0.0	0.0	0.0	0.0	0.0	0.0

Carpathian Mountains	0.0	0.0	0.0	0.0	0.0	0.0
Crimean Mountains	0.0	0.0	0.0	0.0	0.0	0.0
Coastal	0.0	0.0	0.0	0.0	0.0	0.0

5.2.4. Droughts and fire-dangerous weather

In the near future, between 2021 and 2040, Ukraine will face a wide range of risks to crop production from increased droughts and fire-prone weather, with values ranging from 1.6 to 8 points depending on the territorial distribution (Table 5.4). In the Carpathian Mountains, the risk from these phenomena will be low, with average values of 2 points. In the West, East, Centre and Crimean Mountains, the risk will be medium, with values ranging from 3.4 to 4.5 points. Only in the South and Coastal regions will there be a high risk of increased droughts and fire-hazardous weather with average values of 6.0–7.3 points, with maximum values of up to 8 points (Fig. 5.9).

Figure 5.9. – Distribution of risk from increased droughts and fire-dangerous weather for crop production in Ukraine

It should be noted that as of 2025, almost every year in Ukraine, one region or another suffers from drought and fire-hazardous weather. Therefore, taking into account these trends/risks, we can conclude that in the future this will be one of the main problems in crop production in Ukraine. These natural phenomena will occur at different periods of plant growth in different regions and may affect the development of the entire range of crops grown.

Table 5.4. Statistical characteristics of the risk of droughts and fire-dangerous weather for crop production by region

Droughts and Fire Weather						
Region	**2021**			**2041**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	2.0	3.4	4.0	2.0	2.8	6.0
North	2.0	3.8	4.0	2.0	3.9	6.0
Centre	2.0	4.5	6.0	4.0	5.0	6.0
East	4.0	4.3	6.0	4.0	5.6	6.0
South	4.0	6.0	8.0	4.0	6.6	8.0
Carpathian Mountains	1.6	2.1	4.0	0.0	2.1	4.0
Crimean Mountains	3.2	4.3	4.8	4.8	5.6	6.4
Coastal	4.0	7.3	8.0	4.0	7.6	8.0

By the middle of the century (2041–2060), the risk to crop production from droughts and fire-prone weather in the West will decrease, reaching a low level with average values of 2 points. A low level of risk will remain in the Carpathian Mountains, with a value of 2.1 points. The medium level of risk will remain in the North, Centre, East and Crimean Mountains, with average values ranging from 3.9 to 5.6, with maximum values in these regions corresponding to a high level of risk. In the South and Coastal regions, a high level of risk will be observed, and in absolute terms it will be higher than in the previous period. Risk values will be in the range of 6.6–7.6 points, with maximums of 8.0 points.

5.2.5. Mean precipitation

For the near future period of 2021–2040, the risk of reduced mean precipitation for the crop production sector will vary from low to high depending on the region (Fig. 5.10). In the West, North, Centre and Carpathian Mountains, the risk is negligible, with average values ranging from 0.1 to 0.8 points (Table 5.5). The East, South, Crimean Mountains and Coastal areas will have medium level of risk ranging from 3.1 to 4.1 points, with maximum values of 8 points and high risk, characterising areas located in Crimea and on the coast of the Black and Azov Seas.

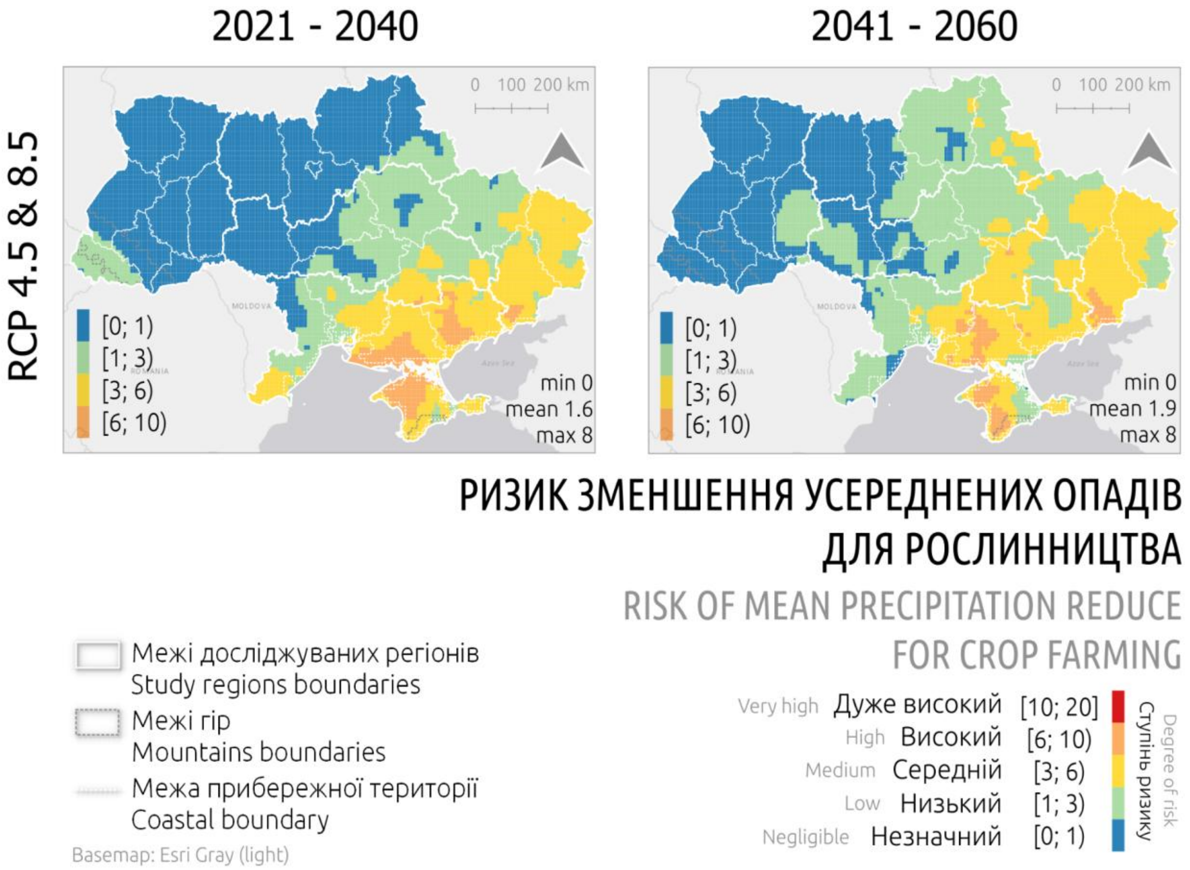

Figure 5.10. – Distribution of risk from a decrease in mean precipitation for crop production in Ukraine

Table 5.5. Statistical characteristics of the risk of reduced mean precipitation for crop production by region

Region	Mean precipitation					
	2021–2040			2041–2060		
	min	mean	max	min	mean	max
West	0.0	0.1	2.0	0.0	0.2	2.0
North	0.0	0.2	2.0	0.0	1.2	4.0
Centre	0.0	1.0	2.0	0.0	1.5	4.8
East	0.0	3.1	6.0	2.0	3.4	6.0
South	0.0	3.4	8.0	0.0	3.2	8.0
Carpathian Mountains	0.0	0.8	2.0	0.0	0.0	0.0
Crimean Mountains	2.0	3.7	4.8	2.0	4.9	6.4
Coastal	1.6	4.1	8.0	0.0	3.0	6.0

By the middle of the century, in the period 2041–2060, the mean risk value will increase slightly compared to the previous period to 1.9, but the minimum and maximum values will remain at the same level. The areas of low, medium and high risk will decrease, but the area of low risk will increase due to a decrease in mean precipitation. In general, as already noted, the risk of a decrease in mean precipitation in the future is negligible, but with an increase in temperature, this will affect plant growth in the form of increased evaporation and exacerbate moisture deficiency, which will reduce crop productivity.

5.2.6. Heavy precipitations and pluvial floods

In the near future, 2021–2040, crop production in Ukraine will face a predominantly medium to high risk of very heavy precipitation, which includes such CIDs as maximum precipitation over 5 days, maximum precipitation in 1 day, and annual very heavy precipitation (Fig. 5.11). As a rule, such precipitation will cause physical damage to plants due to the significant volume of water falling on the soil surface. In some cases, when precipitation falls over several days, there may be a lack of oxygen in the soil due to 100% filling of soil pores with water, which can cause a delay in plant development or their complete death. The mean risk during this period will be 5.6 points, with a fairly significant spread from 0 to 7.5 points (Table 5.6).

Figure 5.11. – Risk distribution from an increase in the number of cases of torrential rainfall and rain floods for crop production in Ukraine

Almost the entire western and northern parts of the country will be at high risk, while the eastern and southern parts will be mainly at medium risk. In the central, eastern and southern parts of the country, there will be isolated areas with a low degree of risk. By the middle of the century, in the period 2041–2060, the mean risk for the crop production sector will increase slightly across the country compared to the previous period. Almost two-thirds of Ukraine's territory, starting from the western part and extending eastward, will be under high risk, with values ranging from 6.5 to 7.5 points. A significant part of the eastern part of the country will be under low and medium risk.

Table 5.6. Statistical characteristics of the risk of an increase in the number of cases of torrential rainfall and rain floods for crop production by region

Heavy precipitations and fluvial floods						
Region	**2021**			**2041**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	3.0	7.1	7.5	1.9	7.2	7.5
North	1.5	6.5	7.5	1.9	7.1	7.5
Centre	1.9	5.2	7.5	1.9	6.5	7.5
East	0.0	4.6	7.5	1.5	3.1	7.5
South	0.0	4.4	7.5	1.5	5.0	7.5
Carpathian Mountains	3.0	6.8	7.5	1.9	5.9	7.5
Crimean Mountains	1.9	5.5	7.5	3.0	5.9	7.5
Coastal	1.9	4.5	7.5	1.9	5.6	7.5

5.2.7. Snowfall and snowcover

In the near future (2021–2040), crop production in Ukraine will face a mostly low and negligible risk of reduced snowfall and snowcover, with mean values of 1.1 points (Fig. 5.12). The former will be observed mainly in the western and northern parts of the country, and the latter in the east and south. By the middle of the century, in the period 2041–2060, the risk of reduced snowcover will increase, but the average will rise to 1.4 points, which corresponds to a low risk level, with only the Carpathian region reaching a risk level of 3, which corresponds to medium risk level (Table 5.7). Importantly, the area subject to negligible risk will decrease significantly, with only the coastal and southern regions remaining.

Figure 5.12. – Distribution of risk from reduced snowfall and snowcover for crop production in Ukraine

Table 5.7. Statistical characteristics of the risk of reduced snowfall and snowcover for crop production by region

Snowfall and snowcover						
Region	**2021**			**2041**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	0.6	1.3	2.3	1.5	1.5	3.0
North	0.0	1.4	2.3	1.5	1.5	2.3
Centre	0.8	1.3	1.5	1.5	1.5	2.3
East	0.8	0.8	1.5	0.8	1.5	1.5
South	0.6	0.8	1.5	0.8	1.1	1.5
Carpathian Mountains	0.8	1.4	2.3	1.5	2.0	3.0
Crimean Mountains	0.8	1.0	1.5	0.8	1.5	2.3
Coastal	0.8	0.8	1.2	0.8	0.8	1.2

5.2.8. Snowfall ≥ 10 mm per day

A negligible risk was obtained from an increase in snowfall of more than 10 mm per day for crop production throughout Ukraine, with values ranging from 0.0 to 0.5 points for two periods in all regions of the country (Fig. 5.13 and Table 5.8).

Figure 5.13. – Distribution of risk from an increase in the number of cases with snowfall ≥10 mm per day for crop production in Ukraine

Table 5.8. Statistical characteristics of the risk from an increase in the number of cases with snowfalls ≥10 mm per day for crop production by region

Snowfall ≥ 10 mm per day						
Region	**2021 – 2040**			**2041–2060**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	0.1	0.3	0.5	0.1	0.3	0.5
North	0.2	0.4	0.5	0.2	0.4	0.5
Centre	0.1	0.3	0.5	0.1	0.3	0.4
East	0.1	0.3	0.5	0.1	0.3	0.4
South	0.1	0.2	0.4	0.1	0.3	0.5
Carpathian Mountains	0.2	0.4	0.5	0.0	0.3	0.5
Crimean Mountains	0.2	0.3	0.4	0.1	0.2	0.3
Coastal	0.0	0.2	0.4	0.0	0.2	0.4

5.2.9. Wind speed

The risk to crop production in the near future (2021–2040) from increased wind speeds is expected to be negligible, with a mean value of 0.2 points across the country. Only in the Carpathians will there be a low risk above 1 point, with a maximum value of 1.3 points, as well as in coastal areas, where the maximum will be 1.9 points (Table 5.9). By the middle of the century, in the period 2041–2060, the risks to crop production from increased wind speeds will decrease and will be negligible, ranging from 0 to 1 point. Only in some areas in the west, the Carpathians, the Crimean Mountains, and coastal areas will the maximum risk be between 1.3 and 1.9 points, which corresponds to a low risk level. In general, this will not have a significant impact on the industry, as the main crop areas are not located in these regions (Fig. 5.14). Wind speeds of up to 8 m/s are considered comfortable for plant growth; higher speeds can cause physical damage to plants. An indirect effect on plant development may also result from increased evaporation with increasing wind speed, but this will not have a significant impact either.

Figure 5.14. – Distribution of risk from increased wind speed for crop production in Ukraine

Table 5.9. Statistical characteristics of the risk of increased wind speed for crop production by region

Wind speed						
Region	**2021**			**2041–2060**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	0.0	0.4	1.3	0.0	0.2	1.3
North	0.0	0.1	0.6	0.0	0.0	0.6
Centre	0.0	0.1	0.6	0.0	0.0	0.6
East	0.0	0.0	0.6	0.0	0.0	0.0
South	0.0	0.1	1.0	0.0	0.1	1.0
Carpathian Mountains	0.6	0.9	1.3	0.5	0.6	1.3
Crimean Mountains	0.0	0.3	0.6	0.0	0.5	1.5
Coastal	0.0	0.3	1.9	0.0	0.2	1.9

5.2.10. Summary

The main risks (average and maximum, presented in Tables 5.10 and 5.11, respectively) that will affect the development of crop production in the future by region of Ukraine will be as follows:

- in the Northern region, in the current period 2021–2040 and by the middle of the century, the highest average and maximum risk assessments will be associated with heavy rainfall and rain floods, extreme heat and droughts, and fire-hazardous weather.

- In the Central region, by the middle of the century, the highest average risk assessment will be from heavy rainfall and rain floods and extreme heat. The maximum risk assessments for all periods will be associated with heavy rainfall and rain floods, followed by extreme heat and droughts and fire-hazardous weather.

- In the Eastern region, the highest average risk assessment will be for extreme heat, both in the near future and in the middle of the century. The maximum risk assessments for the entire period up to 2050 will be for heavy rainfall and flash floods, extreme heat, drought and fire-hazardous weather, and mean precipitation (sequence of phenomena depending on assessments).

- In the Western region, the highest average risk assessments are for heavy rainfall and flash floods, with corresponding values of 7.1 and 7.2 for the two periods, slightly lower values for extreme heat – 4.3 and 5.0, and significantly lower values for the remaining risk assessments. The highest maximum risk assessments for the region are observed for heavy rainfall and flash floods, extreme heat, and drought and fire-hazardous weather, with a very slight increase for the second period – the middle of the century. The assessments for the remaining risks are low.

- in the Southern region, based on average assessments, the greatest risk will be from extreme heat and drought and fire-hazardous weather, with an increase in values until the middle of the century. The values of the remaining risks are small. In the case of maximum risk assessments, according to values from maximum to minimum, they are ranked in the following order: drought and fire-hazardous weather, mean precipitation, heavy rainfall and rain floods, and extreme heat. The remaining risks have negligible risk assessment values;

- For the Western Mountains (Carpathian Mountains) region, two risks are observed by the middle of the century, according to average assessments: heavy rain and flash floods, with a value of 6.8 points by 2030, and extreme heat, with an assessment of 6.4 points by the middle of the century. Other risks have negligible estimates. The maximum risk estimates will correspond to heavy rainfall and flash floods, as well as extreme heat. The next highest risk is drought and fire-prone weather, but its estimates are significantly lower than the previous risks.

- For the Southern Mountains region (Crimean Mountains), the highest average risk assessments are observed for extreme heat, heavy rainfall and flash floods, drought and fire-prone weather, and mean precipitation, with all these risks gradually increasing in assessment values from 2030 to 2050. The remaining risks are negligible. The maximum risk assessments coincide with the types of risks according to the average assessments and show the same trend, with values increasing until the middle of the century.

- In the coastal region, the average risk assessments have the highest values for drought and fire-hazardous weather, extreme heat, and heavy rainfall and rain floods, with a gradual increase until the middle of the century. Other risks are negligible. The maximum risk assessments are for extreme heat, heavy rainfall and flash floods, droughts and fire-prone weather, and mean precipitation. with values remaining unchanged until mid-century for heavy rainfall and flash floods and droughts and fire-prone weather, increasing for extreme heat, and decreasing for mean precipitation until mid-century.

Table 5.10. Distribution of average risk assessments from the considered climate change hazards to crop production in the regions

Average risk assessments in regions	Mid-period	↗ Mean air temperature	↗ Extreme heat	↗ Frost	↘ Mean precipitation	↗ Heavy rain and flash floods (>99pctl)	↗ Droughts and fire-dangerous weather	↘ Snowfall and snowcover	↗ Days with snowfall > 10 mm/day	↗ Wind speed	↗ Coastal climatic impact-drivers
North	2030	2.7	4.3	0.0	0.2	6.5	3.8	1.4	0.4	0.1	0.0
	2050	4.1	5.3	0.0	1.2	7.1	3.9	1.5	0.4	0.0	0.0
Centre	2030	2.7	4.7	0.0	1.0	5.2	4.5	1.3	0.3	0.1	0.0
	2050	4.1	6.4	0.0	1.5	6.5	5.0	1.5	0.3	0.0	0.0
East	2030	2.7	5.4	0.0	3.1	4.6	4.3	0.8	0.3	0.0	0.0
	2050	4.1	6.4	0.0	3.4	3.1	5.6	1.5	0.3	0.0	0.0
West	2030	2.7	4.3	0.0	0.1	7.1	3.4	1.3	0.3	0.4	0.0
	2050	4.1	5.0	0.0	0.2	7.2	2.8	1.5	0.3	0.2	0.0
South	2030	2.7	6.1	0.0	3.4	4.4	6.0	0.8	0.2	0.1	0.0
	2050	4.1	6.4	0.0	3.2	5.0	6.6	1.1	0.3	0.1	0.0
Western Mountains	2030	2.7	4.3	0.0	0.8	6.8	2.1	1.4	0.4	0.9	0.0
	2050	4.1	6.2	0.0	0.0	5.9	2.1	2.0	0.3	0.6	0.0
Southern Mountains	2030	2.8	4.3	0.0	3.7	5.5	4.3	1.0	0.3	0.3	0.0
	2050	4.1	6.4	0.0	4.9	5.9	5.6	1.5	0.2	0.5	0.0
Coastal	2030	2.7	5.5	0.0	4.1	4.5	7.3	0.8	0.2	0.3	0.2
	2050	4.1	6.5	0.0	3.0	5.6	7.6	0.8	0.2	0.2	0.3

Table 5.11. Distribution of maximum risk assessments from the considered climate change hazards to crop production in the regions

Maximum risk assessments in regions	Mid-period	↗ Mean air temperature	↗ Extreme heat	↗ Frost	↘ Mean precipitation	↗ Heavy rain and flash floods (>99pctl)	↗ Droughts and fire-hazardous weather	↘ Snowfall and snowcover	↗ Days with snowfall > 10 mm/day	↗ Wind speed	↗ Coastal climatic impact-drivers
North	2030	2.8	4.3	0.0	2.0	7.5	4.0	2.3	0.5	0.6	0.0
	2050	4.1	6.4	0.0	4.0	7.5	6.0	2.3	0.5	0.6	0.0
Centre	2030	2.8	6.4	0.0	2.0	7.5	6.0	1.5	0.5	0.6	0.0
	2050	4.1	6.4	0.0	4.8	7.5	6.0	2.3	0.4	0.6	0.0
East	2030	2.8	6.4	0.0	6.0	7.5	6.0	1.5	0.5	0.6	0.0
	2050	4.1	6.4	0.0	6.0	7.5	6.0	1.5	0.4	0.0	0.0
West	2030	2.8	6.4	0.0	2.0	7.5	4.0	2.3	0.5	1.3	0.0
	2050	4.1	6.4	0.0	2.0	7.5	6.0	3.0	0.5	1.3	0.0
South	2030	2.8	6.4	0.0	8.0	7.5	8.0	1.5	0.4	1.0	0.0
	2050	4.1	6.4	0.0	8.0	7.5	8.0	1.5	0.5	1.0	0.0
Western Mountains	2030	2.8	6.4	0.0	2.0	7.5	4.0	2.3	0.5	1.3	0.0
	2050	4.1	6.4	0.0	0.0	7.5	4.0	3.0	0.5	1.3	0.0
Southern Mountains	2030	2.8	4.3	0.0	4.8	7.5	4.8	1.5	0.4	0.6	0.0
	2050	4.1	6.4	0.0	6.4	7.5	6.4	2.3	0.3	1.5	0.0
Coastal	2030	2.8	6.4	0.0	8.0	7.5	8.0	1.2	0.4	1.9	0.5
	2050	4.1	8.5	0.0	6.0	7.5	8.0	1.2	0.4	1.9	0.5

5.3. Climate risk assessments for the animal husbandry sector

5.3.1. Mean air temperature

The risks that the animal husbandry sector may face under increase in climate indicators included in the CID category of mean air temperature were assessed. When calculating the risks, CIDs such as mean air temperatures for the year, January, April, July and October were included in the category. The duration of the growing season, despite the high sensitivity (0.5) of the sector to this parameter, did not have an impact, because with increasing of this CID, its impact on the state of the sector would be clearly positive. An increase in other CIDs is considered as a negative factor affecting animal husbandry.

Figure 5.15. – Distribution of risk from an increase in mean air temperature for animal husbandry in Ukraine

It was previously established that the industry has moderate (0.3–0.4) and low (0.1–0.2) sensitivity to an increase in mean air temperatures. When determining the maximum impact (maximum hazard) for the "mean temperature" category, similar values (5) were obtained for most regions of Ukraine. The exception is the values (7.5) obtained for the future period (2041–2060) under the RCP 8.5 scenario (Fig.2.10-2.17). Given that sensitivity does not depend on geographical conditions, the spatial distribution of risks for both the current (medium) and future (high) periods is almost uniform within Ukraine (Fig. 5.15).

Table 5.12. Statistical characteristics of the risk of an increase in mean air temperature for animal husbandry by region

Wind speed						
Region	**2021**			**2041–2060**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	3.4	4.3	4.3	6.4	6.4	6.4
North	3.4	4.3	4.3	6.4	6.4	6.4
Centre	3.4	4.3	4.3	6.4	6.4	6.4
East	3.4	4.3	4.3	6.4	6.4	6.4
South	3.4	4.3	4.3	6.4	6.4	6.4
Carpathian Mountains	3.4	4.3	4.3	6.4	6.4	6.4
Crimean Mountains	4.3	4.3	4.3	6.4	6.4	6.4
Coastal	3.4	4.3	4.3	6.4	6.4	6.4

The indicators of the dispersion of the average risk values for the nodes of the calculation grid shown in the table practically do not change their values: the average for the current period is 4.3, and for the future – 6.4 (Table 5.12).

5.3.2. Extreme heat

The highest weighting coefficients of sensitivity for animal husbandry were obtained for CIDs in the "extreme heat" category. An increase in the number of days with intense heat, a rise in the average of maximum air temperature in summer, and an increase in the number of tropical nights will have a particularly significant impact on the industry. The calculated maximum hazard for this category of factors are within the range of values 5.0 in the Carpathians and Crimean Mountains in the current period and a maximum value of 10.0 for coastal regions in the future period, according to the RC 8.5 scenario, the background indicator of maximum hazard is 7.5, with slightly lower values (5.5) for the Western and Northern regions (Figs. 2.10 – 2.17).

The obtained risk for animal husbandry, calculated taking into account the maximum impact on the industry of factors in the "extreme temperature" category, falls within the medium and high gradations (Fig. 5.16).

Figure 5.16. – Distribution of risk from extreme heat for animal husbandry in Ukraine

For the current period, the maximum values are 8.6 for the Southern region, and the lowest values (5.8) are for the Western, Northern regions and the Crimean Mountains. The spatial distribution of risks for animal husbandry shows that most of Ukraine is in the medium risk zone, and only the southern, a significant part of the eastern and south-eastern parts of the central region are in the high risk zone (Fig. 5.16).

Table 5.13. Distribution of risk from extreme heat for animal husbandry by region

Extreme heat						
Region	**2021**			**2041**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	5.8	5.8	8.6	5.8	6.7	8.6
North	5.8	5.8	5.8	5.8	7.2	8.6
Centre	5.8	6.4	8.6	8.6	8.6	8.6
East	5.8	7.3	8.6	8.6	8.6	8.6
South	5.8	8.3	8.6	8.6	8.6	8.6
Carpathian Mountains	5.8	5.9	8.6	5.8	8.4	8.6
Crimean Mountains	5.8	5.8	5.8	8.6	8.6	8.6
Coastal	5.8	7.4	8.6	8.6	8.8	11.5

In the future period 2041–2060, the mean risk values established for all regions (Table 5.13) fall into the high category, with indicators varying from 6.7 (West) to 8.8 (Coastal). The generalised spatial distribution of the degree of risk shows that for most of

Ukraine it will be high, only in the north-western part of the Western region and the northern part of the Northern region will the degree of risk remain medium, as in the current period. For coastal areas (individual points of the calculation grid), the possible risk of extreme heat is in *the very high category* (Table 5.13), which is explained by the high values of maximum changes in this period and the high sensitivity of the industry to an increase in the values of this category of CID. The high risk of extreme temperature increases may lead to a decrease in productivity, in particular in weight gain or milk yield.

5.3.3. Frost

This category of CID includes cold spells and the number of days with frost. Animal husbandry is highly sensitive to cold spells (0.6) and less sensitive (0.2) to the number of days with frost. However, given the prevailing trends of warming in global and regional temperature change, an increase in the impact of these CIDs is not expected due to the low probability of cold spells and an increase in the number of days with frost. Figures 2.10–2.17 do not show estimates of the maximum impact of factors in this category, and the risk calculation made it possible to classify them as negligible for the entire territory of Ukraine. The risk values for all regions are zero (see Table 5.14) and confirm the spatial distribution of risk levels.

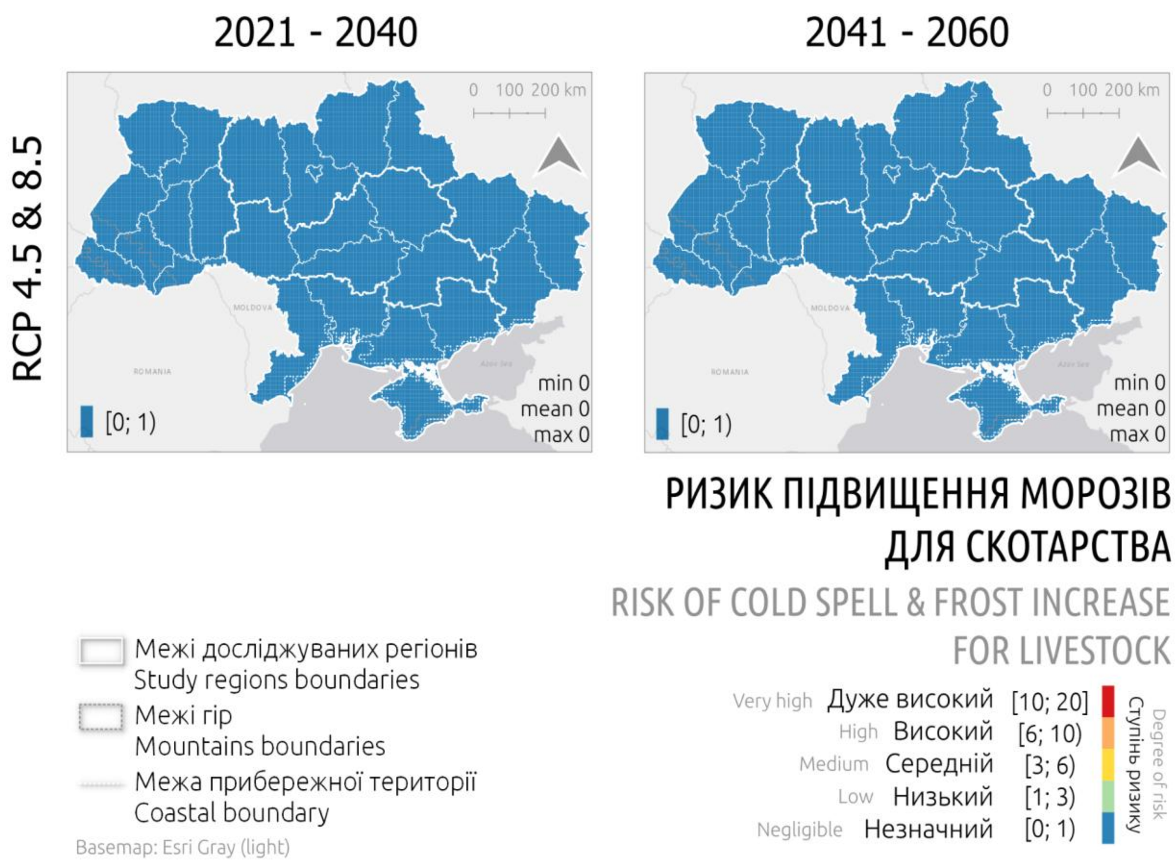

Figure 5.17. Distribution of risks from an increase in the number of frost days for animal husbandry in Ukraine

As shown by the results of calculations for all points of the calculation grid in the current and future periods, no risks to animal husbandry are expected from an increase in the number of days with frost and cold spells in Ukraine (Fig. 5.17 and Table 5.14).

Table 5.14. Statistical characteristics of the risk from an increase in the number of frost events for animal husbandry by region

Extreme heat						
Region	**2021**			**2041**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	0.0	0.0	0.0	0.0	0.0	0.0
North	0.0	0.0	0.0	0.0	0.0	0.0
Centre	0.0	0.0	0.0	0.0	0.0	0.0
East	0.0	0.0	0.0	0.0	0.0	0.0
South	0.0	0.0	0.0	0.0	0.0	0.0
Carpathian Mountains	0.0	0.0	0.0	0.0	0.0	0.0
Crimean Mountains	0.0	0.0	0.0	0.0	0.0	0.0
Coastal	0.0	0.0	0.0	0.0	0.0	0.0

5.3.4. Droughts and fire-dangerous weather

This category of CID includes two factors: the duration of droughts and the number of days with fire-dangerous weather. The sensitivity of the animal husbandry sector to these CIDs is quite high, at 1.1 and 0.3 points, respectively. The maximum impact of the factors included in this category, according to the calculations obtained for the current and future periods, shows high risk in the Southern region and Coastal areas (Fig. 5.18). In addition, high values of maximum threats in the future period were obtained for the Central and Eastern regions and the Crimean Mountains (Fig.2.10-2.17).

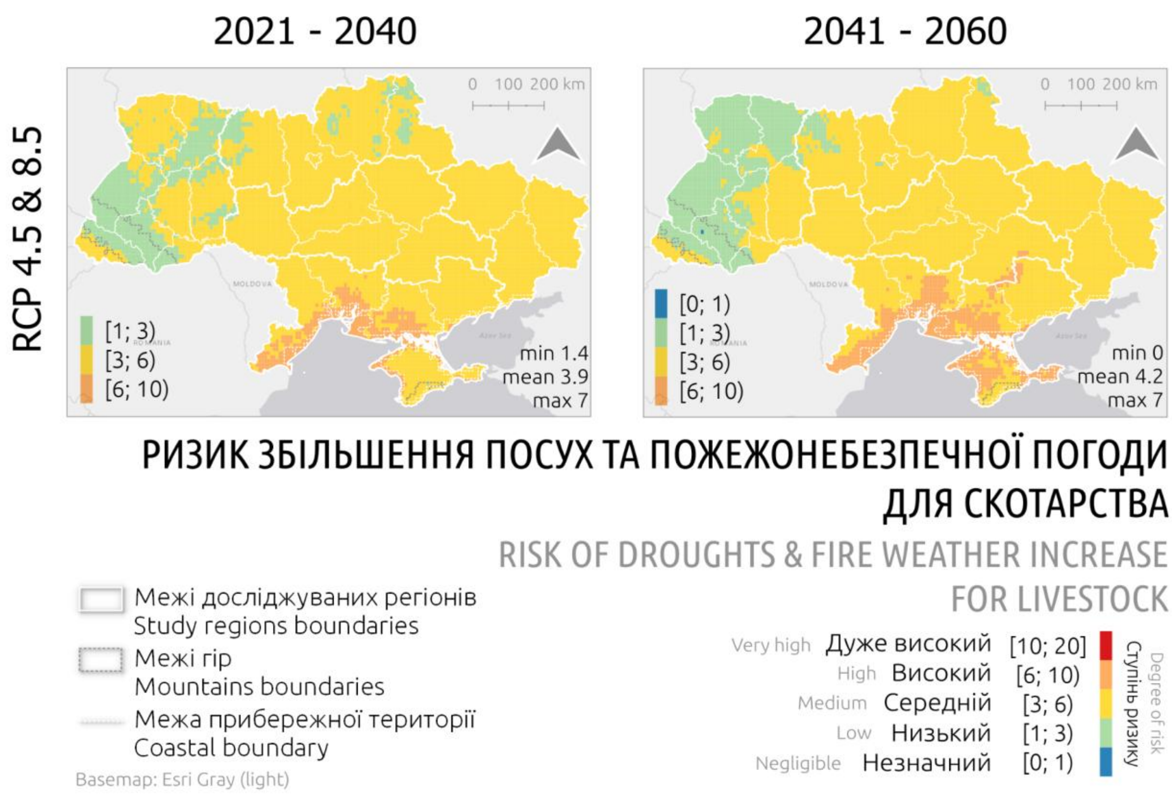

Figure 5.18. – Distribution of risk from increased droughts and fire-hazardous weather for animal husbandry farming in Ukraine

Accordingly, the degrees of risk for the industry have a similar spatial distribution. A high risk based on average indicators within the calculation grid was obtained only for coastal areas, and for the Southern region, such a degree of risk was obtained only for the maximum values of the indicators.

In most of Ukraine, the risk levels for animal husbandry from drought and fire hazard are classified as medium (3.4–5.7). Only in the Carpathians (with the exception of the Transcarpathian lowlands), part of the Western region and some areas of the Northern region does the risk level decrease to low. Calculations have shown that in the future period, even , the areas with low risks from the impact of this category of CID in the above-mentioned regions will increase.

Table 5.15. Statistical characteristics of the risk of droughts and fire-hazardous weather for animal husbandry by region

Extreme heat						
Region	**2021**			**2041**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	1.8	3.0	3.5	1.8	2.5	5.3
North	1.8	3.4	3.5	1.8	3.4	5.3
Centre	1.8	3.9	5.3	3.5	4.4	5.3
East	3.5	3.8	5.3	3.5	4.9	5.3

South	3.5	5.2	7.0	3.5	5.7	7.0
Carpathian Mountains	1.4	1.8	3.5	0.0	1.8	3.5
Crimean Mountains	2.8	3.8	4	4.2	4.9	5.6
Coastal	3.5	6.4	7.0	3.5	6.7	7.0

The data presented in Table 5.15 further confirm the potentially high risks for certain areas of the Coastal Territories (7.0) and the Southern Region (7.0) and medium risks for animal husbandry in the vast majority of Ukraine's regions.

5.3.5. Mean precipitation

This category includes such climatic impact-drivers as a decrease in mean precipitation per year, January, April, July and October. Animal husbandry has an moderate (0.4) sensitivity to a decrease in mean monthly precipitation in April and July and a slightly lower (0.3) sensitivity in October, with even lower sensitivity to other CIDs in the category. The maximum impact of this category (10) is obtained for the Southern region and coastal areas in the current period, with slightly lower values (7.5) for the Central and Eastern regions (Figs. 2.12–2.13). Accordingly, the risk from a decrease in mean monthly and annual precipitation amounts for animal husnabdry is expected to be medium in the region of unstable moisture regime in the south and east of Ukraine in the Kherson, Zaporizhzhia, parts of the Mykolaiv and Odesa regions, the Autonomous Republic of Crimea, as well as in the Donetsk and Luhansk regions (Fig. 5.19). It should be noted that by the middle of the century, there will be some transforming of the spatial distribution of risk levels: areas of negligible risk will decrease, but the Carpathians will move into this category from the "low" category. The areas with a "low" risk rating are increasing in the northern, eastern, central, western part of the southern and in small areas of the western region.

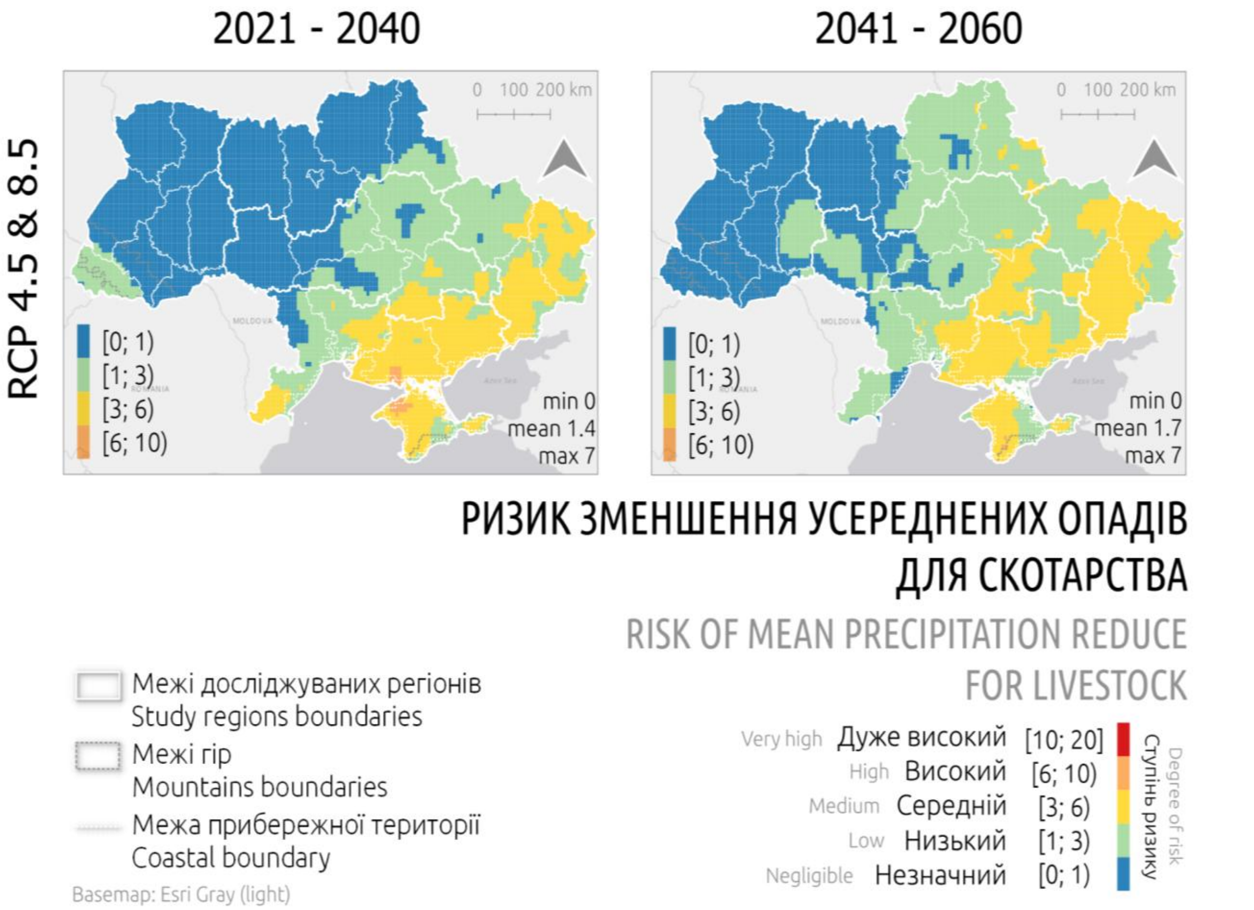

Figure 5.19. – Distribution of risk from reduced mean precipitation for animal husbandry in Ukraine

Table 5.15. Statistical characteristics of the risk of reduced mean precipitation for animal husbandry by region

Region	Mean precipitation					
	2021–2040			2041–2060		
	min	mean	max	min	mean	max
West	0.0	0.1	1.8	0.0	0.2	1.8
North	0.0	0.0	1.8	0.0	1.1	3.5
Centre	0.0	0.9	1.8	0.0	1.3	4.2
East	0.0	2.7	5.3	1.8	3.0	5.3
South	0.0	3.0	7.0	0.0	2.8	7.0
Carpathian Mountains	0.0	0.7	1.8	0.0	0.0	0.0
Crimean Mountains	1.8	3.2	4.2	1.8	4.3	5.6
Coastal	1.4	3.6	7.0	0.0	2.6	5.3

The results of the calculations show that in the current and future periods, only at certain points of the calculation grid in the Southern region, and within the Coastal territories only in the current period, such changes in mean precipitation values may occur that will create *high risks* for animal husbandry (Table 5.15). In addition, in the current period, medium-level risks will arise in the Eastern region and the Crimean Mountains, and in the future period, such risks will have a much wider geographical spread and are likely to form in certain areas of the Northern, Eastern and Central regions, the Crimean Mountains and within the Coastal territories. However, for most of Ukraine, the risks from reduced mean precipitation for animal husbandry will be low or negligible on average.

5.3.6. Heavy rainfall and flash floods

This category of climate change indicators includes: annual amount of very heavy precipitation, maximum amount of precipitation per day and per 5 days.

The assessment of the sector's sensitivity to changes in these climatic impact-drivers showed high weight coefficients (0.5) for the impact of changes in the maximum amount of precipitation over 5 days and moderate (0.3) for the other two CIDs. Analysis of the results of assessing the maximum threats from these factors showed that they are high for almost all regions, reaching conditional 10 points (Figs. 2.10 – 2.17). The calculation of risks from the named category of CIDs was based on a model forecast of increased rainfall and heavy precipitation, and the results obtained showed the probability of a medium degree of risk in those regions where an overall increase in precipitation is expected. The increase in risks from rainfall here indicates that the proportion of heavy (high-intensity) precipitation will increase. The maps show the medium risk levels in the current period for the Western, Northern, Carpathian, and most of the Central and Eastern regions. In the Southern region, the coastal areas, and the Crimean Mountains, there are significant areas where the risks will be low (Fig. 5.20). In the future period, the degree of risk will remain at the same levels, with a slight increase in the medium degree and a clearer localisation of low risks in the Eastern region, in the east of the Central region and in the north-east of the Southern region.

Figure 5.20. Distribution of risk from an increase in the number of cases of torrential rainfall and rain floods for animal husbandry in Ukraine

Table 5.16. Statistical characteristics of the risk from an increase in the number of cases of torrential rainfall and rain floods for animal husbandry by region

Torrential rains and rain floods						
Region	**2021**			**2041**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	2.2	5.2	5.5	1.4	5.3	5.5
North	1.1	4.7	5.5	1.4	5.2	5.5
Centre	1.4	3.8	5.5	1.4	4.8	5.5
East	0.0	3.3	5.5	1.1	2.3	5.5
South	0.0	3.2	5.5	1.1	3.7	5.5
Carpathian Mountains	2.2	5.0	5.5	1.4	4.3	5.5
Crimean Mountains	1.4	4.1	5.5	2.2	4.3	5.5
Coastal	1.4	3.3	5.5	1.4	4.1	5.5

The range of risk level values obtained at the calculation grid points is between 0.0 and 5.5 (Table 5.16). Based on mean and maximum indicators, virtually all regions are now and will remain in the future in the zone of medium risk for animal husbandry from increased rainfall and pluvial floods.

5.3.7. Snowfall and snowcover

This category includes the annual amount of precipitation in the form of snow and the number of days with snowcover ≥ 30%. The risks for the animal husbandry sector of a decrease in these indicators due to climate change were determined. The sensitivity of the industry to these CIDs is low, with weighting coefficients of 0.1 for both indicators. The assessment of the maximum impact of changes in these CIDs in this category showed the highest values for the Carpathians and the Western region (10) in both scenarios for the current and future periods, and the lowest maximum threat values (2.5) in the coastal areas, the south and the east for the current period under the RCP 8.5 scenario (Figs. 2.13–2.15). However, given the low sensitivity of the industry to changes in CIDs in this category, the calculations show a negligible degree of risk for animal husbandry in all regions of Ukraine (Fig. 5.21). An exception can be made for the small territories in the south-west of the Carpathians, where the degree of risk will increase to low in the future.

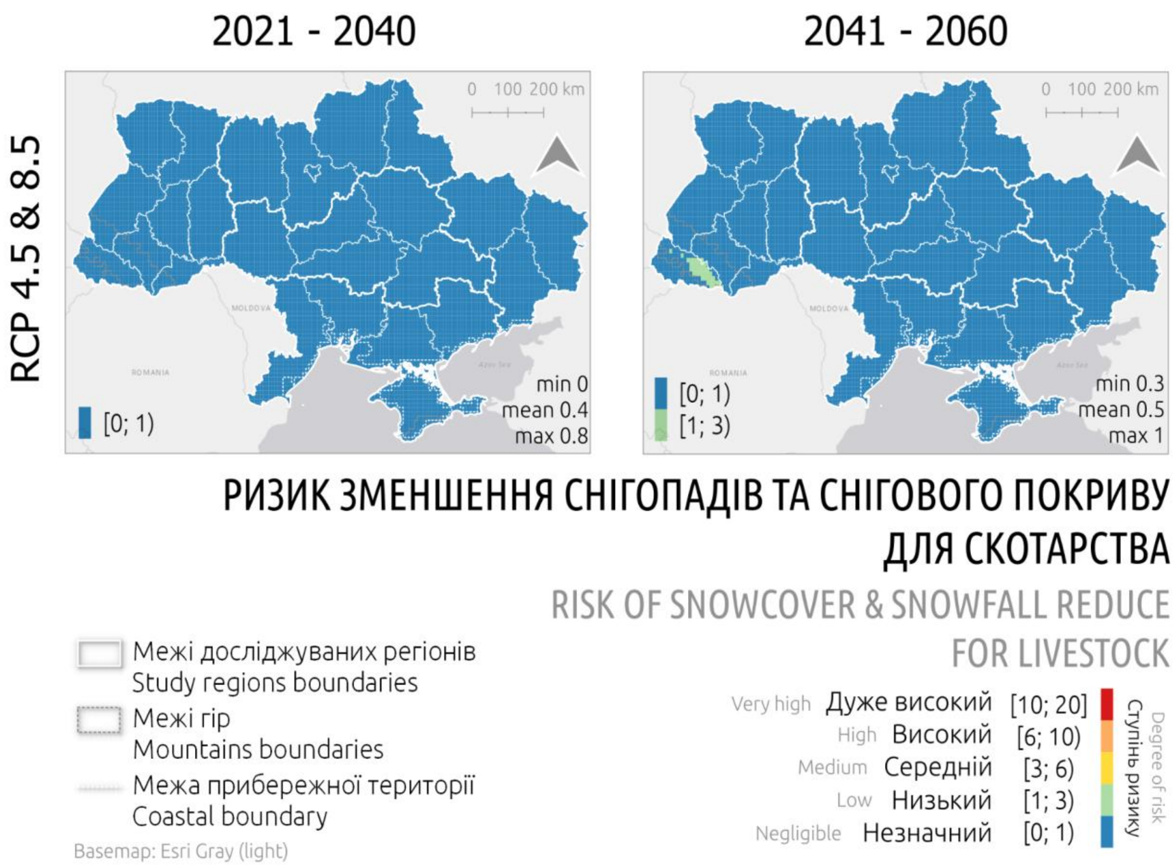

Figure 5.21. – Distribution of risk from reduced snowfall and snowcover for animal husbandry in Ukraine

Table 5.17. Statistical characteristics of the risk of reduced snowfall and snowcover for animal husbandry by region

Region	Snowfall and snowcover					
	2021			2041		
	min	mean	max	min	mean	max
West	0.2	0.4	0.8	0.5	0.5	1.0
North	0.0	0.5	0.8	0.5	0.5	0.8
Centre	0.3	0.4	0.5	0.5	0.5	0.8
East	0.3	0.3	0.5	0.3	0.5	0.5
South	0.2	0.3	0.5	0.3	0.4	0.5
Carpathian Mountains	0.3	0.5	0.8	0.5	0.7	1.0
Crimean Mountains	0.3	0.3	0.5	0.3	0.5	0.8
Coastal	0.3	0.3	0.4	0.3	0.3	0.4

A summary of the risk levels obtained at each point of the calculation grid shows a small spread from a minimum of 0.2 to a maximum of 1.0, which corresponds to the category of negligible risks (Table 5.17). Only at certain points of the grid in the Western region and the Carpathians the projected risk level equal or slightly exceed 1, which gives reason to consider the risks for animal husbandry here to be low.

5.3.8. Snowfall ≥ 10 mm per day

The possible risks to animal husbandry from an increase in the number of days with snowfall of ≥ 10 mm per day are considered. The industry has low sensitivity (0.1) to the impact of this climatic impact-driver. Despite the relatively high values obtained in the aggregate assessment of the maximum threats from an increase in the number of days with moderate snowfall, they are minimal (5) only for the coastal regions and the Crimean Mountains, while for all other regions in both periods they have high maximum values of 7.5–10 (Figs. 2.10–2.17), the change in this climatic factor poses negligible risks to animal husbandry in all regions in both periods (Fig. 5.22). Analysis of the values obtained for each point of the calculation grid shows their small range (0.0–0.5) and belonging to the negligible risk category (Table 5.18).

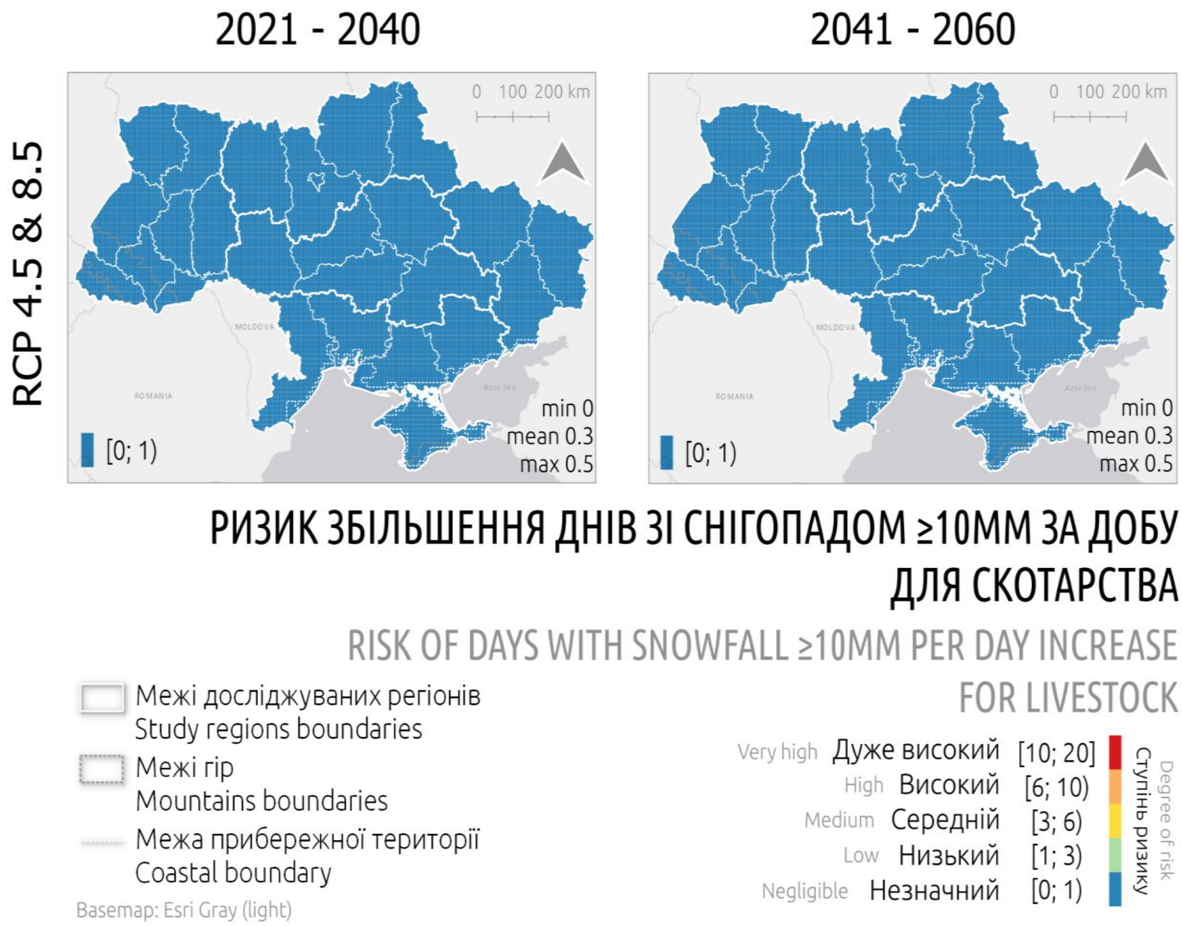

Figure 5.22. – Distribution of risk from an increase in the number of cases with snowfall ≥10 mm per day for animal husbandry in Ukraine

Table 5.18. Statistical characteristics of the risk value from an increase in the number of cases with snowfall ≥10 mm per day for animal husbandry by region

Snowfall ≥ 10 mm per day						
Region	**2021 – 2040**			**2041**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	0.1	0.3	0.5	0.1	0.3	0.5
North	0.2	0.4	0.5	0.2	0.4	0.5
Centre	0.1	0.3	0.5	0.1	0.3	0.4
East	0.1	0.3	0.5	0.1	0.3	0.4
South	0.1	0.2	0.4	0.1	0.3	0.5
Carpathian Mountains	0.2	0.4	0.5	0.0	0.3	0.3
Crimean Mountains	0.2	0.3	0.4	0.1	0.2	0.3
Coastal	0.0	0.2	0.4	0.0	0.2	0.4

5.3.9. Wind speed

The potential risks to animal husbandry are assessed in the event that climate change leads to an increase in mean wind speeds and an increase in the number of days with wind gusts ≥ 10.8 m/s. The sensitivity of animal husbandry to changes in these CIDs is low (0.2) and moderate (0.3), respectively. The generalised maximum threats from an increase in mean wind speed were obtained for the Carpathians and the Western region for the current and future periods under the RCP 4.5 scenario. For wind gusts, the maximum threat indicators are lower and practically do not change spatially (Figs. 2.10–2.17). The risk values calculated on the basis of modelling data from an increase in wind speed CIDs also have a uniform spatial distribution and are classified as negligible (Fig. 5.23). The risk values obtained within the calculation grid and summarised in space and time (Table 5.19) range from negligible values of <1.0 to a maximum of 1.1 in coastal areas, where they are classified as low risk.

Figure 5.23. – Distribution of risk from increased wind speed for animal husbandry in Ukraine

Table 5.19. Statistical characteristics of the risk of increased wind speed for animal husbandry by region

Snowfall ≥ 10 mm per day						
Region	**2021 – 2040**			**2041–2060**		
	min	**mean**	**max**	**min**	**mean**	**max**
West	0.0	0.2	0.8	0.0	0.1	0.8
North	0.0	0.1	0.4	0.0	0.0	0.4
Centre	0.0	0.1	0.4	0.0	0.0	0.4
East	0.0	0.0	0.4	0.0	0.0	0.0
South	0.0	0.1	0.6	0.0	0.1	0.6
Carpathian Mountains	0.4	0.5	0.8	0.3	0.4	0.8
Crimean Mountains	0.0	0.2	0.4	0.0	0.3	0.9
Coastal	0.0	0.2	1.1	0.0	0.1	1.1

5.3.10. Summary

Assessing the risks to animal husbandry from climate change made it possible to identify the most significant risks by category and region and, accordingly, to prioritise those that need to be taken into account in the further development and adaptation to climate change of the industry.

The data presented in summary tables 5.20 and 5.21 indicate that the highest levels of risk for livestock farming in Ukraine may be caused by increases in climate indicators in the following categories: extreme heat, mean temperatures, heavy rainfall and flash floods, droughts, and fire-dangerous weather. The spatial distribution of maximum threats and risk levels for each region studied has been obtained. The results enable industry leaders, individual enterprises and farmers to develop a programme of adaptation measures that will avoid or reduce the risks of climate change on the state, functioning and profitability of the animal husbandry industry, feed production and, undoubtedly, the state of natural pastures.

Table 5.20. Distribution of average risk assessments of the considered climate change hazards to animal husbandry in the regions

Average risk assessments in regions	Mid-period	↗ Mean air temperature	↗ Extreme heat	↗ Frost	↘ Mean precipitation	↗ Heavy rains and rain floods (>99pctl)	↗ Droughts and fire-dangerous weather	↘ Snowfall and snowcover	↗ Days with snowfall > 10 mm/day	↗ Wind speed	↗ Coastal climatic impact-drivers
North	2030	4.2	5.8	0.0	0.2	4.7	3.4	0.5	0.4	0.1	0.0
	2050	6.4	7.1	0.0	1.1	5.2	3.4	0.5	0.4	0.0	0.0
Centre	2030	4.2	6.4	0.0	0.9	3.8	3.9	0.4	0.3	0.1	0.0
	2050	6.4	8.6	0.0	1.3	4.8	4.4	0.5	0.3	0.0	0.0
East	2030	4.2	7.3	0.0	2.7	3.3	3.8	0.3	0.3	0.0	0.0
	2050	6.4	8.6	0.0	3.0	2.3	4.9	0.5	0.3	0.0	0.0
West	2030	4.2	5.8	0.0	0.1	5.2	3.0	0.4	0.3	0.2	0.0
	2050	6.4	6.7	0.0	0.2	5.3	2.5	0.5	0.3	0.1	0.0
South	2030	4.2	8.3	0.0	3.0	3.2	5.2	0.3	0.2	0.1	0.0
	2050	6.4	8.6	0.0	2.8	3.7	5.7	0.4	0.3	0.1	0.0
Carpathian Mountains	2030	4.2	5.8	0.0	0.7	5.0	1.8	0.5	0.4	0.5	0.0
	2050	6.4	8.4	0.0	0.0	4.3	1.8	0.7	0.3	0.4	0.0
Crimean Mountains	2030	4.3	5.8	0.0	3.2	4.1	3.8	0.3	0.3	0.2	0.0
	2050	6.4	8.6	0.0	4.3	4.3	4.9	0.5	0.2	0.3	0.0
Coastal	2030	4.2	7.5	0.0	3.6	3.3	6.4	0.3	0.2	0.2	0.0
	2050	6.4	8.8	0.0	2.6	4.1	6.7	0.3	0.2	0.1	0.0

Table 5.21. Distribution of maximum risk assessments from the considered climate change hazards to animal husbandry in the regions

Maximum risk assessments in regions	Mid-period	↗ Mean air temperature	↗ Extreme heat	↗ Frost	↘ Mean precipitation	↗ Heavy rains and rain floods (>99pctl)	↗ Droughts and fire-dangerous weather	↘ Snowfall and snowcover	↗ Days with snowfall > 10 mm/day	↗ Wind speed	↗ Coastal climatic impact-drivers
North	2030	4.3	5.8	0.0	1.8	5.5	3.5	0.8	0.5	0.4	0.0
	2050	6.4	8.6	0.0	3.5	5.5	5.3	0.8	0.5	0.4	0.0
Centre	2030	4.3	8.6	0.0	1.8	5.5	5.3	0.5	0.5	0.4	0.0
	2050	6.4	8.6	0.0	4.2	5.5	5.3	0.8	0.4	0.4	0.0
East	2030	4.3	8.6	0.0	5.3	5.5	5.3	0.5	0.5	0.4	0.0
	2050	6.4	8.6	0.0	5.3	5.5	5.3	0.5	0.4	0.0	0.0
West	2030	4.3	8.6	0.0	1.8	5.5	3.5	0.8	0.5	0.8	0.0
	2050	6.4	8.6	0.0	1.8	5.5	5.3	1.0	0.5	0.8	0.0
South	2030	4.3	8.6	0.0	7.0	5.5	7.0	0.5	0.4	0.6	0.0
	2050	6.4	8.6	0.0	7.0	5.5	7.0	0.5	0.5	0.6	0.0
Carpathian Mountains	2030	4.3	8.6	0.0	1.8	5.5	3.5	0.8	0.5	0.8	0.0
	2050	6.4	8.6	0.0	0.0	5.5	3.5	1.0	0.5	0.8	0.0
Crimean Mountains	2030	4.3	5.8	0.0	4.2	5.5	4.2	0.5	0.4	0.4	0.0
	2050	6.4	8.6	0.0	5.6	5.5	5.6	0.8	0.3	0.9	0.0
Coastal	2030	4.3	8.6	0.0	7.0	5.5	7.0	0.4	0.4	1.1	0.0
	2050	6.4	11.5	0.0	5.3	5.5	7.0	0.4	0.4	1.1	0.0

The identified risks to the animal husbandry sector from climate change hazards, i.e. the maximum impact of changing climatic impact-drivers, may lead to a direct physical impact on livestock numbers and productivity, a reduction in fodder crop yields, degradation of pastures and a reduction in water reserves. If such trends continue for a long time, this may also create a risk of "locked-in assets" for investors, i.e. assets that will no longer generate economic returns some time before the end of their term.

As climate change can significantly affect the profitability of the animal husbandry sector, it is critical to analyse specific changes in more detail in terms of space and time and to take into account scientific recommendations based on model projections of climate change and the sector's sensitivity to them.

6. CONCLUSIONS AND RECOMMENDATIONS

Ukraine's climate has been changing rapidly over the past 60 years, with the average annual air temperature since 2007 exceeding the norm by 1.5°C or more, and the last decade being the warmest in the history of meteorological observations. The maximum increase in the average annual air temperature was observed in 2019 and amounted to 2.7°C relative to the 1961–1990 norm. The general trend of increasing minimum daily temperatures is greatest during the cold season, and maximum temperatures during the summer. These changes have led to a reduction in the duration of the cold season, the number of frost days and the severity of winters. At the same time, the changes have led to a longer and hotter growing season and an increase in the number of summer days. The precipitation regime in Ukraine has also changed: the annual amount of precipitation has remained virtually unchanged, but there has been a redistribution of precipitation between seasons. An increase in precipitation is observed in autumn, a decrease in winter and a maximum decrease in summer. In addition, the unevenness of precipitation and its intensity in daily values has increased, leading to longer periods of drought. Over the past twenty years, the occurrence of droughts has almost doubled across most of the country, with a dangerous trend towards an increase in the recurrence of drought conditions.

The current increase in the temperature of the surface air layer, with stable positive trends, is non-monotonic in time and uneven in space. Within individual regions, especially in temperate latitudes, both in warm and cold periods of the year, so-called heat or cold waves of varying duration and intensity are formed, often caused by prolonged stationary anticyclones or the arrival of cyclones. This means that the existing nature of changes in surface air temperature has an indirect impact on the course of circulation processes and, accordingly, on precipitation formation with changes in the structure of precipitation fields. In other words, uneven overheating of the underlying surface has consequences in the redistribution of precipitation amounts, with an increased probability of heavy precipitation and the formation of prolonged rainless periods, an increase in the intensity of hail formation and other extreme weather events: droughts, floods, hurricanes, flooding, etc.

Current climate models show that the same trends will continue in Ukraine until the end of the 21st century under both scenarios of greenhouse gas concentration growth in the atmosphere: moderate RCP 4.5 and high RCP 8.5, but it is expected that the intensity of these changes will be higher in the RCP 8.5 scenario.

The consequences of these changes can already be observed and will only intensify in the future: a decrease in the productivity of certain crops due to extremely high temperatures, increased soil degradation and loss of fertility due to the spread of droughts, a reduction in the areas where certain crops are grown and their shift from south to north, abandonment of the cultivation of certain moisture-loving crops due to difficulties in accessing water resources, and a longer growing season, which may also have a negative impact on the development of winter crops and the industry as a whole due to the spread of pests and diseases, etc.

Climate change is one of the leading factors in soil degradation in Ukraine. Its impact is systemic and complex, affecting the biological, chemical and physical properties of the soil: from reduced fertility and loss of structure to salinisation, alkalisation and increased erosion. Such transformations not only threaten the productivity of the agricultural sector, but also disrupt the ecological balance of terrestrial ecosystems.

Rising air temperatures and reduced precipitation will also lead to the depletion of water resources. Animal husbandry, in particular the production of animal feed, currently consumes 30% of all water in agriculture. According to forecasts, with a warming of 2.7°C, water consumption by livestock will increase by 13%, which may exacerbate competition between human needs and agricultural production.

Under the most extreme scenario (RCP 8.5) assessed by the IPCC, which corresponds to a global temperature increase of 4.3°C by the end of the century, one-third of global food production could be pushed beyond the safe climate space (SCS) by 2081–2100.

To determine the levels of climate change impact on crop production and animal husbandry according to the methodology used, the following concepts and numerical assessments were introduced: *sensitivity* to climate change according to specific categories of climatic impact-drivers (CID) and *vulnerability* of sectors to the combined effect of all CIDs, and *risks* to specific *hazard* that have occurred or may occur as a result of adverse weather conditions and long-term climate change.

Global and regional climate change in Ukraine will have the following consequences (common to agriculture):

- shifting of growing areas for some crops from south to north (crops such as sugar beet and soybeans have already moved 150 km north);
- an increase in the growing season, the formation of a new agroclimatic zone in southern Ukraine;
- shift in the location and development of infrastructure for the storage and primary processing of agricultural products in line with new regional conditions for growing crops;
- a decrease in agricultural productivity due to a lack of innovative resource-saving technologies and equipment in the context of rapid climate change;
- intensification of soil degradation and loss of fertility due to the spread of droughts;

- forced change in the structure of crop production due to the introduction of drought-resistant varieties of agricultural plants and the abandonment of certain moisture-loving crops due to difficulties in accessing water resources;
- damage to plants due to diseases and pests as a result of favourable conditions for their overwintering, the prolongation of the warm and growing season, and the active development of pathogens, in particular due to higher winter temperatures;
- a reduction in the production of traditional fodder crops and the need to grow non-traditional crops (sorghum, triticale, etc.);
- the unsuitability of existing microclimate support systems in animal housing facilities under new climatic conditions.

According to the results of calculations and assessments, the main risks of climate change that will affect the development of crop production in the future in the regions of Ukraine are primarily associated with ***heavy rains and floods, extreme heat and droughts, and fire-hazardous weather*** (*see* 5.2.10. Summary). Changes in other climatic hazards generally pose a low risk.

Based on the maximum risks expected by the middle of the century, specific recommendations for inclusion in the strategy for adapting crop production to climate change may be as follows:

- Crop diversification and improvement of soil cover characteristics, planting a mixture of crops, including those that are better adapted to changing conditions, helps to spread the risk of crop loss and preserve the beneficial properties of the soil. Healthy soil is essential for high crop yields and can help retain water and nutrients, which is particularly important in the context of climate change. Practices such as reducing tillage, using cover crops and implementing crop rotations can significantly improve soil condition.
- Effective irrigation methods and soil moisture conservation practices are vital, especially in areas of Ukraine that already face water shortages and are expected to experience an exacerbation of this risk.
- the introduction of integrated pest and pathogen management, and the development and use of resistant varieties to prevent and reduce the impact of pest and disease outbreaks associated with climate change;
- the introduction of new technologies, such as drones and high spectral and spatial resolution satellite data for precision farming, the development of climate-oriented agricultural methods and early warning systems for extreme weather conditions based on modelling and modern methods of observing atmospheric processes;
- effective response to climate challenges requires the implementation of scientifically sound approaches, systematic monitoring of soil conditions, adaptive land use practices and innovations in agricultural technology. Already today, domestic

scientific institutions, in particular the State Agency for Soil Protection, the O.N. Sokolovsky Institute of Soil Science and Agrochemistry, as well as international organisations, in particular the FAO, offer a number of practical solutions to reduce the negative impact of climate change and preserve soil resources for future generations.

The greatest risks to the animal husbandry sector by the middle of the century arise from changes in the following categories of climate change: increased extreme heat, mean air temperatures, heavy rains and floods, droughts, and fire-dangerous weather. It should be noted that for these categories of climate change, the level of risk is mostly medium for the current period and mostly high for the middle of the century. Geographically, the highest risk levels that may affect the industry due to changes in temperature and drought are found in the coastal areas and the southern region. The highest risk levels (average) from heavy rainfall and floods are in the western region and the Carpathians.

An assessment of current climatic conditions and their possible changes in Ukraine allows us to identify important categories of climatic impact-drivers and their combinations that will have a negative impact on the condition of livestock, the conditions for growing fodder crops and the condition of natural pastures, quantitative indicators and the level of water resources supply to the industry. These areas of impact include:

- an increase in mean monthly (especially spring and summer) and annual air temperatures, which will certainly require the use (selection) of new breeds of livestock and new varieties of fodder crops that are adapted to high temperatures and arid conditions;
- an increase in the number of days with abnormally high temperatures, which negatively affects the condition of animals. The onset of periods of extreme heat each time requires a series of measures to reduce the impact of heat stress on the condition of livestock (air conditioning in housing facilities, open shaded pens, additional drinking water, etc.);
- increased frequency of droughts, particularly in combination with extremely high temperatures, will have a particularly strong impact on the condition of fodder crops and water resources;
- sharp temperature fluctuations between seasons and during individual months and days, cold spells in winter will affect livestock and its productivity, and will also reduce the resistance of many feed crops to temperature influences;
- an increase in the frequency of extreme weather events during the warm season (heavy rains, thunderstorms, tornadoes, squalls, hail) will pose a threat to grazing animals and worsen the condition of natural pastures and fodder crops;

- a decrease in the frequency of precipitation and an increase in its intensity will lead to prolonged periods of drought in some regions and to heavy rains and flooding, increased erosion and soil erosion in others;

- Increased unevenness in precipitation during certain periods of the year will lead to an even more uneven distribution of water resources across the country and will affect the supply of drinking water to livestock.

- the absence of persistent snowcover, given the significant drop in air temperature during certain periods, will prevent moisture accumulation in the soil and reduce the yield of fodder crops;

- an increased likelihood of fires, which disrupt the stability of ecosystems, will cause crop losses and reduce the sector's adaptive capacity to climate change;

- with rising air temperatures and high humidity, favourable conditions will develop for the spread of pests, diseases and invasive plant species, which may reduce the productivity of fodder crops and affect the health of livestock. This will require improvements to the system for monitoring the spread of pests, parasites and animal diseases, and the development of measures to prevent infection.

- The animal husbandry sector is considered to be one of the sources of greenhouse gases (methane, carbon dioxide, nitrogen oxide) and other emissions that pollute the environment (ammonia, hydrogen sulphide, organic dust, etc.), which will require the improvement and creation of new technologies for the disposal of animal husbandry waste.

It is known that implementing adaptation measures to prevent potential risks will reduce their level and lessen their negative impact on agriculture. It is worth noting that adaptation measures can be divided into two groups based on their content. The first group includes all measures aimed at reducing threats (risks) from extreme weather conditions (heat, cold, heavy rain). The second group includes measures aimed at adaptation (adjustment) to expected climate change, which are represented by calculated CID values.

The results presented enable industry leaders, individual enterprises and farmers to take them into account when developing a programme of adaptation measures that will avoid or reduce the impact of climate change on the state, functioning and profitability of the crop production and animal husbandry sectors, fodder production, and possibly the state of natural pastures, and minimise the degree of impact of each climate threat.

In summary:

1. The need to implement adaptation measures in agriculture is due to:

1. **Rapid warming**: the average annual temperature in Ukraine has increased by more than 1.5 °C compared to 1961–1990; the last decade has been the warmest decade in the history of observations.

2. **Water balance disruption**: summer precipitation has decreased, autumn precipitation has increased; droughts occur twice as often, and rainstorms are more intense.

3. **Threats to the agricultural sector**: shifting crop growing areas, soil degradation, water shortages, increased heat stress for plants and livestock, and the spread of pests.

2. Justification for meeting the requirements for modern risk and vulnerability assessment:

- **The methodology used is based on the latest IPCC report (IPCC AR6) using 32 Climatic Impact-Drivers (CID)** and allows assessing the impact of changes *not only* in mean air temperature and precipitation, but also in extreme indicators and phenomena (heat, heavy rainfall, droughts, fire-hazardous weather, etc.) with the involvement of specific sensitivity of sectors to each of the CIDs.

- The data and results of simulations already performed for Ukraine under RCP 4.5/8.5 scenarios for 2021-2040 and 2041-2060 were **used** to ensure consistency with previous studies for agriculture (in particular, World Bank, 2021).

3. Recommended principles for integration into the Strategy for Adaptation of Agriculture to Climate Change:

Step	Action (measures)	Expected effect
Institutional framework	Ensure mandatory climate change assessment risk analysis for state programmes, finance and insurance	Uniform criteria for priorities and access to funds
Data systems	Combine meteorological, hydrological, soil and agronomic databases into a national platform; ensure open access	Operational monitoring and targeted solutions
Territorial planning	The resulting maps of risk hotspots for crops and animal husbandry will enable the adjustment and implementation of irrigation, logistics and processing schemes	Reduction of losses and optimisation of investments
Innovation and support	Promote precision farming technologies, selection of drought-resistant varieties/breeds, modernisation of animal husbandry systems	Increasing productivity and sustainability

Finance and insurance instruments	Introduce climate-oriented loans and subsidies; develop agricultural insurance linked to risk indices	Sharing financial risks between the state and producers
Education and advice	Expand the network of advisory services with a focus on developing measures based on climate change assessment and risk-oriented approaches, and adaptive practices	Rapid transfer of knowledge at farm level

4. Targeted measures for crop production

1. **Diversification and crop rotation** – crop mixtures, cover crops, *low-till farming* to conserve moisture and fertility.

2. **Irrigation and moisture-conserving practices** – drip irrigation, mulching, soil improvement.

3. **Pest management** – integrated pest management, early warning, resistant varieties.

4. **Digital solutions** – drones, satellite data, mobile applications for real-time assessment of the risks of extreme climate and weather events.

5. Targeted measures for animal husbandry

1. **Heat adaptation** – ventilated and shaded premises, automated cooling, compound feed with higher electrolyte content.

2. **Breed selection** – breeds resistant to heat and drought; development of alternative feed crops (sorghum, triticale).

3. **Water resources** – reservoir systems and water recovery; pasture management to reduce evaporation.

4. **Emissions reduction** – biogas plants, precision manure application, feeding with low-methane diets.

6. Monitoring and review

- **Performance indicators**: coverage of detailed climate risk analysis based on CID (% of area and livestock), reduction in crop losses/productivity, reduction in water consumption and emissions.

- **Updates every five years** based on new climate projections and the results of the implementation of measures.

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ADDITIONAL RESOURCES

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APPENDICES

Appendix A. Sensitivity (%) and maximum vulnerability values (%) of the crop production sector by CID categories and regions

Table A.1.1. Vulnerability values for the southern region

IPCC CID	IPCC CID Category	Vulnerability in crop production – South.						Sensitivity of crop production – South.
		RCP 4.5			RCP 8.5			
		2021–2040	2041–2060	2081–2100	2021–2040	2021–2040	2021–2040	
Heat and Cold	Mean air temperature	3.25	4	5.75	3.5	5.25	8	11
	Extreme heat	7.75	9.25	11.75	7.75	12.75	17	17
	Cold spells	0	0	0	0	0	0	3
	Frost	0	0	0	0	0	0	9
Wet and Dry	Mean precipitation	5	2.5	5	3.75	5.75	5	16
	Heavy precipitation and pluvial floods	8.25	9.5	9.5	8.25	9.5	12.5	15
	Droughts	13	13	13	13	13	13	13
	Fire weather	0.75	1.5	2.25	0.75	2.25	3	3
Snowfall and Snowcover	Snowcover and snowfall	2.5	2.5	2.5	1.5	2.5	4.5	6
	Moderate snowfall days	0.75	1	0.75	0.75	0.75	0.5	1
Surface wind speed	Mean wind speed	0.25	0.25	0	0	0.25	0.25	1
	Severe wind storm	1	0	0	1	1	1	4
Costal	Relative sea level rise	0	0	0	0	0	0	1
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**42.5**	**43.5**	**50.5**	**40.25**	**53**	**64.75**	**100**

Table A.1.2. Vulnerability values for the central region

IPCC CID	IPCC CID Category	Vulnerability of crop production – Centre						Sensitivity of crop production – Centre
		RCP 4.5			RCP 8.5			
		2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	3.25	4	5.75	3.75	5.75	8	11
	Extreme heat	6.75	9.25	11.75	7.75	11.75	17	17
	Cold spells	0	0	0	0	0	0	3
	Frost	0	0	0	0	0	0	9
Wet and Dry	Mean precipitation	3.75	3.75	5	4.5	4	5	16
	Heavy precipitation and pluvial floods	8.25	9.5	10.5	7.25	8.25	11.75	15
	Droughts	9.75	9.75	9.75	9.75	13	13	13
	Fire weather	0	1.5	2.25	0.75	2.25	3	3
Snowfall and Snowcover	Snowcover and snowfall	2.5	3	4	2.5	4	5.5	6
	Moderate snowfall days	1	0.75	0.75	1	0.75	0.5	1
Surface wind speed	Mean wind speed	0.25	0	0	0	0.25	0.25	1
	Severe wind storm	1	0	0	1	1	1	4
Costal	Relative sea level rise	0	0	0	0	0	0	1
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**36.5**	**41.5**	**49.75**	**38.25**	**51**	**65**	**100**

Table A.1.3. Vulnerability values for the western region

IPCC CID	IPCC CID Category	Vulnerability of crop production – West						Crop production sensitivity – West
		RCP 4.5			RCP 8.5			
		2021 – 2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	2.25	4	5.75	3.75	5.75	7.75	11
	Extreme heat	6.5	6.5	8.25	6.75	8.25	15.75	17
	Cold spells	0	0	0	0	0	0	3
	Frost	0	0	0	0	0	0	9
Wet and Dry	Mean precipitation	0.75	0	0	0.75	0.75	1.25	16
	Heavy precipitation and pluvial floods	8.25	9.5	11.75	8.25	9.5	14	15
	Droughts	6.5	6.5	6.5	6.5	9.75	6.5	13
	Fire weather	0	0.75	0.75	0	1.5	3	3
Snowfall and Snowcover	Snowcover and snowfall	3	3.5	4	2.5	4	6	6
	Moderate snowfall days	1	1	1	1	0.75	0.5	1
Surface wind speed	Mean wind speed	0.5	0.25	0.25	0.25	0.25	0.25	1
	Severe wind storm	2	0	0	2	2	3	4
Costal	Relative sea level rise	0	0	0	0	0	0	1
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Amount		**30.75**	**32**	**38.25**	**31.75**	**42.5**	**58**	**100**

Table A.1.4. Vulnerability values for the eastern region

IPCC CID	IPCC CID Category	Vulnerability of crop production – East						Crop production sensitivity – East
		RCP 4.5			RCP 8.5			
		2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	3.25	5	5.75	3.75	5.75	8	11
	Extreme heat	7.75	7.75	11.75	7.75	11.75	17	17
	Cold spells	0	0	0	0	0	0	3
	Frost	0	0	0	0	0	0	9
Wet and Dry	Mean precipitation	3.75	3.75	5.75	4	4.5	5	16
	Heavy precipitation and pluvial floods	8.25	8.25	9.5	6	6.75	8.75	15
	Droughts	9.75	6.5	9.75	9.75	9.75	13	13
	Fire weather	0	1.5	2.25	0.75	2.25	3	3
Snowfall and Snowcover	Snowcover and snowfall	2.5	3	3	1.5	3	6	6
	Moderate snowfall days	1	0.75	0.75	0.75	0.75	0.75	1
Surface wind speed	Mean wind speed	0.25	0	0	0	0	0	1
	Severe wind storm	0	0	0	0	0	0	4
Costal	Relative sea level rise	0	0	0	0	0	0	1
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**36.5**	**36.5**	**48.5**	**34.25**	**44.5**	**61.5**	**100**

Table A.1.5. Vulnerability values for the northern region

IPCC CID	IPCC CID Category	Vulnerability of crop production – North						Crop production sensitivity – North
		RCP 4.5			RCP 8.5			
		2021	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	2.25	4	5.75	3.75	5.75	7.75	11
	Extreme heat	5	6.5	9	6.5	9.25	15.75	17
	Cold spells	0	0	0	0	0	0	3
	Frost	0	0	0	0	0	0	9
Wet and Dry	Mean precipitation	1.25	2.5	3.75	0.75	2.5	3.75	16
	Heavy precipitation and pluvial floods	8.25	9.5	9.5	7.25	8.25	13	15
	Droughts	6.5	6.5	6.5	6.5	9.75	6.5	13
	Fire weather	0	0.75	0.75	0	1.5	3	3
Snowfall and Snowcover	Snowcover and snowfall	3.5	3.5	5	2.5	4	6	6
	Moderate snowfall days	1	1	1	1	1	0.75	1
Surface wind speed	Mean wind speed	0	0	0	0	0	0.25	1
	Severe wind storm	1	0	0	1	1	1	4
Costal	Relative sea level rise	0	0	0	0	0	0	1
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**28.75**	**34.25**	**41.25**	**29.25**	**43**	**57.75**	**100**

Table A.1.6. Vulnerability values for the Carpathian Mountains region

IPCC CID	IPCC CID Category	Vulnerability of crop production – Carpathian Mountains						Sensitivity of crop production – Carpathian Mountains
		RCP 4.5			RCP 8.5			
		2021 – 2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	3	5	5.75	3.75	6	7.75	11
	Extreme heat	6.5	7.75	9.25	6.75	9.25	14	17
	Cold spells	0	0	0	0	0	0	3
	Frost	0	0	0	0	0	0	9
Wet and Dry	Mean precipitation	0.75	0	0	0.75	0	2.5	16
	Heavy precipitation and pluvial floods	8.25	9.5	11.75	8.5	9.5	12.5	15
	Droughts	3.25	6.5	6.5	6.5	6.5	6.5	13
	Fire weather	0	0.75	0.75	0	0.75	3	3
Snowfall and Snowcover	Snowcover and snowfall	3.5	4	4.5	2.5	4	6	6
	Moderate snowfall days	1	0.75	1	1	1	0.5	1
Surface wind speed	Mean wind speed	0.5	0.5	0.25	0	0	0.25	1
	Severe wind storm	1	0	0	0	1	3	4
Costal	Relative sea level rise	0	0	0	0	0	0	1
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**27.75**	**34.75**	**39.75**	**29.75**	**38**	**56**	**100**

Table A.1.7. Vulnerability values for the Crimean Mountains region

IPCC CID	IPCC CID Category	Vulnerability of crop production – Crimean Mountains						Crop production sensitivity – Crimean Mountains
		RCP 4.5			RCP 8.5			
		2021	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	3	4	5	3	5.25	7.25	11
	Extreme heat	6.5	7.5	11.5	7.5	11.5	16.75	17
	Cold spells	0	0	0	0	0	0	3
	Frost	0	0	0	0	0	0	9
Wet and Dry	Mean precipitation	2.5	0	5	3.25	5.25	6	16
	Heavy precipitation and pluvial floods	8.25	8.25	8.75	7.25	9.5	10.75	15
	Droughts	6.5	6.5	9.75	6.5	9.75	13	13
	Fire weather	0	1.5	1.5	0.75	2.25	3	3
Snowfall and Snowcover	Snowcover and snowfall	2	3	3.5	2	3	5	6
	Moderate snowfall days	0.75	0.5	0.75	0.5	0.5	0	1
Surface wind speed	Mean wind speed	0	0	0	0	0	0	1
	Severe wind storm	1	0	0	1	2	1	4
Costal	Relative sea level rise	0	0	0	0	0	0	1
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**30.5**	**31.25**	**45.75**	**31.75**	**49**	**62.75**	**100**

Table A.1.8. Vulnerability values for the coastal region

IPCC CID	IPCC CID Category	Vulnerability of crop production – Coastal						Crop production sensitivity – Coastal
		RCP 4.5			RCP 8.5			
		2021	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	3.75	5	5.75	3.75	5.25	8	11
	Extreme heat	7.75	10.25	14.25	10.25	14.25	17	17
	Cold spells	0	0	0	0	0	0	3
	Frost	0	0	0	0	0	0	9
Wet and Dry	Mean precipitation	5	2.5	3.75	3.25	4.5	6	16
	Heavy precipitation and pluvial floods	8.25	9.5	9.5	8.25	8.25	11.25	15
	Droughts	13	13	13	13	13	13	13
	Fire weather	0.75	1.5	1.5	0.75	2.25	3	3
Snowfall and Snowcover	Snowcover and snowfall	1.5	3	3	1.5	3	4.5	6
	Moderate snowfall days	0.5	0.75	0.5	0.75	0.75	0.25	1
Surface wind speed	Mean wind speed	0	0	0	0	0	0	1
	Severe wind storm	3	1	0	1	3	2	4
Costal	Relative sea level rise	0.25	0.5	1	0.25	0.5	1	1
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Amount		**43.75**	**47**	**52.25**	**42.75**	**54.75**	**66**	**100**

Appendix B. Sensitivity (%) and maximum vulnerability values (%) of the animal husbandry sector by CEA categories and regions

Table B.1.1. Vulnerability values for the southern region

IPCC CID	IPCC CID Category	Animal husbandry vulnerability – South						Animal husbandry sensitivity – South
		RCP 4.5			RCP 8.5			
		2021 – 2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	4.5	6	8.5	5	7.75	12	17
	Extreme heat	11.25	12.75	15.75	11.25	17.25	23	23
	Cold spells	0	0	0	0	0	0	11
	Frost	0	0	0	0	0	0	4
Wet and Dry	Mean precipitation	4	2	4	3	4.75	4	14
	Heavy precipitation and pluvial floods	5	5.75	5.75	5	5.75	9	11
	Droughts	11	11	11	11	11	11	11
	Fire weather	0.75	1.5	2.25	0.75	2.25	3	3
Snowfall and Snowcover	Snowcover and snowfall	0.75	0.75	0.75	0.5	0.75	1.5	2
	Moderate snowfall days	0.75	1	0.75	0.75	0.75	0.5	1
Surface wind speed	Mean wind speed	0.25	0.25	0	0	0.25	0.25	1
	Severe wind storm	0.5	0	0	0.5	0.5	0.5	2
Costal	Relative sea level rise	0	0	0	0	0	0	0
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**38.75**	**41**	**48.75**	**37.75**	**51**	**64.75**	**100**

Table B.1.2. Vulnerability values for the central region

IPCC CID	IPCC CID Category	Animal husbandry vulnerability – Centre						Animal husbandry sensitivity – Centre
		RCP 4.5			RCP 8.5			
		2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	4.5	6	8.5	5.5	8.5	12	17
	Extreme heat	9.75	12.75	15.75	11.25	15.75	23	23
	Cold spells	0	0	0	0	0	0	11
	Frost	0	0	0	0	0	0	4
Wet and Dry	Mean precipitation	3	3	4	3.75	3.5	4	14
	Heavy precipitation and pluvial floods	5	5.75	7	3.75	5	7.75	11
	Droughts	8.25	8.25	8.25	8.25	11	11	11
	Fire weather	0	1.5	2.25	0.75	2.25	3	3
Snowfall and Snowcover	Snowcover and snowfall	0.75	1	1.25	0.75	1.25	1.75	2
	Moderate snowfall days	1	0.75	0.75	1	0.75	0.5	1
Surface wind speed	Mean wind speed	0.25	0	0	0	0.25	0.25	1
	Severe wind storm	0.5	0	0	0.5	0.5	0.5	2
Costal	Relative sea level rise	0	0	0	0	0	0	0
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**33**	**39**	**47.75**	**35.5**	**48.75**	**63.75**	**100**

Table B.1.3. Vulnerability values for the western region

IPCC CID	IPCC CID Category	Animal husbandry vulnerability – West						Animal husbandry sensitivity – West
		RCP 4.5			RCP 8.5			
		2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	3.5	6	8.5	5.5	8.5	11.5	17
	Extreme heat	8.5	8.5	11.25	9.75	11.25	20.25	23
	Cold spells	0	0	0	0	0	0	11
	Frost	0	0	0	0	0	0	4
Wet and Dry	Mean precipitation	0.75	0	0	0.75	0.75	1	14
	Heavy precipitation and pluvial floods	5	5.75	7.75	5	5.75	9.75	11
	Droughts	5.5	5.5	5.5	5.5	8.25	5.5	11
	Fire weather	0	0.75	0.75	0	1.5	3	3
Snowfall and Snowcover	Snowcover and snowfall	1	1.25	1.5	1	1.5	2	2
	Moderate snowfall days	1	1	1	1	0.75	0.5	1
Surface wind speed	Mean wind speed	0.5	0.25	0.25	0.25	0.25	0.25	1
	Severe wind storm	1	0	0	1	1	1.5	2
Costal	Relative sea level rise	0	0	0	0	0	0	0
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**26.75**	**29**	**36.5**	**29.75**	**39.5**	**55.25**	**100**

Table B.1.4. Vulnerability values for the eastern region

IPCC CID	IPCC CID Category	Animal husbandry vulnerability – East						Animal husbandry sensitivity – East
		RCP 4.5			RCP 8.5			
		2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	4.75	7	8.5	5.5	8.5	12	17
	Extreme heat	11.25	11.25	15.75	11.25	15.75	23	23
	Cold spells	0	0	0	0	0	0	11
	Frost	0	0	0	0	0	0	4
Wet and Dry	Mean precipitation	3	3	4.75	3.5	3.75	4	14
	Heavy precipitation and pluvial floods	5	5	5.75	3	4.25	6.25	11
	Droughts	8.25	5.5	8.25	8.25	8.25	11	11
	Fire weather	0	1.5	2.25	0.75	2.25	3	3
Snowfall and Snowcover	Snowcover and snowfall	0.75	1	1	0.5	1	2	2
	Moderate snowfall days	1	0.75	0.75	0.75	0.75	0.75	1
Surface wind speed	Mean wind speed	0.25	0	0	0	0	0	1
	Severe wind storm	0	0	0	0	0	0	2
Costal	Relative sea level rise	0	0	0	0	0	0	0
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**34.25**	**35**	**47**	**33.5**	**44.5**	**62**	**100**

Table B.1.5. Vulnerability values for the northern region

IPCC CID	IPCC CID Category	Vulnerability of animal husbandry – North						Sensitivity of animal husbandry – North
		RCP 4.5			RCP 8.5			
		2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	3.75	6	8.5	5.5	8.5	11.5	17
	Extreme heat	7	8.5	11.5	8.5	12.75	20.25	23
	Cold spells	0	0	0	0	0	0	11
	Frost	0	0	0	0	0	0	4
Wet and Dry	Mean precipitation	1	2	3	0.75	2	3	14
	Heavy precipitation and pluvial floods	5	5.75	5.75	3.75	5	8.5	11
	Droughts	5.5	5.5	5.5	5.5	8.25	5.5	11
	Fire weather	0	0.75	0.75	0	1.5	3	3
Snowfall and Snowcover	Snowcover and snowfall	1	1	1.5	0.75	1.25	2	2
	Moderate snowfall days	1	1	1	1	1	0.75	1
Surface wind speed	Mean wind speed	0	0	0	0	0	0.25	1
	Severe wind storm	0.5	0	0	0.5	0.5	0.5	2
Costal	Relative sea level rise	0	0	0	0	0	0	0
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**24.75**	**30.5**	**37.5**	**26.25**	**40.75**	**55.25**	**100**

Table B.1.6. Vulnerability values for the Carpathian Mountains region

IPCC CID	IPCC CID Category	Animal husbandry vulnerability – Carpathian Mountains						Animal husbandry sensitivity – Carpathian Mountains
		RCP 4.5			RCP 8.5			
		2021	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	4	7	8.5	5.5	9	11.5	17
	Extreme heat	8.5	9.75	11.25	9.75	11.25	18.5	23
	Cold spells	0	0	0	0	0	0	11
	Frost	0	0	0	0	0	0	4
Wet and Dry	Mean precipitation	0.75	0	0	0.75	0	2	14
	Heavy precipitation and pluvial floods	5	5.75	7.75	5	5.75	9	11
	Droughts	2.75	5.5	5.5	5.5	5.5	5.5	11
	Fire weather	0	0.75	0.75	0	0.75	3	3
Snowfall and Snowcover	Snowcover and snowfall	1.25	1.5	1.5	1	1.5	2	2
	Moderate snowfall days	1	0.75	1	1	1	0.5	1
Surface wind speed	Mean wind speed	0.5	0.5	0.25	0	0	0.25	1
	Severe wind storm	0.5	0	0	0	0.5	1.5	2
Costal	Relative sea level rise	0	0	0	0	0	0	0
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**24.25**	**31.5**	**36.5**	**28.5**	**35.25**	**53.75**	**100**

Table B.1.7. Vulnerability values for the Crimean Mountains region

IPCC CID	IPCC CID Category	Animal husbandry vulnerability – Crimean Mountains						Animal husbandry sensitivity – Crimean Mountains
		RCP 4.5			RCP 8.5			
		2021	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	4	6	7	4.25	7.5	10.75	17
	Extreme heat	8.5	10	14.5	10	14.5	21.75	23
	Cold spells	0	0	0	0	0	0	11
	Frost	0	0	0	0	0	0	4
Wet and Dry	Mean precipitation	2	0	4.25	2.75	4.5	5	14
	Heavy precipitation and pluvial floods	5	5	6.25	3.75	5.75	8.75	11
	Droughts	5.5	5.5	8.25	5.5	8.25	11	11
	Fire weather	0	1.5	1.5	0.75	2.25	3	3
Snowfall and Snowcover	Snowcover and snowfall	0.75	1	1.25	0.75	1	1.75	2
	Moderate snowfall days	0.75	0.5	0.75	0.5	0.5	0	1
Surface wind speed	Mean wind speed	0	0	0	0	0	0	1
	Severe wind storm	0.5	0	0	0.5	1	0.5	2
Costal	Relative sea level rise	0	0	0	0	0	0	0
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Amount		**27**	**29.5**	**43.75**	**28.75**	**45.25**	**62.5**	**100**

Table B.1.8. Vulnerability values for the Coastal Region

IPCC CID	IPCC CID Category	Animal husbandry vulnerability – Coastal						Animal husbandry sensitivity – Coastal
		RCP 4.5			RCP 8.5			
		2021	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	
Heat and Cold	Mean air temperature	5.5	7	8.5	5.5	7.75	12	17
	Extreme heat	11.25	14.25	18.75	14.25	18.75	23	23
	Cold spells	0	0	0	0	0	0	11
	Frost	0	0	0	0	0	0	4
Wet and Dry	Mean precipitation	4	2	3.25	2.75	3.75	5	14
	Heavy precipitation and pluvial floods	5	5.75	6.25	5	5	8.25	11
	Droughts	11	11	11	11	11	11	11
	Fire weather	0.75	1.5	1.5	0.75	2.25	3	3
Snowfall and Snowcover	Snowcover and snowfall	0.5	1	1	0.5	1	1.5	2
	Moderate snowfall days	0.5	0.75	0.5	0.75	0.75	0.25	1
Surface wind speed	Mean wind speed	0	0	0	0	0	0	1
	Severe wind storm	1.5	0.5	0	0.5	1.5	1	2
Costal	Relative sea level rise	0	0	0	0	0	0	0
	Extreme storm surge level (coastal flood)	0	0	0	0	0	0	0
Sum		**40**	**43.75**	**50.75**	**41**	**51.75**	**65**	**100**