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THEORETICAL BASES OF CROP PRODUCTION ON THE RECLAIMED LANDS IN THE CONDITIONS OF CLIMATE CHANGE

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The work is dedicated to theoretical study of current climatic trends in Ukraine and their influence on the agricultural sector of the country's economy together with modern opportunities of crop production increase and efficiency enhancement through the implementation of rational land use policies and the last achievements of information technologies. Robust analysis of meteorological changes and concurrent shifts in crop water requirements through the long-term periods for sustainable high-quality food production is provided. Mathematical models for reference evapotranspiration assessment are developed and introduced for Ukrainian crop producers to enhance the efficiency of agricultural water management under simultaneous stabilization of crop gross production in the conditions of increasing aridity and freshwater deficit. Revision of modern agricultural practices in the field of forest resources management, agrochemicals and pesticides use, land management, etc., is provided in the context of resource-saving and provision of environmentally friendly crop production in the country. Last achievements of remote sensing technologies are integrated in the form of mathematical models for environmental monitoring, crop growth observation and yield forecasting on local and regional scales. Recommendations on agricultural sector policies reformation and implementation of modern information technologies in Ukrainian agriculture are proposed. The monograph is directed to agricultural specialists and scientists, as well as the students who are getting higher education in the field of agronomy, crop science, irrigated agriculture, and precision agriculture.

Keywords: Vegetation Index; Global Warming; Remote Sensing; Reference Evapotranspiration; Irrigation; Afforestation; Mathematical Modeling; Crop Forecasting; Precision Agriculture; Climate Smart Agriculture.

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INTRODUCTION

Crop production is crucial for ensuring food security. The rapid increase in the population of the planet leads to the aggravation of the world food crisis, the main manifestations of which are the shortage of quality food products, the impossibility of ensuring food security in densely populated developing countries, especially where the soil and climatic conditions and material and technical resources are unfavorable for sustainable development of the agro-industrial complex. Agricultural production is one of the branches of the economy most closely related to nature, which is incredibly susceptible to adverse changes in the environment and climatic conditions. Global warming, whose manifestations have been noticed since the middle of the 20th century, requires reviewing the practice of agriculture, first, aimed to reduction of its ecological pressure on the environment and climate, mitigating the negative impact of adverse meteorological factors on the productivity and sustainability of natural and artificial ecosystems. In addition, it is important to transform the production of plant products considering the achievements of the fourth industrial revolution, which involves the industrialization and informatization of all spheres of human activity. Development plant products production requires transition to modern principles of precise and climate-smart agriculture, which allow to significantly increase the productivity of agrophytocenoses by reducing losses from previously unpredictable and difficult to control adverse factors of natural and anthropogenic origin, and as a result, to significantly increase the profitability of agricultural production. Besides, climate-smart agriculture involves possible reduction in negative loads on the climate situation, mainly due to the rational land use and changes in the practice of agricultural activity with the focus on the reduction of greenhouse gas emissions from the agro-industrial complex. Unfortunately, the systems of precise and climate-smart agriculture have received limited distribution in Ukraine, because currently there is a lack of scientific, theoretical, and practical knowledge for their reasonable implementation in farms of various organizational and legal forms. Research on the climatic zoning of the territory of Ukraine, regional requirements for irrigation water supply, the country's territory classification by the hazards of agricultural land degradation, carried out in the Soviet times, in the conditions of significant climatic, material-technical, economic-political, and social changes that had occurred in the last decades, are outdated, and requires thorough revision. Unfortunately, in Ukraine and several other countries of the world, very little attention is paid to the issue of reducing the climatic loads of agricultural activity due to the optimization of technological factors in the production of plant products (mainly through the rationalization and optimization of the use of plant protection products, mineral and organic fertilizers, machine and tractor power, etc.), rational use of agricultural land and measures for the preservation and reproduction of forest plantations, comprehensive reformatting of the agrarian sector for ecologically oriented production of products. Pleiades of domestic scientists, such as, Vozhehova R. A., Ushkarenko V. O., Romaschenko M. I., Tarariko O. G., Shatkovskii A. P., Kokovikhin S. V., Syrotenko O. V., Ilyenko T. V., Kuchma T. L., Pichura V. I., Morozov O. V., Hranovska L. M., Biliaieva I. M., Boiko O. G., et al. are working on solving problematic issues of rational farming in the conditions of global warming and transfer to the systems of industrial precision farming with the involvement of modern systems of satellite monitoring of crops and information technologies. However, until now, there are almost no systematic works in this direction and a number of important issues remain unresolved or insufficiently covered, which slows down the development of the domestic agro-industrial complex and determines the relevance of the chosen topic of the research, which is designed to generalize and provide a theoretical justification for farming on the reclaimed lands of Ukraine in the view of modern agro-climatic conditions that have developed on its territory in recent decades under the influence of global and local climate changes, and current developments in the field of geo-information technologies and remote sensing technologies in agricultural production. Theoretical principles and scientific justification of the plant products production on the reclaimed lands considering current ecological requirements, afforestation, reconstruction of existing and creation of new irrigation systems on the territory of Ukraine, as well as mathematical models and methods of their effective use in modern information technology systems in the process of agrarian production will contribute to the stabilization and increase of the productivity of the national agricultural sector, will allow Ukrainian agricultural producer to reach the level of the most developed countries in the world and occupy a prominent place among the main players in the world market of agricultural products.

CHAPTER 1
CURRENT STATE OF GLOBAL AND UKRAINIAN CROP PRODUCTION IN THE CONTEXT OF GLOBAL WARMING AND THE FOURTH INDUSTRIAL REVOLUTION

1.1. Global warming and its influence on the resource potential and development of agriculture

Climate change is a continuous dynamic process. It will happen as long as there is an atmosphere on our planet with all its components. Climate is one of the factors in the evolution of species and at the same time one of the stimuli for the civilization development. Mankind adapted to the climate, looked for ways to overcome its negative effects, learned to use economically useful meteorological phenomena, and saved their lives during adverse and extreme weather events. However, in recent decades, the climatic situation on Earth has undergone extremely rapid and threatening changes on a planetary scale, and therefore requires the careful attention of the scientific community to solve the related problems as quickly and effectively as possible, since the future existence of humanity on the planet will depend on this (Адаменко, 2009).

Global warming is the most serious and important environmental problem nowadays (Houghton, 2005; Chiabryshvili & Salukvadze, 2010). There are different definitions of the term "global warming". Thus, it is usually understood as the process of a gradual increase in the mean annual temperature of the surface layer of the atmosphere, the Earth's surface, and the World Ocean (Корзун, 2009). In more detail, it is an observed or predicted increase in the mean annual weighted average temperature of the planet, the main components of which are the temperature of the subsurface layer of the World Ocean at a depth of several meters and the surface temperature of the air at a height of 1.5 m from the Earth's surface (Басок & Базєєв, 2020). According to IPCC (Intergovernmental Panel on Climate Change) data, the average global increase in the temperature of the surface layer of the atmosphere for the period 1906-2010 is 0.74±0.18ºC, while the northern hemisphere is warming faster than the southern hemisphere. The rise of the temperature curve relative to the average temperature of the period of 1961-1990 (accepted by most researchers as the "standard" reference point) is observed for the periods of the 1940-50s of the last century, as well as from the 1980s to the present day (Khandekar et al., 2005).

However, an excessive focus on temperature indicators and an increase in the frequency of adverse weather phenomena does not give a complete picture of the process of global warming because in fact it is a much more complicated and complex climatic phenomenon. For the same reason, the search for primary factors of climate change is complicated by the extremely high integrability and multifaceted nature of atmospheric processes and associated meteorological manifestations (Khandekar et al., 2005).

The first mentions of the phenomenon of global warming and attempts to provide a scientific substantiation for climatic changes on the planet can be found in the works of Fourier as early as 1827 (Mudge, 1997). Studies on the radiation balance of the Earth and its atmosphere in relation to various natural factors affecting them are described in the work of Kiehl & Trenberth (1997). And although some people still regard global warming with irony, they change their minds when they personally face the problems it creates in their place of residence, namely extreme heat, prolonged droughts, changes in the length of the weather seasons, etc. (Choi et al., 2020). Several studies show that personal experience leads to a better understanding of the risks associated with climate change and also changes the behavior and peculiarities of conducting economic activities of people who have dealt with the negative effects of global warming in their practice (Akerlof et al., 2013; Myers et al., 2013; Zaval et al., 2014). Personal experience leads people to the opinion of the need to take measures to counteract the climate catastrophe; they are more willing to get involved in the campaign for ecologization and biologization of production and take part in charity actions dedicated to climate issues (Li et al., 2011). Negative personal experience with the consequences of global warming also affects the peculiarities of decision-making regarding health insurance, the purchase of certain things and technical means, etc. (Chang et al., 2018). A change in attitude towards medical insurance, the health care system and sanitary and hygienic measures is especially relevant, as the role of global warming in the spread of deadly infectious diseases and parasites has been proven (Басок & Базєєв, 2020). It is quite possible that the latest SaRS-CoV-2 pandemic gained a planetary scope and extremely high spread not only due to the characteristics of the viral agent itself, but also due to the contribution of the global climatic environment. The impact of the dissemination of true information about the situation in the climate situation on the planet is very significant and affects a whole series of interconnected decisions not only at the level of public policy and industrial production, but also at the level of everyday decisions of an individual (Busse et al., 2015). However, even in developed countries such as the USA, there is still a widespread idea among the population that global warming is a politically profitable fiction (about 30% of the country's citizens think so), and among those who have already believed in the reality of climate change, only 40% believe that it will somehow affect them personally, and therefore they are reluctant to change their lifestyle, get involved in environmental protection activities, etc. (Marlon et al., 2016).

If at the beginning of the 1980s of the last century there was a debate among scientists all over the world about the reality of global climate change, then at the beginning of the XXI century 90% of former skeptics were convinced that global warming is not a myth, but a proven fact (Khandekar et al., 2005). At the same time, 82% of climatologists believe that it is anthropogenic activity that is to blame in the rapid pace of climate change (Оноприєнко, 2016), and according to Choi et al. (2020) consensus on this issue was reached among 97-98% of climate experts. Several scientists believe that as a result of irrational economic management and industrial production, neglect of the rules of economical use of natural resources and violation of the natural balance of ecosystems, favorable conditions have been created for increasing the emission and accumulation of greenhouse gases in the atmosphere (that is, those that are able to absorb infrared radiation from the Earth's surface and to keep it in the surface layer of the atmosphere like a blanket), as a result of which the so-called "greenhouse effect" was artificially created on a planetary scale (CO_2 is considered the main greenhouse gas and the culprit of global warming). Thus, Houghton (2005) points out among the main causes of global warming the excessive use of combustible substances (mainly coal, oil, natural gas) in the transport sector, agriculture, industrial production and housing and communal sphere, as well as the rapid pace of deforestation. Khandekar et al. (2005) blame urbanization and irrational land use. The above-mentioned human activity gives an excessive emission of carbon dioxide into the atmosphere, while the destruction of the natural "lungs of the planet", which ensured the disposal of these emissions, nullifies the possibility of self-regulation of the concentration of greenhouse gases (especially carbon dioxide) in the atmosphere. Therefore, several scientists emphasize that reforestation is one of the effective ways to combat global climate change and reduce the negative impact of rising temperatures on natural and artificial ecosystems (Pozniak & Hnatyshyn, 2021).

However, the anthropogenic concept has opponents who believe that in recent centuries we have witnessed cyclical climate change that was inevitable regardless of human activity. Several researchers see the cause of changes in the climate of the planet in the current position of the latter relative to the Sun, the displacement of the barycenter and the axis of rotation, the change in the duration of the perihelion, the processes of differentiation of matter inside the planet, the activity of volcanoes, changes in the income of solar radiation and the intensification of solar activity, etc. (Broecker & Denton, 1990; Khandekar et al., 2005; Корзун, 2009; Войціцький, 2018).

One of the hypotheses indicates the cyclic nature of climatic changes in terms of natural alternation through certain intervals of time (according to various calculations within 20-50 years and during the analysis of age periods – 60-80 years) of cool-wet and warm-dry periods. Such hypotheses were put forward and supported by numerous scientists of the nineteenth and twentieth centuries (Боголепов, 1907; Кинд, 1976; Дружинин, 1987). The hypothesis of irregular climatic cycles of warming/cooling of the planet is also expressed by modern scientists, who testify that the study of processes in a geological-historical section throughout the history of the Earth's existence indicates the absence of a significant correlation between the global air temperature and the concentration of carbon dioxide in the atmosphere (Khandekar et al., 2005). However, it is impossible to clearly trace and predict climatic cycles due to a huge amount of cosmic and internal planetary factors that affect their duration and intensity, and therefore climatic cycles often overlap each other and do not have clear boundaries, developing according to the type of oscillations (Дроздов & Григорьева, 1963). If this hypothesis is indeed correct, then it is impossible to blame anthropogenic activity and related greenhouse gas emissions for modern climate change. For example, Дудник (2010) claims that natural climatic cycles caused the appearance of a cool-humid phase of the age-scale climate from the beginning of 1978-1979 to 2005, which was followed by the warm-dry phase, the beginning of which fell on 2005-2007, the maximum – for 2011-2015, and the end is predicted in 2025-2028, regardless of the anthropogenic impact and the amount of greenhouse gas emissions. However, it is worth noting that the drawback in the theory is quite evident – warming did not reach its maximum values in 2011-2015, it continues to gain momentum every year. In addition, we see numerous confirmations and scientifically substantiated evidence that greenhouse gas emissions influence the regulation of the planet's climate to some extent, and therefore the question is still open and debatable.

There is also a theory of global warming, based on the hypothesis of the planet's exit from the Little Ice Age, which lasted, according to scientists, within the fifteenth and nineteenth centuries. There are certain facts that confirm the additional impact on the climate of the planet of powerful oceanic currents, for example, El Niño (Адаменко, 2009). Oceanologists consider the World Ocean to be the main climate-forming factor of the planet (Іванов та ін., 2004). In some way or another, anthropogenic activity, along with natural factors, remains one of the driving forces of modern climate change. However, the reasons for the rapid warming of the planet's climate in the period of 1925-1944 remain rather vague, since during this period the emission of greenhouse gases from human activity was much lower than it is now. Researchers attribute climatic changes in such early periods to the combined influence of both anthropogenic activity and extremely rapid growth of intraplanetary multidecadal variations in the World Ocean-Atmosphere system, volcanic and solar activity, as well as the presence of sulfate aerosols in the atmosphere, which led to the release and contributed to the accumulation of additional thermal energy (Crowley & Kim, 1999; Free & Robock, 1999; Tett et al., 1999; Delworth & Knutson, 2000).

It is difficult to say with certainty which of the scientific groups is right about the main driving force of climate change. But in no case are skeptics and people who would deny the very fact of global warming becoming less and less, so obvious are the processes of weather transformations in all regions of the world. It is quite likely that there is a rational idea in both anthropogenic and other hypotheses of climate change. In our opinion, the most complete understanding of the cause-and-effect chains of global warming can be obtained through a harmonious combination of all concepts.

In addition, it is interesting that recent studies do not fully support the widespread theory of a one-sided main effect of carbon dioxide on global warming, prevalent in the current scientific and popular literature. For example, at the end of the XIX century Svante Arrhenius calculated that a doubling of the concentration of

CO_2 in the atmosphere would cause a rise in the global average annual air temperature on the planet by 4-6ºC. However, these calculations have been proven wrong. It was established that there is a very complex relationship between the isolated concentration of carbon dioxide and the temperature of the air, which is not at all linear or even parabolic, as it was believed based on the first calculation models (Чиабришвили & Салуквадзе, 2010). Thus, Florides & Christodoulides (2009) proved that the strength of the regression relationship between the concentration of atmospheric CO_2 and the temperature of the surface layer of the atmosphere is sensitive to the input data set and, therefore, it is impossible to say with certainty about the degree of influence of carbon dioxide on the change in the temperature regime of the planet. Scientists also emphasize that CO_2 has not only negative, but also positive effects on climate and maintaining the stability of the biosphere.

At the same time, the effects and degree of influence on the climate parameters of the planet of the remaining greenhouse gases (methane, nitrogen oxide, organic compounds, water vapor, etc.) have been studied relatively little due to the excessive concentration of attention of the scientific community on carbon dioxide (Houghton, 2005). Recent studies have proven the great role of methane in the formation of climate changes in general and the greenhouse effect in particular (Діаковська, 2019). By the way, the main greenhouse gas, which is neglected for unknown reasons by the vast majority of scientists and forecasters, is water vapor, which has the highest concentration in the atmosphere (up to 36-70%) and a significant nominal contribution to the greenhouse effect (Монин & Шишков, 2000; Авакян, 2017). Therefore, deviations in the plan of studying the influence of greenhouse gases and in the formation of policies to combat the greenhouse effect, neglecting the comprehensive effects of each of the gases on the atmosphere and the temperature regime can cause errors in forecasting the development of climate change and, as a result, the development and implementation of irrational and ineffective measures to combat global warming (Prentice et al., 2001). In addition, it is worth recognizing the correctness of scientists who claim that even the most advanced mathematical models are not able to describe in detail the course of all processes in the atmosphere, which imposes certain limitations on climatological assessments and forecasts, and therefore the mutual cooperation of climatologists, ecologists, biologists, and mathematicians, who are able to offer the best statistical tools for the assessment and forecasting of complex phenomena, is an absolutely necessary prerequisite for successfully solving the problematic issues of global warming (Уайт, 1990).

A special attention is paid to the forecasts of the future scenario of the development of climate change both on the planetary and regional scales. The picture of forecasts looks extremely colorful, because depending on the mathematical apparatus used by the researchers, the volume and quality of the input data chosen for the forecast, taking into account or neglecting the mitigation factors of the negative anthropogenic impact on the climate, the results differ several times: the minimum predicted increase in the average annual temperature of the surface layer atmosphere according to some forecasts will be only +1.6ºC, while according to others it will reach +6.9ºC (Cubasch et al., 2001; Betts et al., 2011). Fyfe et al. (2013) also testified that some prognostic models for estimating the global growth of the average annual air temperature on the planet excessively overestimate its real increase, since the simulated values of temperatures, when further checked by real increases, differ significantly. At the same time, several models underestimated the intensity of global warming. So, for example, at the beginning of the XXI century, optimistic models were developed that predicted an increase in air temperature of only 1.1ºC, which is an unrealistic scenario at the current stage of the development of climatology and according to the latest observations (Bernstein et al., 2008).

IPCC experts consider the most realistic scenario of a temperature increase of +2-4ºC by the end of the XXI century, especially if no global measures are taken to curb the pace of climate change. If none of the countries that have the maximum contribution to the emission of greenhouse gases and atmospheric pollution will not adhere to environmental protection policies, then the probability of the worst (warming by ≥+4ºC) scenario of the development of global warming of the climate will increase. According to the project calculations of IPCC experts, if the current trend in the carbon cycle of the planet is not changed, the +4ºC mark on the global thermometer will be reached already in the early 2060s. Note that the starting point for calculating the temperature increase is the average annual air temperature on the planet for the period 1980-2000 (Betts et al., 2011).

Additionally, to provide an example, the results of the expected level of increase in the global mean annual air temperature as of the 2090s relative to the period of 1861-1890 according to the data of two expert groups, performed according to the HadCM3-QUMP and the IPCC AR4 GCM models and input data set (Table 1.1. 1). There is a significant difference in the level of global temperature rise according to different forecasts, however, the scenario with a warming of ≥+4ºC is still the most likely (Betts et al., 2011).

Table 1.1.1

A comparison between the forecasted raise in the global mean annual air temperature up to 2090s relatively to the period of 1861-1890 by the project calculations of HadCM3-QUMP and IPCC AR4 GCM

Project calculations	The forecasted raise in the global mean annual air temperature, ºC			
	mean	median	minimum	maximum
HadCM3-QUMP	4.0	4.0	2.4	5.3
IPCC AR4 GCM	3.2	3.2	1.9	4.9

Global climate change has a comprehensive impact on ecosystems sustainability, which is recommended to be assessed by the parameters such as sensitivity, adaptive capacity and vulnerability (Houghton, 2005). So, for example, due to the global increase in the temperature of the surface layers of the atmosphere and the World Ocean, glaciers are melting, the water level of the World Ocean is rising, the agro-climatic zoning of the planet is changing due to climatic shifts in the temporal and spatial distribution of precipitation, the temperature regime, the frequency of extreme weather events is increasing, decreasing availability and quality of fresh water, migration of species occurs, biodiversity decreases, a number of species of flora and fauna are at risk of extinction, living conditions and economic activities of people deteriorate, the incidence of infectious, cardiovascular, pulmonary diseases, etc. increases (Шевченко, 2014; Войціцький, 2018; Дєрябіна & Уманська, 2020).

Global warming is a phenomenon of a planetary scale, and therefore it is important to develop a single package of regulatory documents that must be followed by all the countries of the world to overcome the negative consequences of climate change and reduce the rate of increase in the average annual temperature on Earth. So far, this task remains unresolved. There have been many attempts to create an international commission on climate policy; however, views on the necessary measures to mitigate the consequences of the existing ecological crisis differ on many issues (which may be directly related to the above – the scientific community still does not have a final decision on the nature and the main driving forces of global warming), a single strategy and strict regulations for countering the negative anthropogenic impact on the environment have not been developed, and a number of countries in the world do not want to participate and act in accordance with accepted protocols and regulations (Жилина, 2019). All this gives rise to doubts that in the coming years it will be possible to achieve an effective and radical impact on the global emissions of pollutants, greenhouse gases, change the attitude to deforestation, etc. However, even in a situation of uncertainty about the causes of climate change, it is worth listening to the "fuse principle", voiced back in 1992 in Rio de Janeiro: "In the event of the existence of a danger of serious and unavoidable damage, the lack of complete scientific information cannot serve as a reason for postponing effective measures with prevention of environmental destruction" (Корзун, 2009). Kyoto Protocol of 1997was potentially able to change the situation for the better, but it was not ratified by all countries of the world (Адаменко, 2009). The Paris climate agreement, which was adopted in 2015, formally obliges all states to reduce emissions of pollutants and greenhouse gases, but in reality, we see that a number of countries violate the requirements of this agreement and do not care about limiting the emission of air pollutant compounds (Барабаш, 2019). Furthermore, several developing countries, which are powerful emitters of greenhouse gases, cannot quickly and effectively transition to innovative production technologies, are unable to independently ensure the reduction of pollutants due to the transition to alternative energy sources, because they lack financial and technical and technological resources, therefore the problem of reducing greenhouse gas emissions falls heavily on the shoulders of the most developed countries of the world, which, on the one hand, understand their role in ensuring the climate stability of the planet, and on the other hand, are not ready to happily spend their money to support climate initiatives in states in less developed countries (Басок & Базєєв, 2020).

As it was mentioned above, climate changes affect all branches of the national economy and all aspects of human life (Грищук, 2020). However, the agricultural sector, as it is closely related to the natural component and is extremely dependent on soil and climatic conditions, will suffer from climate changes perhaps the most. The burden on the agrarian sector of the economy is also increasing due to the rapid growth of the global population, the shortage of food products and the global ecological crisis associated with the shortage of natural resources (Оноприєнко, 2016).

First, this is true for the changes in the distribution of production by regions of the planet, in the structure of agricultural production and the paradigm of development of the agroindustrial complex, as well as changes in the types of products and the increase in the uncertainty of their production (Светлов, 2018).

Global warming affects all branches of agricultural production. For example, the impact of climate change on the production structure and productivity of fish farming has been proven (Кляшторин & Любушин, 2005). However, the crop production and agriculture will suffer the most. The productivity of agrophytocenoses is significantly dependent on air temperature, available moisture, and CO_2 concentration in the atmosphere. A particularly clear trend toward changes in the growth of biomass with an increase in the concentration of carbon dioxide in the atmosphere was established during the study of the long-term (from 1800 to the present) dynamics of the development of forest plantations. Global warming gradually changes the photosynthetic activity of plants, the intensity of their respiration, the efficiency of moisture use, the intensity of metabolic processes, and the processes of decomposition of organic matter in the soil. All the factors listed above are crucial for crop production (Keeling et al., 1996; Myneni et al., 1997; Cannell, 1998; Hughes, 2000). But there is still no consensus on whether an increase in the concentration of CO_2 in the atmosphere will have a positive or negative effect on the growth processes and productivity of agricultural crops. For example, Cline (2008) believes that if measures are not taken to reduce carbon dioxide emissions into the atmosphere, the productivity of the crop industry will decrease significantly, especially in developing countries, because in these countries, the possibilities of rapid response and the introduction of adaptive agricultural technologies are limited. At the same time, Florides & Christodoulides (2009) believe that CO_2 is a growth stimulator for vegetation, as well as a factor in the evolutionary change of plant physiology.

Currently, the consequences of global warming are obvious in all of the territory of Ukraine. They cause significant fluctuations in the productivity of the agricultural sector (Таракіко та ін., 2020). The process of decontinentalization of the climate is already taking place, its warming within the range of 1.5-2.0ºC is predicted and mainly due to the winter period (Ліпінський, 2002). This is also evidenced by the data of other studies: Northern and eastern Europe suffer the most from rising temperatures in the winter period, and southern Europe (the countries of the Mediterranean basin) in the summer (Vautard et al., 2014). However, each agroclimatic zone has its own subtleties and specifics of the manifestation of global warming.

By some forecasts, part of the agricultural land in the Odesa, Kherson, and Mykolaiv regions may be flooded due to the rise of the water level in the World Ocean and, in its turn, in the Black Sea (Грущинська, 2019). According to various scenarios, the global rise in the level of the World Ocean is predicted at the level of 0.10-0.85 m by the year 2100 (Crunch et al., 2001). Marshes in the Dnieper, Danube, and Dniester deltas may also find themselves under water. The southern part of Odesa may later be cut off from the mainland of the region by the Black Sea (Барабаш, 2019). The increase in the number of days with adverse extreme weather events (drought, dry spells, hail, stormy winds, etc.), which is predicted by various climate models, will also negatively affect the productivity of agricultural production (Бондаренко и др., 2018).

In general, the question of changing the availability and distribution of water resources due to global climate change is extremely relevant. Global warming has a direct impact on the water regime of rivers, forms runoff parameters, affects the level and mineralization of groundwater (Шахман & Лобода, 2016; Пічура та ін., 2018). In Ukraine, the highest probability of significant hydrological drought in summer will be observed in the Ros, Sula, Southern Bug, and Siverskyi Donets rivers ((Шахман & Лобода, 2010; Шахман, 2020). The redistribution of water resources both in time and space under the influence of global warming is not in doubt (Вакалюк & Назаров, 1991). In addition to the water resources themselves, the components of the water management balance will suffer from changes, which will require a reassessment of the conditions of operational water management proncíples (Сиротенко, 1991; Шикломанов & Линз, 1991), especially because according to the forecasts, an increase in water resources and improvement of their quality is not expected on the territory of Ukraine in the forthcoming years. On average, it is quite probable that the climatic runoff in Ukraine will decrease by 25% and in the southern regions by 50%, which, under current trends, may lead to zero river flow in the south of the country (Гопченко & Лобода, 2000). According to the calculations of Лобода та ін. (2015) by 2030, Ukraine expects an increase in available water resources by 60-80% in the North and North-East, as well as by 40% in the Central region. In Transcarpathia and Bukovina, the availability of natural water resources may decrease by 20-30%, and the aridity of the climate was predicted to increase by 3% by 2025 (Лобода та ін., 2011).In the Carpathians, in the Prut river basin, there is a trend towards an increase in the mean annual air temperature and a slight trend towards an increase in the amount of precipitation (mainly in mountainous areas), the climate is characterized as moderately continental, with a trend towards an increase in the amplitude of seasonal air temperature fluctuations (Струк та ін., 2017). At the same time, the maximum decrease in the volume of available water resources will be observed in the South of the country (Kherson region, steppe zone of Crimea) and will reach a maximum of 40% in Odesa region, where especially significantly in recent years there has been an increase in thermal surplus in the autumn-winter period of the year (Дєрябіна & Уманська, 2020). This will put the production of plant products in the nonirrigated areas of the South at risk and will reduce the guarantees of Ukraine's food security. The negative impact of the redistribution of water resources on the territory of the country is already being felt, resulting in a periodic decrease in the gross production of crop production due to intensive droughts in some regions and excessive rainfall in other regions, mass damage by pests and diseases, leaching, wetting, loss of soil fertility and erosion, etc. (Нечипоренко, 2020). Only economical, integrative, and intelligent water use can reduce the vulnerability of all sectors of the economy to the shortage and deterioration of the quality of water resources (Arnell & Liv, 2001).

At the same time, the study by Trenberth et al. (2014) proved that global warming should not be associated with a global risk of aridification, and previous conclusions about such a scenario may be erroneous and related to the imperfection of the assessment, which is performed mainly by the Palmer Drought Severity Index (PDSI). In addition, problems of the quality of forecasts depend significantly on the set of input meteorological data and the mathematical apparatus. However, researchers emphasize that climate change will lead to more intense and rapidly increasing periods of drought in those regions of the planet where they will take place. It is important to emphasize that anthropogenic activity does not affect the spatial distribution of droughts but can cause them to intensify in vulnerable parts of the planet (Hoerling et al., 2010; Dai, 2011).

The uneven distribution of precipitation in time and space will have a significant negative impact on the productivity and sustainability of agroecosystems. For example, in Ukraine, an increase in the amount of precipitation is predicted in the autumn-winter period along with an increase in the aridity of the summer period (Онопрієнко, 2016), which is completely consistent with the results of prognostic studies by European scientists. Thus, Vautard et al. (2014) indicate a significant increase in the amount of precipitation in Central and Northern Europe in the cold period of the year (in the north – even in summer), while the countries of the Mediterranean basin will suffer from a deficit of precipitation in the hottest summer period. Showers and hailstorms will be observed more and more often on the territory of all European countries (except southern ones), regardless of the season. Spring (maximum increase in evapotranspiration) and summer will be the driest periods of the year (Vautard et al., 2014).

Climate change will not only affect meteorological conditions but will also indirectly affect soil properties and fertility. Thus, it has been established that the hydromorphic soils of Central and Central Asia have high risks of intensification of salinization processes under the influence of global warming (Панкова & Конюшкова, 2013). Global warming is an additional factor in the acceleration of humus loss and, therefore, an important integrative method of counteracting the negative impact of climate change on soil cover is the tandem of plant and animal husbandry, when due to a rational system of animal grazing on meadows and pastures and the introduction of high-quality organic fertilizers, scientifically based norms will create prerequisites for positive balance of organic matter in the soil (Pozniak & Hnatyshyn, 2021).

Transformation of soil and climatic conditions under the influence of global climate change will affect the optimal composition of species and the variety of cultivated plants. Therefore, in many regions of Ukraine, due to the lack of natural humidification and insufficient irrigation supply, drought resistant crops such as millet, sorghum, and chickpeas will have an advantage over others. Perhaps the crops of southern latitudes, for example, peanuts, will become more popular. The percentage of spring cereal crops in the structure of sown areas will increase. This is due to the different responses of cultivated plants to extreme weather conditions. According to the study conducted in Germany, corn was the most sensitive to adverse meteorological factors, and the least negative reaction was recorded in winter rye (Harvey, 2000). Climate-induced yield losses for the period 1981-2002 in the world amounted to 88.2 kg/ha for wheat, 10.5 kg/ha for rice, 90.3 kg/ha for corn, 144.9 kg/ha for barley, 19.5 kg/ha for sorghum. Only soybeans showed positive dynamics; the yield increase was 23.1 kg/ha (Lobell & Field, 2007). Increasing preference will be given to drought-resistant varieties and hybrids of crops.

The approach to soil tillage will also change, the main goal of which will now focus on the maximum accumulation and conservation of moisture, especially if the forecasts regarding the transformation of Kherson Oblast and Zaporizhzhia into a semi-desert, as well as the spread of the steppe zone up to Kyiv Oblast, Zhytomyr Oblast and Khmelnytsky Oblast by 2060, come true (Воровка & Чебанова, 2018). A similar forecast on the transformation of the climate of the South and the East into a semidesert (now referred to as the steppe zone), and the climate of the North into a steppe (now called the forest steppe) can be found in other works of Ukrainian scientists (Мельниченко & Трохименко, 2009; Онопрієнко, 2016).

Furthermore, the current trend towards soil carbon sequestration, established in 2019 at the French international conference, designed to offset the emission of greenhouse gases (in particular, CO_2) by absorbing them into the soil creates a favorable environment for the transition to the latest tillage systems, in particular, no-till systems (Pozniak & Hnatyshyn, 2021). However, it should be mentioned that no-till systems will not always have a beneficial climate effect, because on poorly aerated soils, zero tillage leads, along with a decrease in carbon dioxide emissions, to an increase in emissions of other greenhouse gases, in particular, N_2O (according to the data of 45 years of the study – by 0.12-2.00 kg/ha), which is more dangerous, since this greenhouse gas is not disposed of in nature, and instead of an ecologically positive one, we get a negative balance of greenhouse gases (Rochette, 2008). However, in well-aerated soils, the risk of obtaining a negative balance in terms of N_2O emissions is minimal. Therefore, thorough research on this issue is necessary on each type of soil under different agrotechnological conditions of growing agricultural crops for full confidence in the safety and ecological feasibility of no-till technology.

The shortage of natural humidification in the southern region is believed to pose a threat to the sustainable production due to a significant decrease in the productivity of agroecosystems on nonirrigated lands (Грущинська, 2019). Сиротенко и др. (2011) agree with this, predicting a possible decrease in the yield (as of 2050) of spring crops in arid areas up to 20%, winter crops – up to 7%, and cereals in general – up to 14-15%. According to other estimates, warming by 1°C will lead to a 10% decrease in the yield of wheat, rice, and corn (Бондаренко и др., 2018). Lack of moisture and neglect of soil protection rules are the main factors of negative impact on the productivity of the crop production industry in Ukraine (Оглих & Левченко, 2011). Mathematical modeling of grain crop yield in the Sumy region confirmed a negative correlation with temperature and a positive correlation with precipitation (Оноприєнко, 2016).

The estimate of the expected decrease in the productivity of the crop production sector in various countries of the world until 2099 indicates a trend towards a global decline of the latter within the range of 4-35%. None of the countries studied will benefit from further climate change. There will be a minimal impact on crop production in Canada and a maximum impact on Mexico and Ethiopia (Cline, 2007).

Even the slightest climate change will lead to a significant drop in crop productivity, especially in southern latitudes, where, according to the forecasts of climatologists, the most intensive process of aggravation of aridity is expected. For example, according to IPCC forecasts, complete desertification of a number of Mediterranean regions is possible in Europe, while a number of countries in northern latitudes (for example, in North America) will suffer from excessive precipitation and extreme events in the form of showers and hailstorms and can also expect to improve conditions for the growth and development of such crops as wheat, rice, and corn (Cubasch et al., 2001). Mid-latitudes will not yet experience significant changes in moisture supply, but later it will be impossible to avoid the negative impact of excessive temperature increase on plants. Experts note that when the temperature increase exceeds +3ºC, the negative impact on all cultivated plants will be felt in all latitudes, even in the northern ones (Kerr, 2007). Currently, the increase in the value of the average annual temperature of the surface layer of the atmosphere is maximum in the countries of Europe, North America and in the south of Australia – it is in these regions of the planet that the consequences of global warming can be truly devastating in the forthcoming decades. At the same time, extremes in the opposite direction (excessive winter cooling) are observed only in the eastern part of North America. It is interesting that modern global warming is characterized by significant unevenness: it is more pronounced in the northern latitudes, and according to the seasons – in the winter and, more recently, the spring-summer periods. The intensity of the process is higher over the continents than over the surface of the world ocean. The high variability of seasonal trends over the years complicates the forecasting of the future climate change scenario (Груза и др., 2015).

For a better understanding, it is worth explaining the essence of the concept of aridity aggravation (desertification) of the climate. It is understood as a decrease in natural atmospheric humidification due to the lack of precipitation, an increase in the frequency and intensity of drought periods, an increase in the radiation regulation of the earth's surface temperature with the subsequent impact on the surface layer of the atmosphere (Золотокрылин, 2019). The degree of aridity aggravation can be assessed by various methods, but currently the most popular in the world community are the aridity index (AI), the standardized precipitation index (SPI), the standardized total evaporation and precipitation index (SPEI), as well as the above-mentioned Palmer drought severity index (Otterman, 1974; Hayes & Wood, 2012). An aridity radiation index was developed on the territory of the USSR (Будыко, 1977), but it did not gain popularity. Additional and promising methods are based on the data of remote sensing of the Earth, for example, the satellite index of climatic extremes of moisture (Золотокрылин & Титкова, 2012). Furthermore, a satellite index sensitive to climate change is the normalized differential vegetation index (NDVI), which is widespread and is used for scientific and practical purposes (Золотокрылин, 2019). The forecasts on the growth of desertification rates for the coming years do not cause doubts. However, in the opinion of some scientists, it is premature to make a final assessment in the long term (more than 50 years ahead), since even the most advanced mathematical models cannot take into account absolutely all climate-forming factors and possible changes in their activity (especially considering the great variety in approaches to determining the degree of natural moisture deficiency), and therefore aridity aggravation, even in areas where it already occurs and continues, might be a reversible process, which means that a certain probability of improvement in moisture conditions remains even in the most arid regions of the planet (Mortimore et al., 2009).

In the work by Cook et al. (2014) it was shown that the greatest risks to the increase of climate aridity according to the values of the PDSI and SPEI indices will be observed in northwest America, Central America, Mediterranean countries, South Africa, and the Amazon region. At the same time, a significant improvement in moisture supply is likely to take place in the countries of northern latitudes, as well as in East Africa (only in terms of PDSI). The authors also note the unequal sensitivity of the applied climate aridity assessment indices: SPEI appears to be more sensitive to changes in evapotranspiration, which, according to the study, is the main driving force behind the increase in climate aridity in a number of regions of the planet.

It is interesting that the concept of drought can be used in different contexts and evaluated by completely different methods, just like the level of aridity. The difference between aridity, aridity and drought is that the latter is a separate meteorological phenomenon, while the first two concepts are used when describing the climatic features of territories (Лобода та ін., 2011). Meteorological drought is a period when the annual amount of precipitation is less than the average long-term norm (Разии и др., 2005). Agricultural drought is a period in which the water availability of the soil for cultivated plants is reduced to a level that has a negative impact on their productivity.

Climate change affects such an important technological factor in the production of plant products as the optimal terms of sowing and planting of cultivated plants. It is natural that significant shifts in the temperature curve make it necessary to review the terms of the aforementioned technological operation to ensure the best agro-ecological parameters for the growth and development of plants, the maximum disclosure of their genetic productivity potential. So, for example, a number of authors recommend revising the optimal sowing dates of winter wheat in Ukraine, especially in the arid regions of the South, where it is important not only to prevent the overgrowth of the crop in the autumn period in years with an unusually warm autumn-winter period, but also to ensure friendly and strong germination on non-irrigated lands, where due to significant warming and increasing aridity of the summer-autumn period of the year, a high moisture deficit in the soil may be observed, which will create an impediment for the normal germination of crop seeds and inhibit its initial development (Тищенко та ін., 2020).

In addition to optimal sowing and planting terms, the temperature regime also affects the intensity of growth processes. Thus, high temperatures stimulate most crops to accelerate growth and development, as a result of which yields will decrease (Cline, 2008). This factor will be decisive when choosing varieties and hybrids with a certain duration of the growing season.

In the conditions of global climate change, the structure of sowing areas by agro-ecological zones, the composition of cultivated crops, as well as the crop rotation system, which should provide a climate stabilizing effect at the highest possible level of productivity of agro-ecosystems, will require revision (Pozniak & Hnatyshyn, 2021). The fertilization system will also be subject to review, where the role of organic and biofertilizers will increase, and the application of mineral fertilizers will be clearly regulated according to the risks of excess greenhouse gas emissions. The high prospects in the new conditions of crop production also open up to green manure (Pozniak & Hnatyshyn, 2021).

Inevitably, under the influence of temperature increase during the growing season, the prevalence of certain fungal and viral plant diseases will increase. For example, researchers predict an increase in the area of distribution and an increase in the intensity of damage to plants by fusarium wilt, septoriosis, types of rust (the appearance of more aggressive races is possible) on cereal crops, cercosporosis and ramulariosis of beets, alternariosis, late blight of potatoes and tomatoes, helminthosporiosis of corn, etc. The appearance of new pathogens, for example, yellow spotting of wheat leaves, is predicted (Левитин, 2012). The situation with an accurate forecast of the development of harmful organisms on crops will become more complicated, requirements for the frequency and quality of phytosanitary monitoring will increase, etc. It will be much more difficult to control the spread of fungal diseases and to carry out measures for the chemical protection of agricultural plants against diseases because many fungicides, mainly systemic, will have lower effectiveness in the new climatic conditions. The shortened winter period will contribute to the more intensive development of pests, the number of their generations per year will increase, and new species of harmful insects from the southern latitudes will be more easily introduced, and protection against them will become more difficult due to the decrease in the effectiveness of insecticides of a biological nature and from the group of pyrethroids. Therefore, in terms of tackling harmful organisms, the importance of agrotechnical measures, especially rational tillage, will increase again (Боума, 2012). Therefore, in no case should the rules of rational use of plant protection products against pests and diseases be neglected, since saving on planned treatments with insecticides and fungicides under favorable temperature conditions can lead to the explosive development of phytopathogenic organisms in the future. In addition, biological means of plant protection cannot be completely neglected, as well as a rational approach to the formation and observance of crop rotations (Домарацький & Козлова, 2021).

Weed control will also become a problem. Weeds adapt to dynamically changing environmental conditions faster than cultivated plants, and most weeds of the southern ecotype react to increasing air temperatures by intensifying growth, development, and reproduction. An additional problem will be a decrease in the effectiveness of glyphosate and most water-soluble herbicides in new weather conditions, since high temperatures will prevent effective penetration of active substances into weed tissues (Боума, 2012).

Orchards also suffer from the consequences of global warming. Great temperature fluctuations in the autumn-winter period, unpredictable spring frosts, hail, drought – all this negatively affects the health and productivity of the orchard. In addition, warming promotes the activation of rodents that damage the trunks of fruit trees, which requires more careful care in terms of wrapping the trunks with a special film or net. The use of rodenticides will increase, along with the above-mentioned increase in preventive treatments against diseases and pests during the growing season. To level the negative impact of sharp temperature fluctuations, it is worth using mulching materials and shelter. The requirements for the quality of pruning will increase and the terms of its execution will change, which will require retraining and upgrading the qualifications of agronomists and gardeners (Постоленко, 2020).

However, one cannot fail to note the positive changes associated with global warming. So, for example, according to the data from Kherson Regional Hydrometeorological Center, the duration of the meteorological winter and the increase in the duration of the meteorological summer are observed in Kherson oblast. At the same time, the spring and fall periods remain unchanged. This results in an increase in the duration of the growing season in the region, which, under the conditions of adaptation and optimization of agricultural technologies, the use of irrigation, will allow easy to obtain two (and sometimes even three) yields of certain crops (potatoes, corn, vegetables), as well as to expand the arsenal of cultivated plants by the species from southern latitudes, including citrus fruit crops and promising cotton. In terms of plant protection, along with many problems listed above, positive points as increasing the effectiveness of contact fungicides and fungicides from the azole group can be observed. In addition, a change in the ratio of carbon and nitrogen in plant tissues will help phytopathologists: global warming will contribute to an increase in the relative carbon content in plants, which, in its turn, will become an inhibitory factor in the development and spread of such diseases as powdery mildew of cereals and potato blight. At the same time, in areas with a sufficient level of natural moisture and on irrigated lands, the increase in temperatures will contribute to the improvement of the effectiveness of soil herbicides, which, unfortunately, will become irrelevant on non-irrigated lands of arid regions (Боума, 2012). In addition, an increase in the efficiency of electricity production from alternative sources (primarily solar and wind energy) is expected, which will contribute to the greening of production and the reduction of the price of "green" energy.

To ensure the sustainable development of crop production in the new conditions of farming, the following tasks must be solved (Оноприєнко, 2016):

- to develop innovative adaptive technologies for crop cultivation considering new climatic conditions and modern requirements for product quality;
- identify climatic factors that are critical to agricultural crops and find ways to overcome or minimize their negative impact on productivity;
- to adapt agricultural technologies to the new conditions of the planet's agrosphere.

It is important to note that the effectiveness of the adaptation of the agricultural sector to new climatic conditions will largely depend on the accuracy of regional forecasts of changes in meteorological parameters and their integration into the models for forecasting the growth and development of cultivated plants, as well as on the appropriate scientific support of agricultural technologies (Сиротенко и др., 2011).

Generalized recommendations for the preservation of the flora of Ukraine and the world, which, along with the development of the agro-industrial complex, is an important task for ensuring sustainable development, were successfully claimed by Компанець (2021):

- education and science should serve to increase responsible and a conscious attitude to the environment;
- creation and strict supervision of protected areas;
- restriction and prohibition of deforestation, promotion of preservation and improvement of the sanitary conditions of natural forest areas, increase of their resistance to environmental stressors, especially in the area of the Carpathian forests, which are currently in the most vulnerable state (Стойко, 2009);
- rational use of wood and associated by-products (straw, plant residues, tree bark, branch fragments, etc.) during agricultural and industrial production;

- renewal of existing forest plantations and afforestation of the most vulnerable areas to desertification, renewal and expansion of the system of forest shelter belts;
- economical and scientifically substantiated use of natural resources in the agro-industrial sector, especially water resources and soils;
- land reclamation according to scientifically based programs;
- monitoring the condition of the flora and control over the implementation of appropriate protective and restoration measures.

The adaptation of the Ukrainian agricultural sector to the new and dynamically changing climatic conditions will require a comprehensive approach and should include the implementation of innovative projects and reforms in the spheres of state policy with respect to the management and protection of natural and land resources, the use of the latest GIS and IT in agriculture, a review of the socioeconomic aspects of management and state organizational and legal regulation of economic activity, a new look at the development of rural areas, and the provision of specialized professional education in the field of agriculture (Яремко, 2020).

Taking into account all the stated facts, modern agricultural science has faced a difficult and extremely important issue that needs a quick and rational scientifically sound solution – ensuring food security while preserving biodiversity and reducing anthropogenic loads on the environment and climate in conditions of population growth and a decrease in the amount of available natural resources. To successfully solve this task, it is necessary to monitor and forecast the development of ecological processes in agrocenoses, to closely cooperate with climatologists to determine the current state and the nearest perspective of meteorological conditions for the production of agricultural products, to perform theoretical work on updating irrelevant agroclimatic parameters of agricultural land zoning, to provide tools for effective management of water and other natural resources in conditions of their scarcity, to determine and take into account in the process of agro-industrial production its role as a climate-creating factor, etc.

1.2. Industrialization and informatization in plant science and agriculture

Today, global agricultural production is undergoing significant transformations associated with the sixth stage of industrialization due to the wide implementation of the technological achievements of the fourth industrial revolution. The greatest successes in this regard have been achieved by leading countries as the United States and the People's Republic of China, which can serve as a clear example for other states that seek to switch to the most modern technologies to produce livestock and plant products (Jung & Khoe, 2018).

Industrialization of the agro-industrial complex is inevitable. It is caused by the change in socio-economic requirements and the style of the relationship between the consumer and the producer, scientific and technical progress, and intensified by the recession in the agrarian sector of the economy, which occurred in the 1980s of the last century. The following are the characteristics of the transformation of the agricultural sector of several countries, the positive and negative sides of the process.

It is generally accepted that the industrial development of agricultural production is most likely to have a positive effect on the agroindustrial complex and food security. Most people understand the industrialization of agriculture as the transition to a manufacturing style of production. However, such a view is very limited since, in fact this concept includes a complex of structural, organizational-economic, technological, and sometimes even political changes, the ultimate goal of which is to overcome the food crisis, economic growth, and environmental protection (Urban, 1991).

The first mentions about the industrialization of agricultural production appear in the scientific literature immediately after the end of the Second World War. For example, Chang (1949) concludes that industrialization, not only of the agrarian sector of the economy, is a necessary and inevitable prerequisite for the further development of production. He emphasizes that agricultural production should receive modern equipment and innovative technologies, but this is not enough to ensure the sustainable development of agriculture. The socio-economic component of village and rural development, care for people employed in agricultural production, should also be subject to improvement. Chang (1949) pointed to the USA, Australia, Great Britain, and the USSR as powerful industrialized countries where the level of mechanization of agricultural production, at that time, reached extraordinary heights. However, even then, the author notes the need for a transition from small family farming, which is common in the USA, to highly concentrated specialized production in large, consolidated farms. In addition, Chang (1949) notes that in countries such as Germany, Japan, France and Belgium, industrialization and improvement of agricultural productivity were not as much associated with the intensification of mechanization as with the improvement of the fertilization system of cultivated plants, the development of new approaches to crop rotation and therefore organizational and economic approaches to improving the efficiency of agricultural production cannot be neglected.

Smith (1985) proposes interesting opinion that successful industrialization requires clear division of labor and its specialization, as well as an understanding that in specific spatial and temporal conditions this division of labor and the degree of its involvement in production will be limited by the level of development product or service market. Thus, industrialization inevitably leaves its footprint on the employment structure of the population.

Historically, the agricultural sector of the US economy has undergone a series of complex transformations, the main driving forces of which were new socioeconomic requirements for the agricultural production against the background of the rapid development of agrochemistry, mechanization, electrification, and informatization, as well as an increase in the need for food to ensure adequate nutrition of a rapidly increasing population (in 1890, the population of the country was only 63 million, while now it exceeds 350 million). First, attention is paid to the gradual increase in the concentration of agricultural production, which is expressed in a significant reduction of agricultural enterprises. For example, in 1954, the US agroindustrial sector was represented by almost 5 million farms, while at the end of the twentieth century this figure barely reached 0.6 million. The changes in the number of agricultural enterprises caused significant changes both in land use and in the basic principles of agricultural production and its promotion on the market. The entire structure of the agrarian sector of the economy has undergone changes. Simultaneously with the concept of industrial agriculture, in the middle of the twentieth century, in the USA, the concept of sustainable agriculture emerged, which emphasized that no industrialization would be successful if it did not aim at the rational use of natural and other production resources, as well as the production of products that would be environmentally friendly and form the basis of a healthy diet. Naturally, there is a contradiction between the maximum profitability of production and its maximum ecological purity. However, the Americans admit that no success in the development of the agroindustrial sector of the economy could be expected without the invention and introduction into production of more and more modern technical means for soil cultivation, sowing and planting, plant care and harvesting, expanding the base of scientific knowledge regarding the formation productivity of cultivated species of plants and animal breeds and their involvement in the production process. Industrialization, which at this stage goes hand in hand with informatization, is the cornerstone of modern agricultural production in the United States. It is interesting that some authors believe that the beginning of industrialization in the USA started at a time when farmers stopped spending all their working time actually on running a farm and began to divide it between agricultural and production activities and providing services to other farmers-compatriots for a certain remuneration. In general, the very process of industrial transformation in the USA took place (and continues until now) reluctantly, meeting certain resistance, especially among hereditary family farmers. There are opponents of the further transition of the country's agriculture to an industrial basis, whose main arguments are a decrease in the quality and variety of food products, neglect of agricultural laws and rules of healthy nutrition for the sake of obtaining the cheapest possible products, significant changes in labor migration and the threat of job losses in rural areas, and the destruction of traditional US family farming. In addition, a number of problematic issues of organizational and legal regulation arose. There is still a fierce struggle between small family farms and the agricultural holdings. There are still disputes about the positive or negative impact of industrialization on the US environment, as well as the problems of improving the countryside and ensuring the socio-economic protection of the rural population. It is worth admitting that objectively, far from everywhere, the industrial production of agricultural products in the USA is equally successful and provides an equally high socioeconomic result due to the high variety of not only agroclimatic, but also socio-cultural conditions and traditions, and even different legislative frameworks in different states of the country (Castle, 1990; Hamilton, 1994).

The concentration of production, the introduction of high-value modern intensive agricultural technologies, the change of vertical management to reduce the cost of production, the reduction of losses from unpredictable adverse factors along with the unification of the production process and the unification of product quality, as well as the lower sensitivity of large agricultural enterprises to adverse economic conditions of management, are the main driving forces of industrialization in the USA. It is interesting that in the process of industrialization in the country, the number of very large and very small farms increased, while medium-sized ones practically disappeared. If at the beginning of the 1990s the share of GDP in the agricultural sector of the US economy of small farms was 94%, then already in 2003 it decreased to 28%. Furthermore, the system of economic relations in terms of forming contracts to produce agricultural products underwent changes (Ahearn et al., 2005).

The industrialization of the agricultural sector changes not only the process of agricultural production and its organizational and legal regulation, but also the model and strategy of agrarian policy in terms of rural development, agricultural science and education. All this happens in response to changes in the economic, political, and social life of mankind, as a reaction to modern challenges.

It is interesting that historically, the industrialization of agricultural production in the developed countries of Western Europe (Great Britain, Germany, the Netherlands) was unevenly distributed in time, certain regions that had more favorable agroclimatic conditions were more successful in terms of introducing innovations in agricultural production. In addition, industrialization changed the characteristics of rural development, and significantly influenced the development of trade and industry in these countries (Jones, 1977). It is believed that the transition to industrial bases allowed developed countries to significantly intensify the production of agricultural products compared to those developing countries. Analysis of the experience of Japan and other developed countries of the world allows us to assert that the above assumption is correct (Hayami, 1969).

Schneider (2011) points out on three main features of industrial agriculture:

- large-scale production with high specialization and homogeneity of products;
- high-tech production that guarantees maximum profits for minimum capital investments;
- vertical integration and strict control of all links of the production process.

Boehlje (1996) emphasizes the following features to tell industrial agriculture from conventional one:

- manufacturing production process;
- systematic approach to production and selling;

- structuring and readjustment of trade and production chains;
- new types of coordination in agricultural activities;
- new types of risks;
- increased requirements to production power and control of production systems;
- total informatization of production processes.

Boehlje (1996) considers the main problem of accelerating the pace of industrialization to be the low level of interest of agricultural producers in the transition to a new level of organizational and economic regulation of the process of production and selling, while they perceive innovative technologies, technical means, new achievements of selection and genetics quite willingly.

However, agricultural industrialization has its opponents among the scientific community as well. Therefore, Ikerd (1993) believes that the industrial agricultural production, the main idea of which is to improve the quality of human life by giving greater opportunities to consume products at a lower price, contradicts the holistic approach of sustainable agriculture development, which perceives the production of products and a person’s life as a whole system and sees the possibility of improving the quality of the latter's life only in relation to the improvement of the functioning of all other constituent elements of this system. The industrial method of production has its advantages; however, it cannot ensure systematicity and comprehensiveness, as it is mainly focused on increasing the productivity of agro-ecosystems at minimal costs, and therefore cannot be considered suitable for the sustainable development of the industry. Glover (1988) believes that industrial agriculture will lead to social disorganization, destruction of the countryside, and related institutions. Savory (1989) also supports the opinion that industrial development is not the right way, a systematic, balanced approach is needed, the only way to achieve stability and prosperity. However, time has shown that the industrial development of agro-industrial production is becoming dominant and in tandem with innovations in other sectors of the national economy, it is able to meet the high requirements of sustainable and environmentally safe production.

Meanwhile, Hendrickson & James, Jr. (2004) testify that industrialization and the associated unification of agricultural production create an unfavorable environment for adopting ethically justified (especially in the livestock and poultry sectors) and rational technological solutions, since small agricultural producers have a limited set of options for conducting economic activities, and as a result of economic pressure, they must use methods that are often undesirable from an ethical and ecological point of view in order not to suffer losses due to the inability to compete with agricultural holdings. For example, Hinrichs & Welsh (2003) point out to a decrease in the rate of biologization and ecologization of technologies in poultry farming due to the industrial development of the industry. In agriculture, most authors associate industrialization with the introduction of genetically modified crops into mass production, although this is not a necessary condition. Certain negative consequences in the initial period of industrialization of the agroindustrial complex (1945-1980) were observed in Germany, namely, contamination of groundwater with mineral fertilizers and pesticides, soil erosion, and deterioration of their physical and mechanical properties under the influence of unreasonably wide use of heavy, powerful tractors and agricultural machines. This was due to the hypertrophied system of industrialization against the background of the idea of reliable food supply to the country. This was especially true in eastern Germany, where, under the influence of the USSR, new achievements in science and technology caused excessive enthusiasm, and human beings were believed to have the right to take everything from nature. This approach created the prerequisites for too aggressive and irrational one-sided industrialization without considering the negative consequences for the environment and the person himself. Now, this bitter experience should be in front of the eyes of everyone involved in the modernization of agro-industrial production, to prevent unwanted deviations in this matter. The general features of the industrialization of agricultural production in Germany at the beginning of the 1960s differed little from the latter in the USA and consisted in the concentration and unification of production, increased mechanization, changes in the structure of the economic sector and organizational and legal forms of management and promotion of products on the market (Bauerkämper, 2004).

Sonka (2003) points out the following major driving forces of agricultural industrialization and informatization.

- differentiation and segmentation of the agricultural products market;
- growing importance of information and information systems in the development of economy;
- strict requirements to environmental protection and products quality from the point of view of biologization;
- appearance of new information technologies based on geoinformation systems, remote sensing and automation in the framework of "Internet of Things" (IoT) technologies.

From the point of view of crop production, industrialization is mainly manifested in the creation of large agricultural holdings that grow a limited number of intensive crops in short crop rotations using the most modern machines and tools for fast and high-quality execution of technological operations (wide-grip units, controlled and programmable tractors, planters, harvesters) according to the most modern cultivation technologies, taking into account the requirements for biologization and rational environmental management (Schneider, 2011). The main goal of industrialization is to increase the productivity of arable land. At the same time, product quality, although certain minimum requirements are set for it, is not the cornerstone of industrial production, which puts it in a certain contradiction to the modern requirements of nutrition and dietetics, since medical experts emphasize that not only the amount of consumed product plays an important role, but also its qualitative characteristics and the nutrients content is incredibly important for human health (Elmadfa & Meyer, 2010; Miller & Spoolman, 2011). Furthermore, a number of scientists are concerned about the fact that industrial farming systems are often not free from the temptation to abuse pesticides and agrochemicals (in particular, mineral fertilizers, herbicides) in pursuit of the maximum productivity of agrophytocenoses, which certainly has a long-term negative effect on the environment, as well as the quality of the products obtained and their sanitary and hygienic safety for consumers (Nicolopoulou-Stamati et al., 2016). The temptation of a comprehensive introduction of GM crops is causing some concern. Therefore, without additional levers of strict control over compliance with current sanitary, hygienic, ecological, and ethical requirements, it is impossible to talk about ensuring food security at the expense of industrialization. Powerful information systems designed to monitor and manage the crop production production process are extremely helpful in this case, providing opportunities for robust control of compliance with all the above-mentioned requirements in the production process and environmental response to anthropogenic intervention. It has been proven that the technologies of precise digital agriculture allow to reduce the amount of pesticides used by 60% and mineral fertilizers by 30%, respectively (Rider et al., 2006). According to Ukrainian researchers, the use of pesticides and agrochemicals can be reduced by 30-50% with the rational use of precision farming technologies (Марчук, 2012; Руденко, 2020). In addition, nonproductive costs of fuel and lubricants are additionally reduced by 15% and even more (Burliai et al., 2020), which additionally contributes to the reduction of agrarian pressure on the current climate situation. Information technologies in combination with modern access to remote sensing of crops create favorable conditions for highly accurate programming of yields and planning of economic activities (Uskov et al., 2020).

Modern agriculture is in the middle of the path of transformation, not only at the technical and technological level, but also at other levels, such as ecologization and biologization of production, changes in the size and organizational form of farms, business models, formation of price policy, marketing and logistics, etc. More and more attention is paid not only to the efficient and rational use of natural resources in the production process, but also to their preservation and restoration. An important tool for ensuring the fulfillment of the tasks set before modern agricultural production is information technology, with the advent of which it is possible to significantly increase the predictability of the behavior of agroecosystems, establish control over them, monitor the use and ecological parameters of resources, etc. Informatization is not only a lever but also the main driving force of the industrialization of agricultural production in the current stage of technological development (Drabenstott, 1995). If earlier the production of agricultural products was considered a matter of experience, skills, and creative approach of the landowner, now this process is scientifically based and carefully controlled, to a large extent unified and routine. An example could be given in the form of precision agriculture, which is gradually replacing conventional farming systems in the developed countries of the world. From an economic point of view, soon, the quality indicators of crop and livestock products may be unified to such an extent that competition between agricultural producers will be possible only in view of the use of increasingly less expensive technologies for obtaining raw materials or finished products (Boehlje & Gray, 2009).

Precision agriculture (according to the terminology of the International Society of Precision Agriculture – ISPA) is a management strategy that involves the collection, processing and analysis of temporal, spatial and individual data and combines them with other important information to support rational management decisions in accordance with the expected variability of farming conditions to increase efficient use of resources, growth of production productivity, improvement of quality characteristics of products, maximization of profitability and ensuring the stability of production of plant products (Бурляй, 2021). Unal & Topakci (2014) add such an element as environmental protection as a result of the rationalization and optimization of the use of natural resources and the adoption of managerial technological decisions. The main goal is to optimize and stabilize crop production (Bongiovanni & Lowenberg-DeBoer, 2004). Among domestic scientists, Савицький (2017) most successfully and closely approximates the terminology of ISPA to the description of precision agriculture: "precision agriculture is a fundamentally new management strategy in agribusiness, which is based on the use of digital technologies, new technical means and involves the implementation of technological measures to grow plants with taking into account the spatial heterogeneity of the field". Федірець (2013) gives a similar interpretation of the concept with a special emphasis on taking into account heterogeneities within the same field. However, some domestic scientists still do not quite understand the essence of precision agriculture, confusing it with adaptive farming systems, climate-oriented agriculture, and yield programming (which also took place in traditional agriculture), which distorts and distorts the true essence of an innovative approach to the production of plant products (Марчук, 2012).

Main goals, pursued by industrial agriculture, are listed in the work by Бурляй (2021). Analyzing the experience of domestic and foreign scientists and specialists, he proposed the following key positions of industrial agricultural development:

- increasing the efficiency of the use of core and revolving funds of production;
- increasing productivity and labor conditions;
- improvement of agricultural enterprise management;
- improvement of operational planning, control and adjustment of the production process;
- cutting production costs;
- improvement of environmental and economic efficiency of agricultural technologies;
- rational environmental management;

- maximum intensification and automation of the production process based on innovative agricultural technologies;
- increasing the competitiveness of production and new marketing approaches to the sale of products.

The modern process of plant production is largely a digitized process based on modern information technologies, which provide a new, extremely high level of optimization of the use of production resources, cost reduction and improvement of the productivity of agrophytocenoses. However, scientists emphasize that "bare" technologies without adequate scientific support and professional management cannot guarantee their practical effectiveness, since the wrong understanding and use of huge flows of information, inept adjustment of equipment, and incorrect interpretation of data can bring harm rather than benefit. Therefore, great attention is now being paid not only to the development of agricultural information systems based on IoT, but also to the formation of specialized agricultural information management to ensure their optimal and highly efficient functioning (Yan-e, 2011). Currently, the transition to IoT technologies in the greenhouse sector of the PRC made it possible not only to implement intelligent management and remote control over all links of the production process, but also to reduce the water consumption of cucumbers by 37.5 mm, to reduce the general rates of application of mineral fertilizers by 150 kg/ha, and the volume of use of plant protection products by 35%. All these facts, along with a high level of automation and ecologization of production, allowed the increase in the profitability of cucumber greenhouse production by 3.1 thousand dollars US per year (Anonymous, 2020). IoT-greenhouses use such innovative technical and technological means as acute microclimate sensors, a service engine, moisture balance modules, SmartPAR wireless control systems, robotic monitoring systems for nutrient deficiency and damage to plants by diseases, pests, etc. All these achievements would be impossible without the presence of highly qualified personnel who skillfully configure and operate agar information systems (Дишкант, 2020).

It is important to understand the specifics of innovative development based on informatization and the digital economy in each individual branch of national production, especially in such extremely complex and complicated, closely related to natural potential industry as the agroindustrial complex, which, moreover, in a number of countries of the former USSR is technologically run down, and cannot be renovated without foreign experience, investments, and technical equipment that must be considered during the digital transformation of agricultural production (Ulezko et al., 2019; Zhukova & Ulezko, 2019).

It should be mentioned that researchers indicate the need for the most effective transformation of agriculture on modern principles, since a strong agricultural sector for most developing countries is a prerequisite for the further strengthening of other sectors of the economy and the state as a whole (Hye, 2009). For example, the economic development and transformation of Thailand, which in the 1960s was a typical agrarian country with more than 80% of the population employed in agriculture, owes much to the rational model of using agricultural resources as a springboard for powerful industrial development of the state in further, which as a result made it possible to switch to a fully industrial model of the country's development already in the early 1990s – the share of GDP from agricultural production decreased from 39.8 to 12.4%, and from industry increased from 18.2 to 39.2%, respectively. It is interesting that in Thailand the leading role in the structure of agricultural production has always belonged to crop production, 70-74% of the total GDP obtained at the expense of agricultural activity (Krongkaew, 1995).

The same is true for Africa, which has great prospects of becoming a continent with a powerful agro-industrial complex if the reorganization of agricultural production on an intensive industrial basis is successfully carried out on its territory. Currently, the main obstacles on the way to success in Africa are the insufficient qualification of personnel in agricultural production, the lack of necessary reforms and legislative regulation of relations in the agricultural sector, the low attractiveness of African countries for foreign investors (increasing the attractiveness of foreign investments is an urgent problem of the agroindustrial complex in Ukraine as well), problems in the field of environmental protection and gender inequality, very low level of informatization of the sector, insufficient public funding and low attractiveness of agriculture for young people, etc. (Woldemichael et al., 2017). The researchers testify that industrialization and informatization are currently almost the only way to overcome the food crisis in African countries, and they suggest taking the experience of South Korea as an example of successful transformation of the agricultural sector.

By the way, a real popularization of industrial and "smart" agriculture has begun in a number of countries. Therefore, in Changji National Agricultural Scientific and Technical Park (PRC) on the territory of more than 34 thousand hectares, the advantages of innovative development of the agricultural sector and the implementation of the most modern technical and technological achievements in production are demonstrated: satellite monitoring and navigation, automatic driving, automatic water saving irrigation, smart fertilizer supply systems, "green" technologies for the production of plant products, etc. This park is a good example of what agriculture of the future should be and the advantages the transition to industrialization (the level of mechanization and automation of the production process – 94.6%), intelligent technologies for the production of agricultural products provides. Park specialists actively implement the latest developments of domestic and foreign scientists, test new machinery and equipment, and provide recommendations to Chinese farmers (Дышкант, 2019).

It is obvious that traditional agriculture is gradually losing its position, as it cannot provide further increase in the return on capital investments along with the high ecological safety of obtaining agricultural products, which is one of the main requirements to ensure national food security and conservation of nature. Modern agricultural machines and tools allow performing technological operations with high accuracy (variation of 3-5%); a wide range of macro- and micro-fertilizers, plant protection agents, immuno- and growth-regulating preparations in the developed countries of the world has reached its optimum (and in some countries, such as the PRC, it has even exceeded it by a number of indicators); modern advances in breeding and biotechnology make it possible to create highly productive and maximally technological varieties and hybrids of agricultural crops. For example, Dutch scientists proved that the automation of wheat cultivation allows further increase its yield while reducing production costs, which is a promising direction. The application of remote sensing data of the Earth is a source of operational information about the course of processes within agroecosystems, allows monitoring the efficiency of the use of natural resources, to monitor the state of the environment, forecasting dynamic changes in the environmental parameters of natural objects due to anthropogenic influence, and solving a wide range of operational and strategic tasks of a technological a plan for the production of plant products in systems of precision agriculture with maximum productivity and quality, minimum costs per unit of production, and as low as possible negative anthropogenic pressure on the environment (Маковецький & Осіпов, 1999; Войтюк, 2000; Кравчук, 2008; Панков и др., 2012) . The rational use of natural, financial and labor resources is impossible without a comprehensive approach to the adaptation of the modern agroindustrial complex to changes in the soil-climatic and organizational-economic conditions of the production of plant products, appropriate scientific, consulting and informational support, coordination of all components of the management system, rational differentiation and as much as possible a full cycle of waste-free production, which is quite possible to achieve due to the implementation of innovative approaches to the industrialization and informatization of agriculture (Тиллоева & Махмадов, 2020).

Осецький & Куліш (2020) consider the agro-industrial complex to be the most promising branch of the economy of Ukraine, which is of primary importance for the state and one of the first to receive subsidies for the introduction of innovative industrial technologies, because the development of national agriculture is impossible without the introduction of innovative, compliant with the requirements of the industrial revolution 4.0, technical-technological, organizational-economic, social and scientific-educational elements in the agro-industrial complex (Ломовських, 2021; Павліщий & Судомир, 2021). Transformation of the national agro-industrial complex on an industrial basis is a way to increase labor productivity and competitiveness of the Ukrainian economy (Осецький & Куліш, 2020). Prospects and directions of innovative development of agriculture were studied by Янковська (2010), Шпикуляк & Грицаєнко (2016), Долгошея (2011). The importance of the innovative development of the agroindustrial complex is proven by the fact that, in 2018, agriculture, forestry and fisheries represented 12% of the national gross added value. Since 2013, the share of agriculture in the structure of the national gross value added has never fallen below 10% (Осецький & Куліш, 2020).

It is impossible to meet the modern requirements for agriculture – energy and resource saving, economy, manufacturability, high environmental safety – without the integration of information technologies, geo-information systems and automated management decision-making systems in agricultural practice. Буталенко та ін. (2021) indicate the system computerization, automation and informatization of technological processes along with the rational use of material, technical and natural resources within the framework of innovative agricultural technologies with the use of the most modern technical equipment, tools, and machines, as the main directions for the further development of domestic agricultural production. So, for example, the practice of world agriculture includes the use of smart programmable cultivators equipped with special cameras and sensors, which are independently able to distinguish cultivated plants from weeds and perform high-precision inter-row cultivation with the help of complex mechanics of automatic steering in the process of soil cultivation on row crops. This not only improves the quality of cultivation and minimizes injury to cultivated plants, but also creates prerequisites for optimizing labor costs in agriculture (Огійчук, 2020). In modern industrial orchards and greenhouses, artificial pollination using drones (Dropcopter), specialized pollination machines (Bramblebee), small robots that mimic pollinating insects, like drones (Robobee), etc. are being actively implemented. This improves the productivity of plantations, increases the quality of the harvest, and optimizes the costs for handwork (Дишкант, 2020). Special robotic harvesters are created and implemented into production for harvesting strawberries, both for greenhouse plants and for field berry plantations – Octinion, Croo Harvests, Agrobot SW 6010 (Дышкант, 2019). And the use of tensiometers in conjunction with modern systems of automated soil moisture monitoring and irrigation scheduling is the gold standard in systems of precision water-saving agriculture and is already being actively implemented in Ukrainian fields (Павелківський & Павелківська, 2020).

Modern computer-based systems of mapping, technology park monitoring, automated analytics and planning (so-called management decision support systems), management and interaction with staff and customers, the use of drones for aerial photography and studying the state of crops, modern mobile applications for operational control and technological management process, programmable machines and tools for soil cultivation, fertilizer application, spraying, sowing, and harvesting, etc. open new horizons for the agrarian business of Ukraine. Unfortunately, as of 2019, Ukraine ranked only 47th in terms of the Global Innovation Index, i.e., innovative development is still not inherent in the domestic economy (Осецький & Куліш, 2020).

According to Савицький (2017), precision agriculture is the only option to solve the food problem associated with the rapid increase in the global population under the conditions of soil preservation, ecological sustainability insurance, reduction of the pesticide and agrochemical load on agroecosystems, etc. The scientist emphasizes that the key factors that will contribute to the transfer of Ukrainian agricultural production to the principles of precision agriculture are:

economic – reducing the costs for technological operations, plant protection and fertilization; ecological – reduction of environmental pollution due to optimization of the use of natural resources and reduction of anthropogenic load; demographic – increasing the quality of products while stabilizing their income; social – improvement of working conditions for the population employed in the agricultural sector (Савицький, 2017).

To maintain and further increase the power of the agricultural potential, it is extremely necessary to accelerate the pace of transfer of agricultural activity based on informatization and to use the experience of leading countries in this direction. For example, in the USA, about 80% of agricultural producers use modern technologies of precision agriculture, while in Ukraine this figure is modest, only 20-30% (McBratney et al., 2005). According to Рапацький & Мушеник (2020), most Ukrainian farmers are stuck in the agriculture of the 1970s and 1980s of the last century.

The above-mentioned statement is supported by the work of Кобченко (2017), where the insufficient level and quality of informatization of agriculture is also pointed out as an important problem of the modern agricultural sector of Ukraine. The author emphasizes that only an intensive path of development, which involves a significant increase in the efficiency of the use of available production resources, is correct, and in the conditions of total informatization and digitization in all areas of human life, agriculture should be a priority as one of the leading branches of the domestic economy. Otherwise, the competitiveness of the national agricultural producer on the global market will decline more and more over time. Кобченко (2017) considers one of the main problems to be the lack of a unified state strategy and standard for informatization of agricultural production, therefore all initiatives at this stage belong to the agricultural producers themselves, which creates a certain chaos, nonsystematic introduction of information technologies in the crop production, because now the main consumers of innovations in this field are large agricultural holdings, often with foreign capital, and small domestic farmers are practically deprived of the opportunity to join the world of precision agriculture. The state support and training of every Ukrainian farmer, financial and technical support, the provision of relevant information, theoretical knowledge, and practical skills by scientific and educational institutions in the effective implementation of information technologies in production are of great importance.

Of course, the holding-oriented system of crop production, which, unfortunately, is dominating in Ukraine, is not always bad. In fact, it is difficult to deny the fact that it is the large agricultural holdings that are the locomotive of Ukrainian agricultural production, it is in these companies that the most highly qualified and experienced workers usually work, it is here that innovative technologies are introduced, it is in their fields that record harvests are harvested. But the export-oriented nature of such agricultural and economic formations, along with the dependence on the foreign owner of the main capital, cannot but cause concern in undermining the guarantees of food security of Ukraine. Occupying more and more arable land, displacing the domestic farmer, whose products are aimed at meeting the needs of the Ukrainian consumer, agricultural holdings pose a direct threat to the food security of the state, as they export huge volumes of products abroad, which theoretically could remain on the territory of Ukraine and satisfy the needs of the inner consumer. In addition, if a domestic farmer creates jobs for the village, then agricultural holdings, in most cases, do not. Unfortunately, until now, mainly agricultural holdings are the main consumers of high-value, state-of-the-art information products for precision agriculture, making smaller national agricultural producers even less competitive (Федорчук, 2020).

Мушеник (2021) reckons the main problems of wide implementation of information technologies in the agro-industrial production of Ukraine in the following:

- insufficient effectiveness of state regulation in the sphere of material and technical and organizational and economic relations in this sector of the national economy;
- lack of the necessary infrastructure for the development of informatization of the agro-industrial complex;
- relatively low interest and awareness of business entities regarding the introduction and use of information technologies in the production process.

It is important to note that Мушеник (2021) emphasizes that informatization cannot be carried out unilaterally. A comprehensive approach is needed and it should include such components as informatization of production, informatization of agroindustrial management and marketing, informatization of agrarian education and science, and informatization of the countryside as a whole.

Akmarov et al. (2019) also pay attention to the importance of the integrated development of science and practice in the informatization of agricultural production. The issue of the lack of highly qualified personnel for the effective implementation of the most modern developments is particularly acute, which is linked to the insufficient development of the scientific and educational sector in the field of agricultural informatics in the countries of the former USSR. It is worth considering state funding and support for the development of training programs and advanced training of specialists and scientists in the field of digital agriculture, because currently in Ukraine a limited number of higher education institutions provide training in precision agriculture and informatization of agricultural production.

It should be noted that the state understands its leading role in the development of informatization of agricultural production. Thus, back in the days of the Ministry of Agrarian Policy and Food of Ukraine, the following legislative documents regarding the informatization of agriculture were approved, namely: Order "On approval of the Plan of measures for the development of the information society in the agro-industrial complex of Ukraine for 2007-2015" dated September 10, 2007, No. 653; Laws and concepts "On computerization" and "Informatization of agricultural industry"; Resolution "On approval of the Regulation on the Register of information, telecommunications and information and telecommunications systems of executive authorities, as well as enterprises, institutions and organizations belonging to the sphere of their management" dated August 3, 2005 No. 688 (Ясінецька & Мушеник, 2020).

The broad prospects for informatization of crop production in Ukraine are supported by the presence of highly qualified specialists in the field of information technologies, who are among the top 11 countries in the world. Therefore, the tandem of IT specialists and farmers is very promising, as it will not only give a new impetus to the development of domestic agriculture, but will also create a new platform for mutually beneficial cooperation at the junction of the two industries due to the creation of new opportunities to earn and increase profits not only for farmers, but also for cyber specialists (Рапацький & Мушеник, 2020).

A particularly relevant area of informatization of the crop production is the use of geoinformation systems and remote sensing data, which allow to quickly manage the execution of technological operations due to the programming of the movement of tractors in the fields and the consumption of mineral fertilizers or pesticides, to track the movement of machinery, to monitor the condition of soils and vegetation on large areas in a short period of time, etc. (Рапацький & Мушеник, 2020). The integration of remote sensing data into automated management decision-making significantly improves the effectiveness of the latter. For example, if earlier in order to form an idea about the physical and mechanical properties, melioration state, and fertility of the soil of the field, it was necessary to perform a rather time-consuming work of selecting samples according to an established grid of points, now thanks to modern soil scanners (operating on the principles of electromagnetic induction and also equipped with special optical and electronic sensors, a sampler, and electrodes) you can get a set of ready-made information that can be easily converted into a map if necessary, in a matter of minutes without high labor and time costs and without a laboratory. Soil scanners are aggregated with any vehicle, and at a speed of 10 km/h across the field, they are, on average, able to take 16 full-fledged "samples" (Навродський, 2021).

Geoinformation systems and technologies have already been implemented in almost all branches of the national economy, which require collection, accumulation, structuring, and an analytical-synthetic approach to spatial information processing (Шипулін & Кучеренко, 2009). These technologies are closely integrated with information technologies and means for remote sensing, modern technology that, during technological operations, is controlled by geolocation and geotagging data from GPS navigators.

The application of remote sensing data in tandem with modern geoinformation systems opens up new opportunities to map cultivated areas, studying their structure in large areas, and assess the dynamics of changes in the structure of land use, which is a necessary prerequisite for effective crop production. In addition, they can be used to solve operational technological tasks in precision farming systems, such as quality control of crop spraying, mineral fertilizer application, harvesting, etc. (Нейштадт, 2007).

Earlier, a better understanding of the essence of informatization of the production of plant products based on precision agriculture by foreign scientists was given. Мушеник & Гаврилюк (2020) offer a simplified understanding of the concept, highlighting three main stages of the production process inherent in precision agriculture:

- collection and accumulation of data on the economy as a whole, individual fields, plots, cultivated crops and crop rotation, material and technical support, etc.;
- analytical processing of the data;
- adoption and implementation of managerial and technological decisions.

In our opinion, this scheme lacks the fourth, no less important stage – control over the quality of the implementation of the decisions made and monitoring of the results of economic activity to eliminate the deficiencies identified as a result.

An interesting generalization of the field of application of precision agriculture based on digital technologies and the impact of the latter on the production process of crop production is the scheme proposed by Rudenko (2020). The author emphasizes the following constituents:

- agronomic survey of fields (collection of field data, selection of heterogeneity zones, selection of soil samples, soil conductivity);
- soil tillage (differentiated execution of technological operations, effective implementation of no-till and strip-till technologies, determination of the depth of tillage);
- pre-sowing preparation (differentiated application of plant protection agents and fertilizers, monitoring and quality control of technological operations);
- sowing (differentiated sowing of seeds, simultaneously with the application of fertilizers, monitoring of the uniformity of sowing);
- plant care (monitoring of plant growth and development stages, crop condition, identification of problem areas, differentiated and accurate application of plant protection agents and mineral fertilizers in top dressings);
- harvesting (monitoring and process management, determination of gross harvest, yield, grain moisture).

This requires the use of specialized software, online services and mobile applications, modern equipment equipped with GPS and the necessary sensors, drones, software products to support managerial decision-making and personnel management, etc. (Руденко, 2020). Computer modeling is an extremely promising way to improve the optimization of production process management in the agro-industrial complex. A special program complex "Agroecosystem" has already been developed in Ukraine, which allows modeling and evaluating the mutual influence of various agrotechnological solutions on the efficiency of production and its economic and ecological parameters (Тарарiко та iн., 2020).

In his turn, Ulezko et al. (2019) propose the following directions of agricultural informatization:

- transfer to IoT, robotics and automation;

- development of digital platforms for complex management and implementation of decisions;
- modernization of the approach to management and work with information in the agricultural sector, ensuring open access to the data required in the agricultural production process;
- development and maintenance of information infrastructure in satisfactory condition, improvement of reliability and speed of interaction and communication channels between nodes of information systems and personnel, provision of the agro-industrial complex with electronic equipment necessary for successful informatization;
- optimization of interaction between the supplier and the consumer using electronic commercial platforms.

Finally, let us note that informatization for the sake of informatization, the transition to digital technologies simply for the sake of "numbers" is a path to nowhere. Irrational, ill-conceived, one-sided, without taking into account the real state, opportunities for effective implementation and real needs for digital technologies in each specific case may not only not bring the desired benefit in the form of increased productivity and improvement of working conditions of farmers, optimization of resource use and increased production profitability, but also cause significant damage and create additional chaos in an insufficiently prepared organizational system of the economy, lead to misunderstanding and discomfort among unprepared employees. The transformation of agriculture on a modern basis should include a set of measures, as already stated above, and not only technical-technological, but also scientific-educational, pedagogical, psychological, organizational-economic in nature, since technology is a human assistant, and not the other way around (Свириденко, 2020). Only taking into account the above, the transition of agricultural production to industrial foundations will not have negative consequences related to the migration of the rural population to large cities, the loss of the practice of traditional gardening and horticulture on homestead plots, the narrowing of the spectrum of cultivated plants and the loss of valuable varieties, unemployment in rural areas, gender inequality, etc., as happened in certain areas of Colombia (Piniero, 2016).

Conclusions to Chapter 1

1. Global warming is a problem of planetary scale that affects all areas of human activity, while agriculture and food security remain particularly vulnerable. The reasons for climate change are unknown for sure until now, however, the latest research testify about the combined influence of numerous factors such as greenhouse gas emission and accumulation, planetary cycles, solar activity, major streams of the world ocean. Regardless of the factors causing global warming, there is an urgent need to develop and implement mitigation policies and reduce harmful

impacts of human activity on climate. Today agrarians face issues of revising current agroclimatic zoning, restructuration of croplands, change in crop composition, revision of sowing and planting terms, system of plant protection, tillage, fertilization, and plant care, etc. The importance increases not only in regions of risky agriculture but also in almost in all the regions of the world. Crop production adaptation to new climatic conditions considering all their positive and negative influences is a prerequisite for food safety and agricultural sustainability. Solving the question of reasons in the chain of «climate – crop production» (for example, dependence of yields on climate, role of agricultural land use practices in climate change), implementation of innovative technological means in agrarian science, education and practice, development of the transfer strategy to achieve efficient climate smart agriculture.

2. Crop production industrialization is a required reaction of agrarian sector to the current challenges, namely, food crisis under the impact of global climate change, dramatical increase in global population, decrease in available natural resources under simultaneous deterioration of their quality. Informatization is a constituent of industrialization because comprehensive introduction of innovative information technologies and systematic approach to data collection, accumulation, generalization, and analysis it is impossible to achieve a success in transformation of conventional agriculture into precision digitalized one. An important constituent of informatization is implementation of remote sensing data in the decision support systems based on IoT, which provide an opportunity for operational access and analysis of huge data sets regarding soil and plants state, planning and programming production and efficient adjustment of agrotechnological measures in limited time span, track the dynamics of production processes in time and space. Besides, deep integration between all the constituents of agricultural production process is required, and it can be realized using correspondent equipment and technical means in the systems of automation and control, while electronic platforms guarantee the best way for the products to reach global market.

CHAPTER 2
METHODOLOGY OF SCIENTIFIC RESEARCH

2.1. Mathematical statistics methods in data processing

None of modern scientific studies can gain its value without mathematical and statistical processing of the data involved. Sometimes, the mathematical apparatus is of decisive importance in the quality of assessment and the correctness of the conclusions made by the scientist based on the results of research. The current study applied both conventional and common methods of mathematical and statistical data processing, as well as complex modern mathematical models to create reliable forecasts and assess trends in the development of the studied phenomena.

Pearson's linear correlation coefficient indicates the strength of the relationship between the studied variables (Hinkle et al., 1998). The calculation was carried out using BioStat v7 and Microsoft Excel 365 according to formula 2.1.1:

$$R_{XY} = \frac{\sum_1^N (x_i - \bar{x})(y_i - \bar{y})}{(N-1) s_X s_Y} \tag{2.1.1}$$

where: s_X, s_Y – standard deviations in X and Y, respectively; N – number of samples; x_i, y_i – values of the studied parameters; $\bar{x}, \bar{y}$ – means for X and Y, respectively.

The strength of the correlation by the value of the coefficient is established by various methods, but a general idea of its tightness can be obtained using the reference table (Table 2.1.1). The direction of correlation is determined by the sign "+" (direct) and "–" (reverse).

Table 2.1.1

Absolute value of the coefficient	Tightness (strength) of interconnection
0.90-1.00	Very strong
0.70-0.90	Strong
0.50-0.70	Moderate
0.30-0.50	Slight
0.00-0.30	Very slight or absent

The coefficient of variation is an important statistical parameter, especially in studies with biological objects and natural phenomena. Indicates the degree of dispersion of the numerical characteristics of the object under study. It can be expressed as a number (from 0 to 1) or as a percentage. The calculation was performed according to the generally accepted method (Abdi, 2010; Lee et al., 2015).

The coefficient of variation is used to assess the degree of variability of the characteristics of the object under study. It is accepted to consider variability at the level of <10% as weak, at the level of 10-25% as medium, and >25% as strong (Lakin, 1990). The calculation was performed according to formula 2.1.2:

$$CV = \frac{SD}{x} \tag{2.1.2}$$

where: *SD* – standard (root mean square) deviation; *x* – mean value.

The root mean square deviation (or standard deviation), which is a numerical expression of the uncertainty of a feature or parameter of the object under study and serves to provide an idea of its range and potential upper and lower limits (Barde & Barde, 2012), was calculated according to formula 2.1.3 proposed by Bland & Altman (1996):

$$SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - x)^2} \tag{2.1.3}$$

where: *N* – number of samples; x_i – index value; *x* – mean value.

Linear regression (both pair and multiple) allows one to establish the features of the dependence between the studied parameters and describe them using a linear equation (model).

When performing regression analysis according to the standard algorithm, regression statistics, variance analysis, model coefficients and its residuals are calculated (Anscombe, 1973; Cook & Weisberg, 1982; Neter et al., 1996; Pedhazur, 1997; Stevens, 2002; Huber, 2004; Belsley et al., 2005; Айвазян, 2001). Additionally, statistical criteria can be calculated for a comparative assessment of model quality.

Regression statistics include correlation coefficients R and coefficients of determination R^2 (normal, adjusted and predicted), as well as root mean square error. The coefficient of determination serves to assess the quality of the fit of the model curve, as well as an indirect measure of the accuracy and reliability of the model. It is calculated according to formula 2.1.4:

$$R^2 = 1 - \frac{SS_{error}}{SS_{total}} \tag{2.1.4}$$

The adjusted (or normalized) coefficient of determination considers the number of predictors (influential input data) that explain the variables in the model, and is calculated according to algorithm 2.1.5:

$$R^2_{adj} = 1 - (1 - R^2)\frac{N-1}{N-k-1} \quad (2.1.5)$$

where: k – number of predictors; N – number of samples.

The mean square error (*MSE*), which indicates the deviation of the value of the variable modeled by the regression equation from the real value, was calculated according to formula 2.1.6 (as the average value of the squared errors of the model):

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2 \quad (2.1.6)$$

where: n – number of input samples; $Y_i - \hat{Y}_i$ – difference between real and forecasted values.

In addition, the root mean square error (*RMSE*) is calculated, which is one of the most frequently used indices for assessing the accuracy of regression models, is sensitive to the number of data in the sample that significantly differ from the general regularity and distort the approximation curve (Willmott & Matsuura, 2006; Pontius et al., 2008). It is calculated according to formula 2.1.7:

$$RMSE = \sqrt[2]{MSE} \quad (2.1.7)$$

The predicted coefficient of determination is calculated to estimate the predictive value of the model considering the predicted sum of squared residuals d (*PRESS*) according to formulas 2.1.8-2.1.9:

$$R^2_{pred} = 1 - \frac{PRESS}{SS_{Total}} \quad (2.1.8)$$

$$PRESS = \sum d_i^2 \quad (2.1.9)$$

An additional parameter is *PRESS RMSE*, the value of which is determined considering the amount of data in the sample according to equation 2.1.10:

$$PRESS\ RMSE = \sqrt{PRESS/_{N}} \quad (2.1.10)$$

The equation of the standard linear regression model has the form 2.1.11:

$$Y = a_1x_1 + a_2x_2 + \cdots + a_kx_k + c + e \quad (2.1.11)$$

where: Y – dependent parameter; a_i – regression coefficients for each x_i; c – constant (not obligatory part of the equation); e – error (residuals).

Analysis of variance (*ANOVA*) for the regression model includes, along with the calculation of the so-called "table and reference" indicators (number of degrees of freedom, sample sum of squares, Fisher's test, Fisher's test significance level at $p<0.05$), the calculation of the mean square (*MS*) to estimate variations according to formula 2.1.12:

$$MS = \frac{SS}{DF} \tag{2.1.12}$$

where: *SS* – sum of the squares; *DF* – degree of freedom.

Analysis of residuals (differences between pairs of actual and model-predicted data) is not a required element of regression analysis. However, sometimes it is advisable to calculate standardized residuals (es_i) and Studentized residuals (r_i) according to the appropriate formulas (2.1.13-2.1.14):

$$es_i = \frac{e_i}{\sqrt{MSE}} \tag{2.1.13}$$

$$r_i = \frac{e_i}{s(e_i)} \tag{2.1.14}$$

where: *MSE* – mean square error; e_i – residuals; $s(e_i)$ – standard deviation for the residuals.

Polynomial regression is a type of regression analysis of data in which the relationship between variables is described by a polynomial of the nth degree. Often, due to their nonlinearity, such models better describe the features of natural processes in agroecosystems. However, polynomial models are not pure nonlinear models. Technically, polynomial regression is a variant of multiple linear regression (Gergonne, 1974; Chang et al., 2010). Adjustment and construction of the model curve are performed by the method of least squares. The equation of the polynomial model has the form (2.1.15):

$$Y = \beta_0 + \beta_1 x + \beta_2 x^2 + \cdots + \beta_n x^n + \varepsilon \tag{2.1.15}$$

where: β – regression coefficients; x – independent argument; n – polynomic degree; ε – random error.

Regression coefficients are calculated according to formula 2.1.16-2.1.17 (Green, 2003):

$$\beta_0 = \frac{1}{M}\sum_i y_i - \frac{\beta_1}{M}\sum_i x_i \tag{2.1.16}$$

$$\beta_i = \frac{M\sum_i x_i y_i - \sum_i x_i \sum_i y_i}{M\sum_i x_i^2 - (\sum_i x_i)^2} \quad (2.1.17)$$

where: M – number of inputs; x – independent argument; y – dependent function.

Calculations and development of regression models, graphs of their approximation were performed in the BioStat v7 software and Microsoft Excel 365 spreadsheets.

To assess the presence of a reliable trend in time series of data and to determine the direction of the trend, the Mann-Kendall test was performed, and the value of Sen's slope was calculated at a confidence interval of 95% or p<0.05 (Mann, 1945; Kendall, 1975; Gocic & Traikovic, 2013). The technique consists in performing a sequence of calculations according to the following algorithm (2.1.18-2.1.25):

$$S = \sum_{i=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_i) \quad (2.1.18)$$

$$var = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_t f_t(f_t - 1)(2f_t + 5)\right] \quad (2.1.19)$$

$$z = \begin{matrix} (S-1)/se & S > 0 \\ 0 & S = 0 \\ (S+1)/se & S < 0 \end{matrix} \quad (2.1.20)$$

$$Sen's\ slope = Median\left\{\frac{x_j - x_i}{j - i} : i < j\right\} \quad (2.1.21)$$

$$N = C\ (n, 2) \quad (2.1.22)$$

$$K = se \times z_{crit} \quad (2.1.23)$$

$$Lower = x_{(N-K)/2} \quad (2.1.24)$$

$$Upper = x_{(N+K)/2+1} \quad (2.1.25)$$

where: $x_1 \ldots x_n$ – time series; t – tied ranks; f_t – rank frequency; se – square root of the examined value; N – amount of data in the time series (x_i, x_j) where $i < j$; se – standard error of the test.

Calculations were performed in the Real Statistics software package (an add-on for Microsoft Excel 365).

To improve the visualization of the statistical processing of time series of data, control maps were constructed, which involves the calculation of the arithmetic mean value for the sample, the values of the upper (*UCL*) and lower (*LCL*) control limits. A control chart (in some sources referred to as Shewhart chart) is a graph used to visually display the variability of a process over time and its control. In the work, control charts of type *P* were constructed. The method was proposed by Shewhart

(1931). Calculations were performed in the BioStat v7 software package according to the Page (1954) algorithm as provided below (2.1.26-2.1.28):

$$Sp = \frac{p(1-p)}{N} \tag{2.1.26}$$

$$LCL = T - 3Sp \tag{2.1.27}$$

$$UCL = T + 3Sp \tag{2.1.28}$$

where: *Sp* – sigma; *p* – mean value; *T* – target share (part).

One of the time series forecasting methods used in the work is the Holt-Winters triple exponential smoothing method using the *AAA* type algorithm. Predictive calculations and graphs were performed in the Microsoft Excel 365 software complex with a confidence interval of 95% or $p<0.05$ (Winters, 1960). Damaged and missed data in the time series were automatically replaced with values calculated by the interpolation method. The seasonality parameters of the forecast depended on the investigated phenomenon and period. The calculation algorithm for building a forecast is given below (2.1.29-2.1.36):

$$u_i = \alpha\left(\frac{y_i}{s_{i-c}}\right) + (1-\alpha)(u_{i-1} + v_{i-1}) \tag{2.1.29}$$

$$v_i = \beta(u_i - u_{i-1}) + (1-\beta)v_{i-1} \tag{2.1.30}$$

$$s_i = \gamma\left(\frac{y_i}{u_i}\right) + (1-\gamma)s_{i-c} \tag{2.1.31}$$

$$y_i = (u_{i-1} + v_{i-1})s_{i-c} \tag{2.1.32}$$

$$y_{i+h} = (u_i + hv_i)s_{i+h-ch'} \tag{2.1.33}$$

$$h' = INT\left(\frac{h-1}{c}\right) + 1 \tag{2.1.34}$$

$$v_c = \frac{1}{c}\sum_{j=1}^{c} y_j \tag{2.1.35}$$

$$s_i = y_i/u_c \tag{2.1.36}$$

where: $0 < \alpha \leq 1$; $0 \leq \beta \leq 1$; $0 \leq \gamma \leq 1-\alpha$; u_i – baseline; v_i – trend (slope); s_i – seasonality; $1 \leq i \leq c$.

Another forecasting method that has found its application in the study is SARIMA – a seasonal autoregressive model based on an integrative moving average. This model is built based on ARMA and ARIMA, that is, the basic model without taking seasonality into account. Briefly, the algorithm for forecasting the phenomenon or the development of the dynamics of the indicator value according to the SARIMA algorithms is given below (Bas Cerdá et al., 2017; Chen et al., 2018).

Basic ARMA(*p,q*) is expressed by the equation (2.1.37):

$$y_i = \phi_0 + \sum^{p} \phi_j y_{i-j} + \varepsilon_i + \sum^{q} \theta_j \varepsilon_{i-j} \quad (2.1.37)$$

If $\varphi_0 = 0$ (mean stochastic is taken to have zero value) than the operator transforms as follows (2.1.38-2.1.39):

$$\phi(L)y_i = \theta(L)\varepsilon_i \quad (2.1.38)$$

$$\phi(L)y_i = \left(1 - \phi_1 L^1 - \phi_2 L^2 - \cdots - \phi_p L^p\right)y_i = \left(1 - \sum_{j=1}^{p} \phi_j L^j\right) y_i$$
$$\theta(L)\varepsilon_i = \left(1 + \theta_1 L^1 + \theta_2 L^2 + \cdots + \theta_q L^q\right)\varepsilon_i = \left(1 + \sum_{j=1}^{q} \theta_j L^j\right) \varepsilon_i \quad (2.1.39)$$

It must be noted that ARIMA (*p, d, q*) process z_i could be expressed as upper, but z_i must be replaced with $z_i = y_i - y_{i-d}$. It is important: parameters (*p, d, q*) determine type of the model (for example, 0, 0, 0 or 1, 1, 1). At the same time, ARIMA (*p, d, q*) process y_i could be expressed without constants as follows (2.1.40):

$$\phi(L)(1-L)^d y_i = \theta(L)\varepsilon_i \quad (2.1.40)$$

Constants could be added if necessary, using the following equation (2.1.41):

$$\phi(L)(1-L)^d y_i = c + \theta(L)\varepsilon_i \quad (2.1.41)$$

SARIMA is the same, but with specific operators responsible for seasonality. SARIMA(*p,d,q*) × $(P,D,Q)_m$ without constants is expressed as follows (2.1.42-2.1.44):

$$\phi(L)\Phi(L^m)(1-L)^d(1-L^m)^D y_i = \theta(L)\Theta(L^m)\varepsilon_i \quad (2.1.42)$$

$$\Phi(L)y_i = \left(1 - \Phi_1 L^1 - \Phi_2 L^2 - \cdots - \Phi_p L^P\right)y_i \quad (2.1.43)$$

$$\Theta(L)\varepsilon_i = \left(1 + \Theta_1 L^1 + \Theta_2 L^2 + \cdots + \Theta_q L^Q\right)\varepsilon_i \quad (2.1.44)$$

Therefore, we have *P* seasonal autoregression determinants (with the coefficients $\Phi_1, \ldots, \Phi_P$), *Q* seasonal moving averages (with the coefficients $\Theta_1, \ldots, \Theta_Q$) and *D* seasonal differential determinants for *m* seasonal periods.

If two types of differential determinants are established (corresponding to *d* and *D*), then SARIMA (1,0,1) × $(1,0,1)_{12}$ looks as follows (2.1.45-2.1.48):

$$\phi(L)\Phi(L^{12})y_i = \theta(L)\Theta(L^{12})\varepsilon_i \tag{2.1.45}$$

$$(1-\phi_1 L^1)(1-\Phi_1 L^{12})y_i = (1+\theta_1 L^1)(1+\Theta_1 L^{12})\varepsilon_i \tag{2.1.46}$$

$$(1-\phi_1 L^1 - \Phi_1 L^{12} + \phi_1\Phi_1 L^{13})y_i = (1+\theta_1 L^1 + \Theta_1 L^{12} + \theta_1\Theta_1 L^{13})\varepsilon_i \tag{2.1.47}$$

$$y_i - \phi_1 y_{i-1} - \Phi_1 y_{i-12} + \phi_1\Phi_1 y_{i-13} = \varepsilon_i + \theta_1\varepsilon_{i-1} + \Theta_1\varepsilon_{i-12} + \theta_1\Theta_1\varepsilon_{i-13} \tag{2.1.48}$$

Residuals could be expressed as follows (2.1.49):

$$\varepsilon_i = y_i - \phi_1 y_{i-1} - \Phi_1 y_{i-12} + \phi_1\Phi_1 y_{i-13} - \theta_1\varepsilon_{i-1} - \Theta_1\varepsilon_{i-12} - \theta_1\Theta_1\varepsilon_{i-13} \tag{2.1.49}$$

Forecasts are expressed as follows (2.1.50):

$$y_i = \phi_1 y_{i-1} + \Phi_1 y_{i-12} - \phi_1\Phi_1 y_{i-13} + \theta_1\varepsilon_{i-1} + \Theta_1\varepsilon_{i-12} + \theta_1\Theta_1\varepsilon_{i-13} \tag{2.1.50}$$

Alike the mentioned above, SARIMA(p,q) × $(P,Q)_m$ without constants may be expressed as follows (2.1.51):

$$\phi(L)\Phi(L^m)y_i = \theta(L)\Theta(L^m)\varepsilon_i \tag{2.1.51}$$

Or equivalently (2.1.52):

$$\begin{aligned}
&\left(1-\sum_{j=1}^{p}\phi_j L^j\right)\left(1-\sum_{j=1}^{P}\Phi_j L^{jm}\right)y_i = \left(1+\sum_{j=1}^{q}\theta_j L^j\right)\left(1+\sum_{j=1}^{Q}\Theta_j L^{jm}\right)\varepsilon_i \\
&y_i = \left(\sum_{j=1}^{p}\phi_j L^j\right)y_i + \left(\sum_{j=1}^{P}\Phi_j L^{jm}\right)y_i - \left(\sum_{j=1}^{p}\phi_j L^j\right)\left(\sum_{j=1}^{P}\Phi_j L^{jm}\right)y_i \\
&+\left(\sum_{j=1}^{q}\theta_j L^j\right)\varepsilon_i + \left(\sum_{j=1}^{Q}\Theta_j L^{jm}\right)\varepsilon_i + \left(\sum_{j=1}^{q}\theta_j L^j\right)\left(\sum_{j=1}^{Q}\Theta_j L^{jm}\right)\varepsilon_i + \varepsilon_i
\end{aligned} \tag{2.1.52}$$

Then the forecast is expressed according to following equation (2.1.53):

$$\begin{aligned}
&y_i = \left(\sum_{j=1}^{p}\phi_j L^j + \sum_{j=1}^{P}\Phi_j L^{jm} - \sum_{j=1}^{p}\sum_{k=1}^{P}\phi_j\Phi_k L^{km+j}\right)y_i \\
&+\left(\sum_{j=1}^{q}\theta_j L^j + \sum_{j=1}^{Q}\Theta_j L^{jm} + \sum_{j=1}^{q}\sum_{k=1}^{Q}\theta_j\Theta_k L^{km+j}\right)\varepsilon_i + \varepsilon_i
\end{aligned} \tag{2.1.53}$$

The equation above may be transformed as follows further (2.1.54):

$$y_i = \left(\sum_{j=1}^{p} \phi_j y_{i-j} + \sum_{j=1}^{P} \Phi_j y_{i-jm} - \sum_{j=1}^{p} \sum_{k=1}^{P} \phi_j \Phi_k y_{i-km-j}\right)$$
$$+ \left(\sum_{j=1}^{q} \theta_j \varepsilon_{i-j} + \sum_{j=1}^{Q} \Theta_j \varepsilon_{i-jm} + \sum_{j=1}^{q} \sum_{k=1}^{Q} \theta_j \Theta_k \varepsilon_{i-km-j}\right) + \varepsilon_i \quad (2.1.54)$$

In case of φ_0 presence, the equation is expressed as follows (2.1.55):

$$y_i = \phi_0 + \left(\sum_{j=1}^{p} \phi_j y_{i-j} + \sum_{j=1}^{P} \Phi_j y_{i-jm} - \sum_{j=1}^{p} \sum_{k=1}^{P} \phi_j \Phi_k y_{i-km-j}\right)$$
$$+ \left(\sum_{j=1}^{q} \theta_j \varepsilon_{i-j} + \sum_{j=1}^{Q} \Theta_j \varepsilon_{i-jm} + \sum_{j=1}^{q} \sum_{k=1}^{Q} \theta_j \Theta_k \varepsilon_{i-km-j}\right) + \varepsilon_i \quad (2.1.55)$$

The forecasts in the study were performed in the Real Statistics add-on for Microsoft Excel 365.

Forecast accuracy was assessed by mean absolute scaled error, mean absolute error in percentage (normal and symmetric), mean absolute error (*MASE*, *MAPE* or *SMAPE*, *MAE*) and root mean square error (*RMSE*) (Hyndman & Koehler, 2006).

MASE calculation is performed by the formula 2.1.56-2.1.57 (Hyndman et al., 2008):

$$MASE_{non-seasonal} = \frac{\frac{1}{J}\sum_j |e_j|}{\frac{1}{T-1}\sum_{t=2}^{T} |Y_t - Y_{t-1}|} \quad (2.1.56)$$

$$MASE_{seasonal} = \frac{\frac{1}{J}\sum_j |e_j|}{\frac{1}{T-m}\sum_{t=m+1}^{T} |Y_t - Y_{t-m}|} \quad (2.1.57)$$

where: e_j – forecast error; J – number of forecasted pairs; Y – forecasted value; T – forecast period; $F_t = Y_{t-m}$ – function for differentiation of the forecast periods.

MAPE and *SMAPE* are determined using the formula 2.1.58-2.1.59 (Armstrong, 1985; De Myttenaere et al., 2016):

$$MAPE = \frac{100\%}{n}\sum_{t=1}^{n} \left|\frac{A_t - F_t}{A_t}\right| \quad (2.1.58)$$

$$SMAPE = \frac{1}{n}\sum_{t=1}^{n} \left(\frac{|F_t - A_t|}{(A_t + F_t)/2}\right) \quad (2.1.59)$$

where: A_t – actual index value; F_t – forecasted (modeled) index value.

MAE is calculated by the equations 2.1.60-2.1.61 (Willmott & Matsuura, 2005):

$$MAE = \frac{\sum_{i=1}^{n} |e_i|}{n} \quad (2.1.60)$$

$$|e_i| = |y_i - x_i| \tag{2.1.61}$$

where: y_i – forecasted (modeled) index value; x_i – actual index value.

For some selected models, additional statistical criteria were determined.

The Durbin-Watson (*DW*) criterion is a statistical marker of autocorrelation in a regression model (first-order autocorrelation, ρ_1), calculated according to equation 2.1.62 (Ратникова, 2006):

$$DW = \frac{\sum_{t=2}^{n}(\epsilon_t - \epsilon_{t-1})^2}{\sum_{t=1}^{n}\epsilon_t^2} \approx 2(1-\rho_1) \tag{2.1.62}$$

Akaike's Information Criterion (*AIC*) is a statistical indicator for estimating the error of an out-of-sample forecast and serves as an indicator of the quality of a statistical model. The general form of equation (2.1.63) for calculating the criterion is as follows (Akaike, 1974):

$$AIC = 2k - 2\ln(\hat{L}) \tag{2.1.63}$$

where: k – number of the model parameters; L – maximized value of the trust function.

For a more accurate assessment of the quality of models with a small data set, the adjusted Akaike criterion (*AICc*) is calculated considering the sample size (n) according to formula 2.1.64 (Konishi & Kitagawa, 2008):

$$AIC_c = AIC + \frac{2k^2+2k}{n-k-1} \tag{2.1.64}$$

Bayesian information criterion (*BIC*) or Schwartz's criterion is a criterion for choosing the best model. A smaller *BIC* corresponds to a better model. This statistical criterion is closely related to the Akaike criterion described above. Calculated according to formula 2.1.65 (Findley, 1991):

$$BIC = \ln(n)k - 2\ln(\hat{L}) \tag{2.1.65}$$

BIC is usually more reliable estimator than *AIC*.

The Hannan-Quinn criterion (*HQC*) is an additional alternative criterion for selecting the best model. It is calculated according to equation 2.1.66 (Hannan & Quinn, 1979):

$$HQC = -2L_{max} + 2k\ln(\ln(n)) \tag{2.1.66}$$

It is considered one of the most stable and reliable criteria, however, it is worth noting that it has not gained such widespread use as the Akaike and Bayesian criteria.

Statistical criteria were calculated in the BioStat v7 software package.

2.2. Computations and mapping technique

To calculate the climatic features of the growing season in the Kherson region, the duration of the latter was taken as III-X months inclusive.

Evapotranspiration was calculated according to the standard Penman-Monteith (reference) and Holdridge (potential for the annual period) equations, and Penman-Monteith calculations were performed in the FAO ET_o Calculator program (Holdridge, 1959; Raes & Munoz, 2009), as well as in the EVAPO mobile application. The moisture deficit was defined as the difference between the moisture input from precipitation and the costs of evapotranspiration. The aridity index (*AI*) was calculated according to formula 2.2.1 (Haider & Adnan, 2014):

$$AI = \frac{R}{ET} \tag{2.2.1}$$

where: *R* – precipitation, mm; *ET* – evapotranspiration, mm.

Mapping of moisture regimes was performed in the Adobe Illustrator program based on Soil Explorer data and the results of climate aridity assessment in the regions of Ukraine according to the author's methodology (see Section 3.2). Graphical models are built using the Microsoft Excel 365 graphics processor.

The total productivity of 1 ha of arable land was defined as the sum of the yields of the main agricultural crops in the region for a specific year.

Normalized difference vegetation index (*NDVI*) was calculated by the formula 2.2.2 (Rouse et al., 1973):

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{2.2.2}$$

where: *NIR* – near infrared spectra value; *Red* – red spectra value.

Enhanced vegetation index (*EVI*) is calculated as follows 2.2.3 (Білинський & Книш, 2021):

$$EVI = 2.5\,\frac{NIR - Red}{NIR + 6Red - 7.5Blue + 1} \tag{2.2.3}$$

where: *NIR* – near infrared spectra value; *Red* – red spectra value; *Blue* – blue spectra value.

Mobile (for devices based on Android OS) and online applications (available via a link for devices with any OS) were created on the basis of regression models obtained as a result of statistical and analytical processing of experimental data using programming capabilities in Microsoft Excel 365 spreadsheets and Zoho Sheets.

2.3. Data sources

Numerous statistical retrospective historical time series of data from various sources were used to perform the study, which formed the basis of the analytical and synthetic work and established the peculiarities of the course of the researched processes in the agroclimatic sphere of the world, Ukraine, and its individual regions.

The average annual air temperature in the Kherson oblast for the period of 1879-2020, the amount of precipitation (annual and monthly) for the period of 1905-2020 were obtained at Kherson Regional Hydrometeorological Center, as well as data from open sources of meteorological information (https://metepost.com, https://pogodaiklimat.ru).

Volumes of water used for irrigation, total productivity of 1 ha of arable land in Kherson oblast for the period of 2005-2019, the area of forest plantations and productivity of the main agricultural crops in the region for the period of 1990-2019 were taken from the Statistical Yearbooks of Ukraine, Ecological Passports of Kherson Oblast for a corresponding period.

Average annual air temperature in Ukraine for the period of 1753-2020 were obtained at the statistical portal BI Portal (https://stat.world/biportal/).

Data on soil moisture in the territory of Ukraine based on satellite surveys of the American agency Soil Information for Environmental Modeling and Ecosystem Management (Soil Information for Environmental Modeling and Ecosystem Management) as part of the Soil Explorer application (Miller et al., 2018; Schulze et al., 2021).

Annual and monthly air temperature, annual and monthly precipitation in the regions of Ukraine for the period of 1961-2020 were taken from the main hydrometeorological stations and observations of Ukraine, as well as from the data and information of reference books (Ліпінський та ін., 2003; Галік & Басюк, 2014), open sources of meteorological information (https://meteopost.com, https://pogodaiklimat.ru).

Global average annual air temperature for the period of 1750-2020 based on the data of the statistics portal BI Portal (https://stat.world/biportal/).

Global concentration of greenhouse gases (carbon dioxide, methane, nitrogen oxide) in the atmosphere for the period of 1750-2020, ozone concentration in the atmosphere and the size of the ozone hole for the period of 1979-2020 was taken according to the statistical portal Our World in Data (https://ourworldindata.org).

Data on the emission of greenhouse gases from the crop industry, the amount of pesticide use, mineral fertilizers application, the area of agricultural land, arable land, forest plantations, the amount of tractor use per 100 km^2 of land area for the period of 1990-2016 were obtained at the FAOSTAT open database (https://fao.org/faostat/en/).

Data on MODIS NDVI and MODIS EVI (resolution 250 m, smoothed time series, 16-day intervals of image arrival) for the vegetation cover of Kherson oblast for the period of 2012-2021 were taken from the satellite image provision service of the University of Natural Resources and Life Sciences, Vienna. Further processing of the images was carried out in the QGIS 3.10 software using the tools of raster and vector analysis, layer statistics, with preliminary cutting off the parts of the images that do not correspond to the vegetation cover, according to the vegetation masks of Kherson oblast, delivered by NextGIS service.

The yield of grain corn, grain sorghum, winter wheat and soybeans and the time of onset of the phenological phases of the crops for the period of 2017-2018 (for winter wheat – 2017-2019) were taken according to the field research of the Department of Irrigated Agriculture of the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences within the framework of the study on the tillage systems in crop rotations. The experimental fields were located at the coordinates 46°44'36.5"N 32°42'07.0"E; 46°44'39.5"N 32°42'32.0"E; 46°44'33.3"N 32°42'33.7"E; 46°44'30.3"N 32°42'08.5"E (Vozhehova et al., 2020ab). Yields of sweet corn as well as its phenology for 2016, 2019-2020 were obtained during the experiments held on the irrigated fields of AC «Radianska zemlia» (Лиховид, 2017) and PF «Kulyk» (Лиховид, 2020a,b,c,d,e) within the framework of studying the crop reaction to various tillage depths, plants density, fertilization rates, hybrids, growth regulation substances, etc.. Further linking of the experimental plots to the corresponding values of NDVI was carried out by the means of geotagging using the platform for satellite monitoring of the crops state OneSoil AI, which provides NDVI value according to the combined data from the satellite images of Copernicus Sentinel-1 and Sentinel-2 (resolution of 250 m, each pixel corresponds to the plot of 5×5 m). The OneSoil AI platform uses artificial intelligence algorithms to process satellite images, so Sentinel-2 images are used for automatic recognition of cultivated plant species by the system, and Sentinel-1 images are used to filter distortions and reduce the error of vegetation index calculation. NDVI data are received regularly at 8–16-day intervals (periodically the intervals are shortened or extended depending on meteorological conditions and the season).

Yearly NDVI dynamics study for various crops and fallow field was carried out for the fields of the Institute of Irrigated Agriculture of NAAS (winter wheat, winter barley, winter rapeseed, peas, chickpea, grain sorghum, grain corn, spring potato), AC «Radianska zemlia» (sweet corn), PF «Kulyk» (sweet corn, spring potato), agricultural holding «In-Agro» (tomato). The OneSoil AI platform was used to establish monthly average and phenophase average NDVI values. Data on the seasonal dynamics of NDVI was compared with the averaged dates of the onset and finish of the main phenological phases of the studied crops (according to the results of field observations) to link the value of the vegetation index to the corresponding growth and development stage. Phenological phases were recorded according to the common scientific methodology (Ушкаренко та ін., 2020).

The study on the correspondence between FGCC (obtained in the field conditions using mobile app Canopeo) and NDVI (obtained at the OneSoil AI platform) was held on the fields of the Institute of Irrigated Agriculture of NAAS, AC «Radianska zemlia», PF «Kulyk», agricultural holding «In-Agro» during 2021. Each FGCC-NDVI pair contains 100 input images (both surface and satellite). Determination of FGCC and NDVI values was carried out during the growing season of the studied crops according to the main phases of their growing season. The Canopeo mobile app with a standard algorithm for calculating FGCC values was used on fixed plots of the experimental fields. The photographs for calculating the fraction of green canopy cover were taken according to the recommendations provided on the official application website (https://canopeoapp.com/). The screens of the canopy were taken by Sony Xperia XZ2 Premium. The NDVI values of the OneSoil AI were taken in the same time span when the photographs were taken with a discrepancy not exceeding 3 days.

Conclusions to Chapter 2

In the study modern methods of mathematical and statistical processing of experimental data and tools to develop mathematical models and creating forecasts were used. Data from open statistical sources and data provided by the state statistical services of Ukraine were involved. In addition, the data of previous field studies carried out both as part of the research work of the scientific staff of the Institute of Irrigated Agriculture of NAAS, and as part of individual research work in the fields of private farms and agricultural holdings in recent years were involved, which increases the value of the conclusions obtained as a result of processing large arrays of heterogeneous data obtained in different agroclimatic and production conditions, and the acquired theoretical knowledge and conclusions will be relevant and interesting from a scientific and practical point of view not only at the regional, but also at the all-Ukrainian level.

CHAPTER 3
GLOBAL WARMING AND CROP PRODUCTION IN UKRAINE

3.1. Risk assessment in agriculture due to the climate change. Irrigation as a factor of sustainable crop production and food safety guarantees

An important prerequisite for ensuring the sustainable production of plant products under the conditions of climate change is the assessment of the risks associated with the deficit of natural humidification, both in the short-term and long-term perspective.

Climate change provokes an imbalance in the inflow and outflow of natural moisture. The increase in air temperature along with the insufficient amount of precipitation and uneven distribution in time and space causes a negative moisture balance, which in turn creates prerequisites for the development of desertification processes.

Assessment of the impact of global climate change on agroecosystems should be comprehensive, multimethodological, determination of moisture availability and risks of increased aridity should be carried out considering several indices. Therefore, the best results are provided by an integrative approach to the assessment of possible risks in agriculture based on the values of the direct moisture deficit, the aridity (dryness) index, and the duration of periods without effective precipitation. In addition, isolated assessment of the temperature regime is also of scientific and practical interest.

A retrospective analysis of data on the average annual temperature in Kherson oblast for the period of 1879-2020 testified to the dynamic growth of this indicator, especially in the last two decades (Fig. 3.1.1). Statistical analysis using the Mann-Kendall method with the calculation of Sen's slope proved the presence of a reliable (confidence interval 95% or $p<0.05$) trend towards climate warming in the region (Table 3.1.1). Clustering of the years of the studied period (1895-2020, previous years were excluded due to the lack of data for the 25-year distribution) by the value of the average annual air temperature made it possible to divide them into 6 main classes: Class I – average annual air temperature <7-8ºC; II class – 8-9ºC; Class III – 9-10ºC; IV class – 10-11ºC; Class V – 11-12ºC; Class VI – >12ºC. The distribution of years of the studied period by clusters shows that the V and VI classes of years, which represent the years with the highest temperatures, mainly consist of the years of the period of 1995-2020, and only the years 2007, 2019 and 2020 belong to the VI class (Fig. 3.1.2).

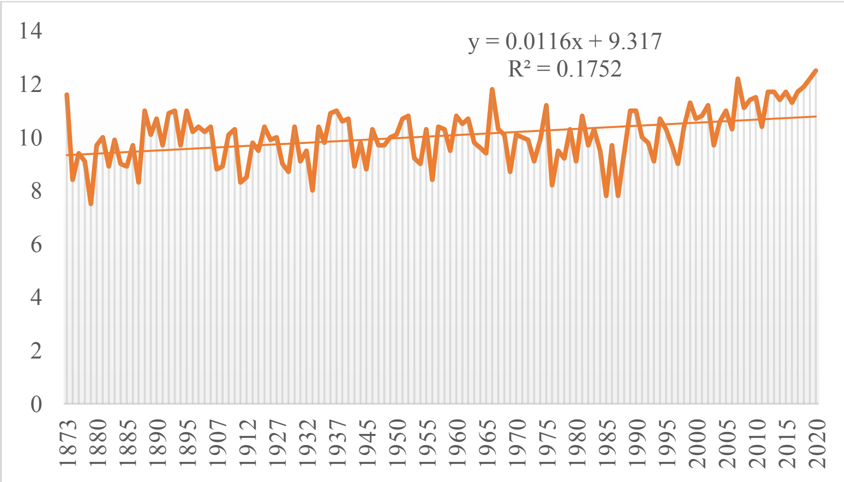


Fig. 3.1.1. Dynamics of the average annual air temperature in Kherson oblast for 1879-2020

Table 3.1.1

Results of Mann-Kendall and Sen's slope test for the average annual air temperature in Kherson oblast in the period of 1879-2020

Statistical indices	Average annual air temperature
alpha	0.05
MK-stat	2220
s.e.	473.68
z-stat	4.68
p-value	2.81×10^{-6}
trend	yes
slope	0.0124
lower	0.0074
upper	0.0167
Trend direction	↑

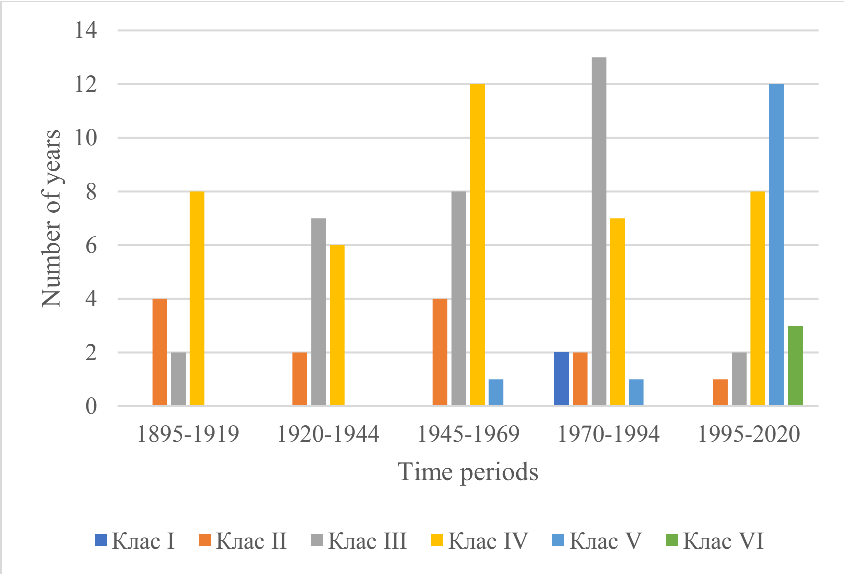


Fig. 3.1.2. Clusters of the years by the values of the average annual air temperature in Kherson oblast during 1895-2020 (dark blue – Class I; red – Class II; grey – Class III; orange – Class IV; blue – Class V; green – Class VI)

Thus, the results of clustering additionally confirm the gradual increase in the average annual air temperature in the region, and as a result, the warming of the climate and its transformation in the direction from temperate-continental to subtropical in terms of temperature regime, which, on the one hand, opens up new opportunities for expanding the practice of double-cropping, wide introduction of post-harvest and post-cut crops, introduction of crops from southern latitudes, as well as crops with a long growing season, etc. However, all this is possible only if there is a sufficient level of humidity, and the rise in temperature is known to be one of the factors in increasing the moisture loss due to evaporation. Therefore, a thorough analysis of the conditions of the supply of moisture in quantity and quality is required (first, the uniformity of the distribution of precipitation over time is meant).

Kherson oblast is one of the regions providing national production of grain crops (primarily winter wheat and winter barley), soybeans, sunflowers, and vegetable crops. It is well known that Kherson region belongs to the zone of risky agriculture – evaporation here prevails over the income of natural moisture, so it is not surprising that the region has had one of the most developed irrigation networks since Soviet times, which includes the Inguletska, Kakhovska, Krasnoznamyanska irrigation systems and systems in the area of the North Crimean Canal, which provide water supply for 309.4 thousand hectares or 17.4% of the total area of arable land in the region (Morozova et al., 2019). Mass construction and commissioning of irrigation networks is a prerequisite for ensuring the production of plant products in the region, and the role of irrigation, according to scientists, will only grow in the coming years (Вожегова та ін., 2013, Goloborodko & Dymov, 2019).

The study of the dynamics of precipitation distribution according to indicators of the number of days without effective, i.e., less than 5 mm (Адаменко, 2014), annual precipitation and the maximum duration of the period without effective precipitation for 1971-2020 showed the absence of a trend as in the first (the coefficient of determination of the trend for decade periods R^2 is 0.0831, that is, less than 10%, which indicates the insignificance of the established statistical regularity along with the negative results of the Man-Kendall and Sen's slope tests), as well as the second case (the coefficient of determination of the trend for decade periods R^2 is 0.0979, that is, less than 10%, which indicates the insignificance of the established statistical regularity along with the negative results of the Mann-Kendall and Sen's slope tests) (Fig. 3.1.3, Fig. 3.1.4, Table 3.1.2).

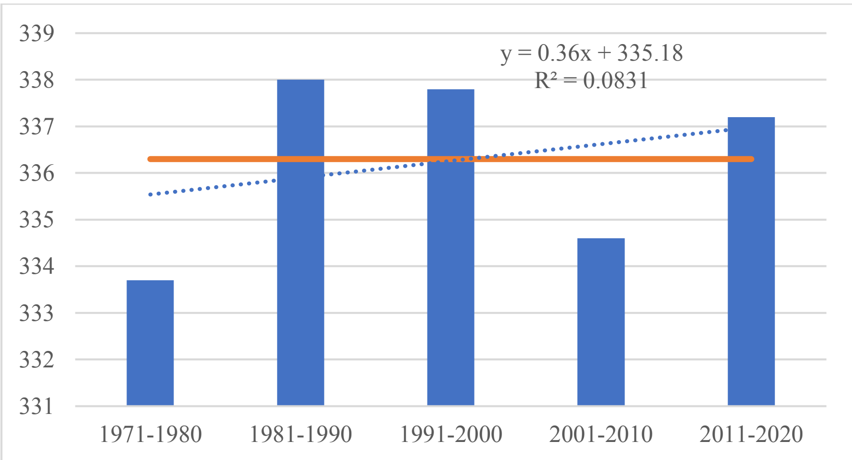


Fig. 3.1.3. Number of days without effective rainfall for decade periods of 1971-2020 (blue – number of days; orange – average for the studied period; dotted line - trend)

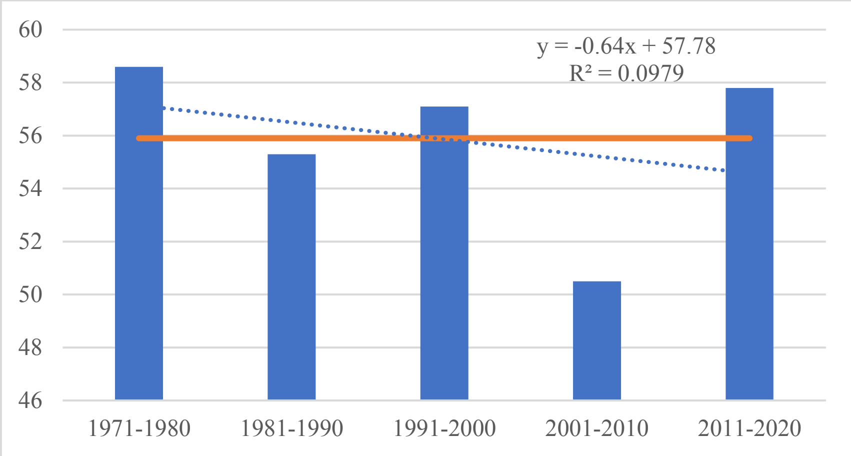


Fig. 3.1.4. The longest periods without effective rainfall for 1971-2020 (blue – period duration; orange – average for the studied period; dotted line - trend)

Table 3.1.2

Results of Mann-Kendall and Sen's slope test for the number of days and duration of the period without effective rainfall in Kherson oblast during 1971-2020

Statistical indices	Number of days without effective rainfall	Duration of the period without effective rainfall
alpha	0.05	0.05
MK-stat	33	–19
s.e.	119.22	119.49
z-stat	0.27	–0.15
p-value	0.79	0.88
trend	absent	absent
slope	0	–0.05
lower	–0.12	–0.41
upper	0.14	0.33

Long-term (for the period 1905-2020) annual data on the air temperature, precipitation amount, uniformity of precipitation distribution (expressed by the value of the coefficient of variation *CV*), the level of potential evapotranspiration (determined according to Holdridge) and the deficit of natural moisture both for the year and for the growing season period (from March to October) in the Kherson region are presented in Fig. 3.1.5.

Table 3.1.3

Results of Mann-Kendall and Sen's slope test for main meteorological indices in Kherson oblast for 1905-2020*

Statistics	AAT	ATGS	AR	GSR	AE	GSE	AMD	GSMD	ARD	GSRD
MK-stat	2220	1532	1100	885	1387	1501	-354	282	465	449
s.e.	473.68	350.92	402.99	403.00	345.82	345.83	350.93	408.34	345.67	345.77
z-stat	4.68	4.36	2.72	2.19	4.01	4.34	–1.01	0.69	1.34	1.30
p-value	2.81×10^{-6}	1.28×10^{-5}	0.0064	0.0283	6.13×10^{-5}	1.44×10^{-5}	0.3144	0.4913	0.1794	0.1951
trend	yes	yes	yes	yes	yes	yes	no	no	no	no
slope	0.0124	0.0152	0.7460	0.5217	0.6795	0.9127	–0.4026	0.2432	0.0008	0.0009
lower	0.0074	0.0090	0.2154	0.0667	0.3824	0.5322	–1.3065	–0.4516	–0.0004	–0.0005
upper	0.0167	0.0215	1.3404	1.0286	0.9826	1.2888	0.3750	0.9516	0.0020	0.0022
Trend direction	↑	↑	↑	↑	↑	↑	–	–	–	–

*

Note: AAT – annual air temperature, ºC; ATGS – air temperature in the growing season, ºC; AR – annual rainfall, mm; GSR – growing season rainfall, mm; AE – annual evapotranspiration, mm; GSE – growing season evapotranspiration, mm; AMD – annual moisture deficit, mm; GSMD – growing season moisture deficit, mm; ARD – annual rainfall distribution; GSRD – growing season rainfall distribution.

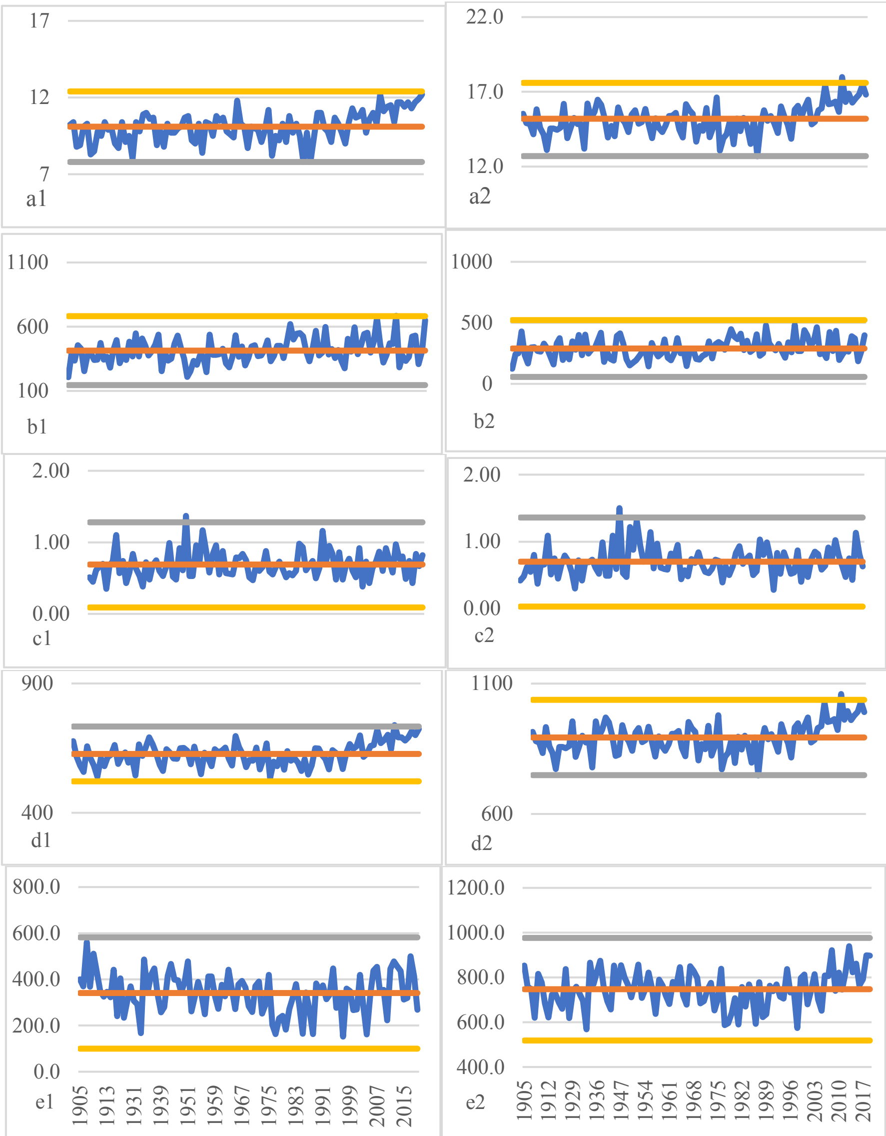


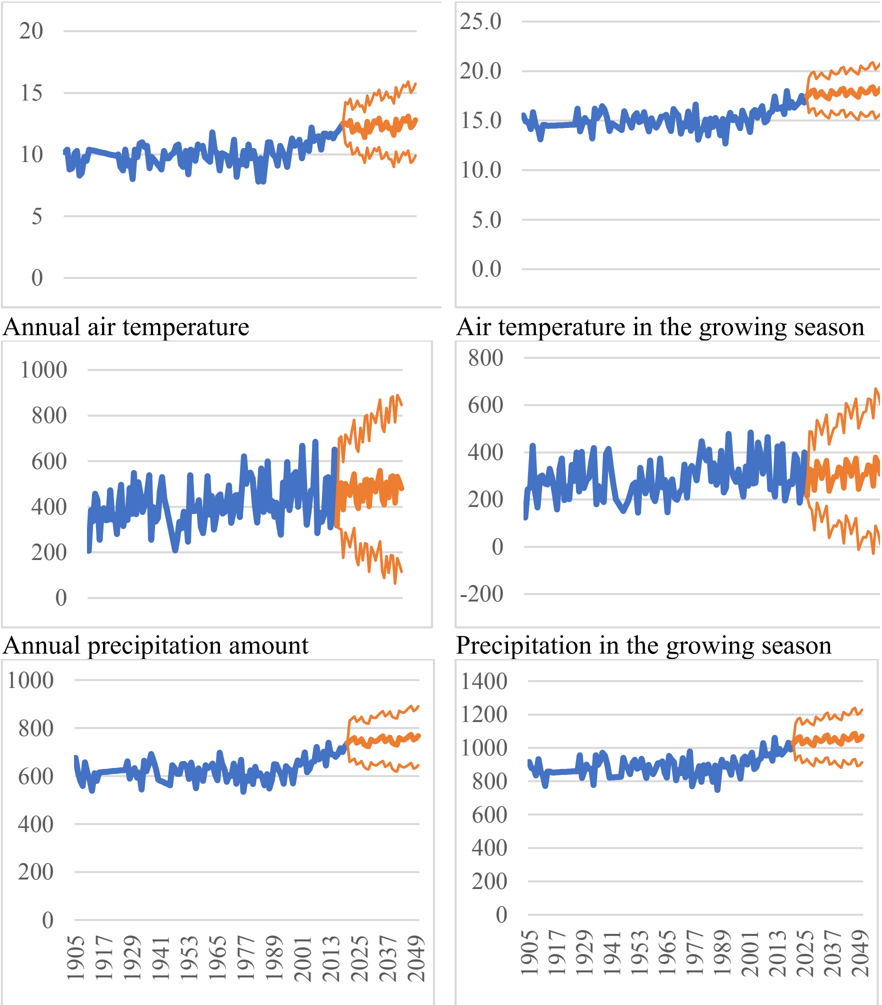
Fig. 3.1.5. Long-term (1905-2020) meteorological analysis of climate conditions in Kherson oblast (blue – meteorological parameter value; red – average value; grey -–UCL; yellow – LCL)*

**Note*: a1 – average annual air temperature, ºC; a2 – average temperature in the growing season (March-October), ºC; b1 – annual precipitation, mm; b2 – precipitation amount in the growing season, mm; c1 – coefficient of variation (*CV*) for the precipitation distribution during the year; c2 – coefficient of variation (*CV*) for the precipitation distribution during the growing season (March-October); d1 – annual evapotranspiration, mm; d2 – evapotranspiration in the growing season, mm; e1 – annual moisture deficit, mm; e2 – moisture deficit in the growing season, mm; UCL – upper control limit; LCL – lower control limit.

The results of the Mann-Kendall and Sen's slope test indicate that in the Kherson region there is no tendency to an increase in the deficit of natural moisture income (calculated as the direct absolute difference between evapotranspiration and the income of natural humidification with precipitation) and a change in the temporal distribution of precipitation. At the same time, statistically significant trends were established to increase air temperature, amount of precipitation, and potential evapotranspiration in the region, both for the year as a whole and during the growing season (Table 3.1.3).

Forecasting of air temperature, precipitation and potential evapotranspiration by the method of triple exponential smoothing by the Holt-Winters method (seasonality of the forecast – 12 years, according to the results of studies by Минасов (2006); confidence interval – 95%) confirmed the presence of a trend towards a significant increase in these indices until 2050 , and the clearest trend is observed for the warming of the temperature regime, and the least clear – for the increase in the amount of precipitation (Fig. 3.1.6). Forecast statistics and an assessment of their accuracy are presented in Table. 3.1.4.

The results of the calculations show the high accuracy of air temperature forecasts (especially during the growing season, testified by the lowest values of *MASE*, *SMAPE*, *MAE*, *RMSE*), while the forecast of precipitation amounts has the lowest accuracy and is characterized by high errors and the greatest amplitude between low and high probability reference values, especially for the annual amount of precipitation. This is explained by the rather high level of internal variation of this meteorological indicator, which on average is 67% for the annual period, and 70% for the growing season (for the prognostic input set of data for 1905-2020).



Annual air temperature

Air temperature in the growing season

Annual precipitation amount

Precipitation in the growing season

Annual evapotranspiration

Evapotranspiration in the growing season

Fig. 3.1.6. Air temperature, precipitation amounts and evapotranspiration forecasts for Kherson oblast up to 2050 (blue – actual values; orange thick – forecast; orange thin – low and high probability lines)

Table 3.1.4

Statistics for air temperature, precipitation amounts and evapotranspiration forecasts for Kherson oblast up to 2050

Statistics	Метеорологічний показник					
	AAT	ATGS	AR	GSR	AE	GSE
Alpha	0.25	0.17	0.25	0.25	0.17	0.17
Beta	0	0	0	0	0	0
Gamma	0	0.08	0.25	0.25	0.08	0.08
MASE	0.94	0.80	1.17	1.05	0.86	0.81
SMAPE	0.07	0.04	0.23	0.26	0.05	0.04
MAE	0.74	0.66	105.34	82.15	30.25	38.44
RMSE	0.89	0.88	128.13	97.92	37.36	51.74

To compare the average meteorological indices for the studied period (1905-2020) with those predicted for the period of 2021-2050 and for the combined period (1905-2050), the calculations were summarized in Table. 3.1.5.

Table 3.1.5

Air temperature, precipitation amounts and evapotranspiration in Kherson oblast in the studied period (1905-2020 pp.), forecasted period (2021-2050 pp.) and combined period (1905-2050 pp.)

Period	Meteorological indices					
	AAT	ATGS	AR	GSR	AE	GSE
1905-2020	10.11	15.20	412.96	289.06	628.63	894.63
2021-2050	11.99	16.90	479.24	314.07	749.58	1049.14
1905-2050	10.49	15.50	424.64	292.48	651.39	921.84

The predicted increase in the studied meteorological indices comparing to the period of 1905-2020 is given in the Table. 3.1.6.

Table 3.1.6

Increase in the air temperature, precipitation amounts and evapotranspiration in Kherson oblast in the period of 2021-2050 comparing to 1905-2020, %

Period	Meteorological indices					
	AAT	ATGS	AR	GSR	AE	GSE
2021-2050	18.60	11.18	16.05	8.65	19.24	17.27

The conducted research and forecast revealed a tendency towards an increase in the air temperature, amount of precipitation, and potential evapotranspiration in the Kherson oblast both in the annual and in the growing seasons. This fact agrees with other studies, which state that the trend of gradual increase in global air and land surface temperature has been maintained in recent decades (Bloschl & Montanari, 2010; Sobrino et al., 2020). However, temperature trends in different parts of Europe differ significantly, so our results are useful for a better understanding of processes that occur in the arid southeastern zone of the continent (Krauskopf & Huth, 2020). It is important that the air temperature tends to increase less during the growing season than on an annual scale. This suggests that the global and local warming of the climate is mainly due to the increase in temperature in the winter period of the year, while the rise of the heat curve in spring and summer is less significant. We find confirmation by the above in the study by Osadchyy & Babichenko (2013), who summarized their findings on the dynamics of air temperature changes in Ukraine, stating that the largest increase of this indicator by 3.0°C was recorded in January, while the average value of the increase was equal to 1.0°C.

As a result, an increase in air temperature leads to a corresponding increase in the related index, potential evapotranspiration. Potential evapotranspiration is one of the main meteorological parameters in aridity and crop risk assessment, which is sometimes used to make reasonable irrigation management decisions instead of reference evapotranspiration (Jensen et al., 1990). High evapotranspiration, which is not covered by sufficient precipitation, leads to crop losses. The Kherson region is a zone of risky agriculture, where precipitation has never covered the moisture expenditures for evaporation; therefore, it is a zone of the highest saturation with irrigation systems in Ukraine (Ромащенко, 2013). Some Ukrainian scientists and specialists in the field of climatology are concerned that in recent decades there has been a tendency towards a sharp increase in potential evaporation, which is obviously additionally accompanied by a certain decrease in the amount of precipitation, and this indicates an increase in the risks of increasing aridity in the region (Голобородько & Димов, 2019). However, this conclusion is the result of an overestimated risk of increasing natural moisture deficit and cannot be confirmed by mathematical analysis of long-term meteorological data, which was reflected in our study. It was established that there is a clear trend towards an increase in the amount of precipitation both in the annual and in the growing season. However, it should be recognized that the increase in precipitation in the future is less than the increase in air temperature and potential evapotranspiration by 2.53-2.55% and 3.19-8.62%, respectively. The superiority in the increase in evapotranspiration during the growing season (8.62%) is obvious, and it can serve as an indirect signal for the expectation of a further increase in the aridity of the climate in the territory of Kherson oblast. However, we emphasize additionally that now there is no mathematically reliable trend toward a significant increase in the direct deficit of natural moisture supply in the region.

Crop production is extremely sensitive to climate change (Porter & Semenov, 2005). Therefore, it is advisable to take additional steps to mitigate the risks associated with the increase in air temperature and evaporation during the growing season, namely: heat stress for agricultural crops, rapid spread of pests and pathogens, etc. (Sutherst et al., 2011). Furthermore, weather conditions have a direct impact not only on yield, but also on the meliorative state of soils, their agrophysical and chemical properties, fertility, as well as on the morphological characteristics of agricultural crops and the level of their physiological resistance to adverse factors (Lavrenko et al., 2018; Lykhovyd, 2019).

According to scientists, rational irrigation in the regions with insufficient natural humidification, such as Kherson oblast, will most likely lead to an increase in the yields of crops (Kang et al., 2009). However, excessive use of artificial irrigation systems can harm the ecological sustainability of the environment by increasing the load on rivers and other natural water sources, intensive leaching of nutrients from soils, the risk of salinization, etc. (Fernández-Cirelli et al., 2011). Therefore, it is necessary to first provide a scientifically based assessment of the effectiveness of irrigation in ensuring the stability of crop production in the region.

In addition, as it has been mentioned above, the assessment of agroclimatic conditions based only on the common meteorological indices and direct moisture deficit is insufficiently informative. Scientists have developed numerous meteorological indices, among which the aridity (dryness) index is the most interesting in the modern conditions of growing aridity of the climate due to the rapid increase in air temperatures.

The assessment of the dynamics of the climatic situation in the Kherson region according to this index is ambiguous for different periods of time. Thus, if we evaluate aggregate data for the period 1905-2020, it is not possible to detect a mathematically significant trend in the change in the level of aridity in the region, although a certain tendency to decrease the value of the aridity index can be clearly observed. Perhaps this is due to the missing data for several years (1907, 1909-1910, 1916-1925, 1934, 1941-1945). At the same time, the assessment of the aridity index for the period of 1973-2020 indicates the presence of a mathematically reliable trend towards a decrease in the value of this indicator, which is evidence of an increase in climatic drought in the region (Table 3.1.7, Fig. 3.1.7-3.1 .8).

Forecasting the dynamics of changes in the aridity index by the method of triple exponential smoothing according to Holt-Winters (seasonality of the forecast is 12 years) indicates that in the future there is a statistically high probability of further intensification of the drought in the Kherson region, and by 2050 the aridity index may reach the mark of 0.22, which corresponds to extremely dry conditions (Table 3.1.8, Fig. 3.1.9).

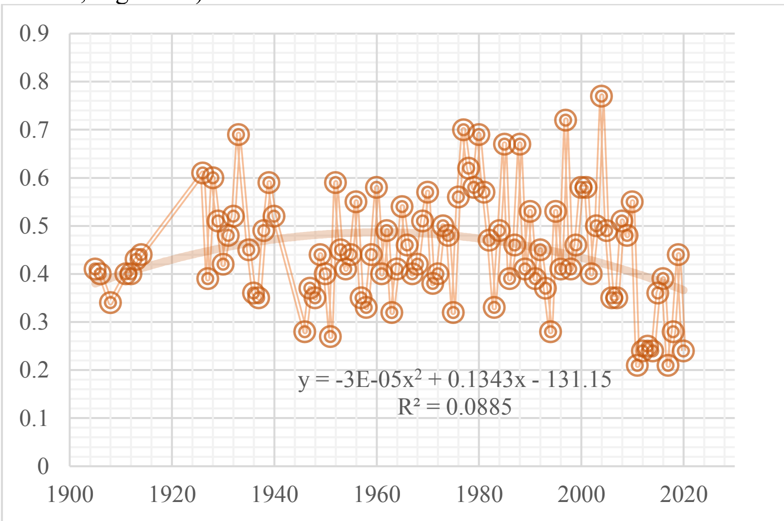


Fig. 3.1.7. Aridity index in Kherson oblast for the period of 1905-2020

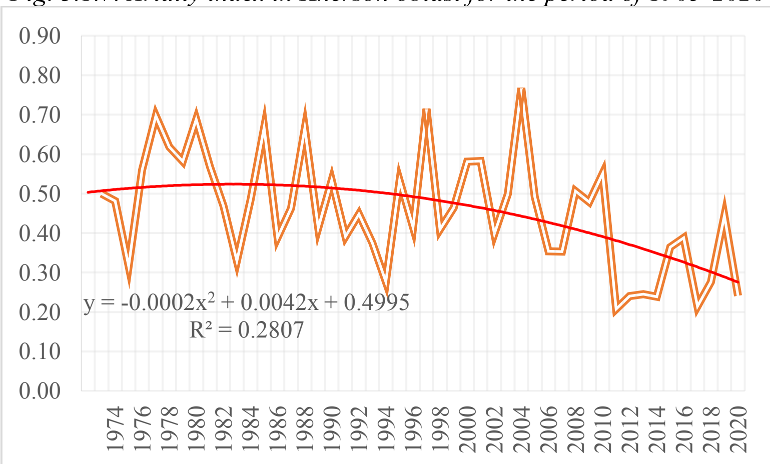


Fig. 3.1.8. Aridity index in Kherson oblast for the period of 1973-2020

Therefore, the assessment of the climatic situation in the region according to the aridity index, in contrast to the assessment of the direct deficit of natural moisture supply, indicates the need to study irrigation as a fundamental factor in the stabilization of crop production in Kherson oblast, since it is currently the main lever to mitigate the negative impact of air and soil drought.

Table 3.1.7

Results of Mann-Kendall and Sen's slope test for aridity index in Kherson oblast for the periods of 1905-2020 and 1973-2020

Statistics	1905-2020	1973-2020
alpha	0.05	0.05
MK-stat	–275	–380
s.e.	315.63	112.51
z-stat	–0.87	–3.37
p-value	0.39	0.00076
trend	no	yes
slope	–0.0004	–0.0052
lower	–0.0013	–0.0076
upper	0.0005	–0.0025
Direction of trend	–	↓

Table 3.1.8

Aridity index forecast statistics for Kherson oblast for 2021-2050

Statistics	Value
Alpha	0
Beta	0
Gamma	0.18
MAPE	0.33
MAE	0.13
MSE	0.02

The role of irrigation in ensuring the stability of crop production is confirmed by the study of the dynamics of the total productivity of the major crops per 1 ha, namely grain crops (wheat, rye, barley, oats, grain corn, millet), sunflower, potatoes, vegetables, fruits, and berries in Kherson oblast over the past 15 years (2005-2019). Along with the increase in aridity in the region, the productivity per 1 ha of the arable land increases (Table 3.1.9). Statistical calculations indicate the presence of an almost equal correlation between productivity parameters, the level of aridity (expressed through the aridity index) and the volumes of water used for irrigation, and in the first case it is inverse (R –0.4619; R^2 0.2133; moderate relationship), and in the second case it is direct (R 0.4759; R^2 0.2264; moderate relationship) (Taylor, 1990). This indicates that the increase in the volume of water used for irrigation had a positive effect on the productivity of arable land by leveling the negative impact on the yield of cultivated crops from the increase in aridity in the region, which is confirmed by the trend towards growth according to the results of the statistical analysis of the time series (Table 3.1.10). At the same time, it should be noted that despite the possibility of tracing the trend towards increasing aridity of the climate in the Kherson region for the period 2005-2019, the Mann-Kendall statistical test does not reveal a reliable trend at the 95% confidence interval, although the usual regression analysis indicates the presence of a weak trend to a decrease in the value of the aridity index, which can be seen from the negative coefficient of the argument of the regression equation –0.0111 (Fig. 3.1.10).

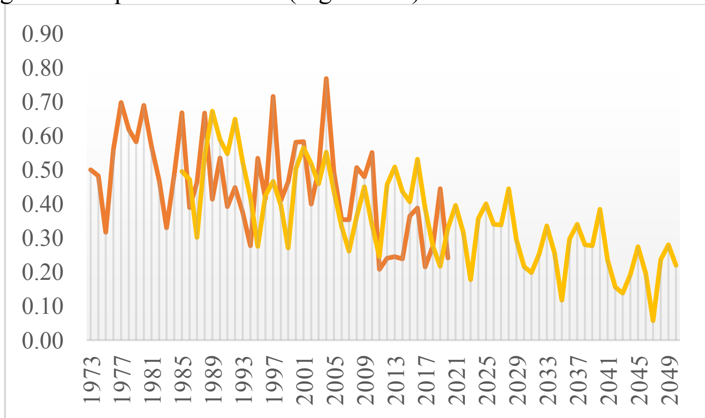


Fig. 3.1.9. Aridity index forecast for Kherson oblast for 2021-2050

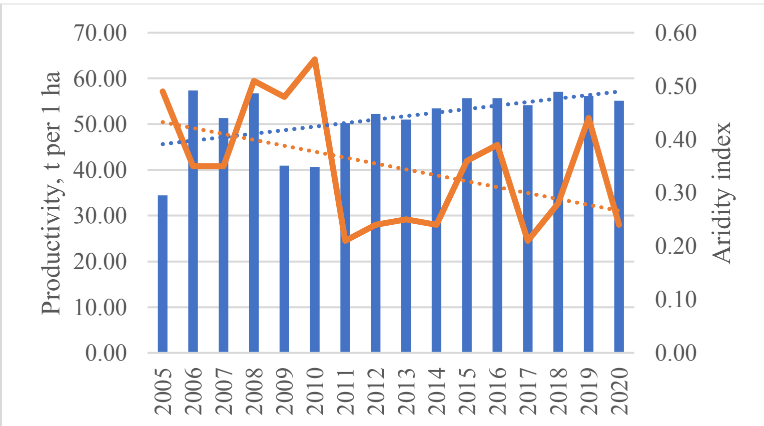


Fig. 3.1.10. Total productivity per 1 ha of arable land and aridity index in Kherson oblast for 2005-2019 (blue – total productivity of 1 ha of arable land; orange – aridity index; dotted lines – trend lines for productivity and aridity index, respectively)

The clearest trend to increase was recorded for the volume of irrigation water use (R^2 0.7378), which additionally confirms the conclusion about the clear and strong dependence of the productivity of crops in the region on irrigation, especially against the background of modern changes in weather conditions (Fig. 3.1.11).

Table 3.1.9

Climate change, total productivity per 1 ha of arable land and irrigation water volumes usage in Kherson oblast for 2005-2019

Year	Evapotranspiration, mm/day	Precipitation, mm/day	Aridity index	Irrigation water volumes used, million m^3	Total productivity per 1 ha of arable land, t
2005	2.60	1.28	0.49	515.0	34.41
2006	2.48	0.88	0.35	519.5	57.34
2007	2.96	1.04	0.35	825.6	51.33
2008	2.54	1.29	0.51	594.0	56.75
2009	2.67	1.28	0.48	686.9	40.91
2010	3.41	1.88	0.54	695.2	40.69
2011	3.75	0.78	0.20	877.6	50.22
2012	4.25	1.02	0.23	943.6	52.26
2013	3.73	0.92	0.24	988.6	50.98
2014	4.19	1.00	0.23	984.1	53.46
2015	3.94	1.44	0.35	960.6	55.70
2016	3.73	1.45	0.38	913.8	55.72
2017	3.96	0.85	0.20	1203.0	54.12
2018	4.07	1.12	0.27	1174.0	57.09
2019	4.02	1.78	0.43	923.4	56.15

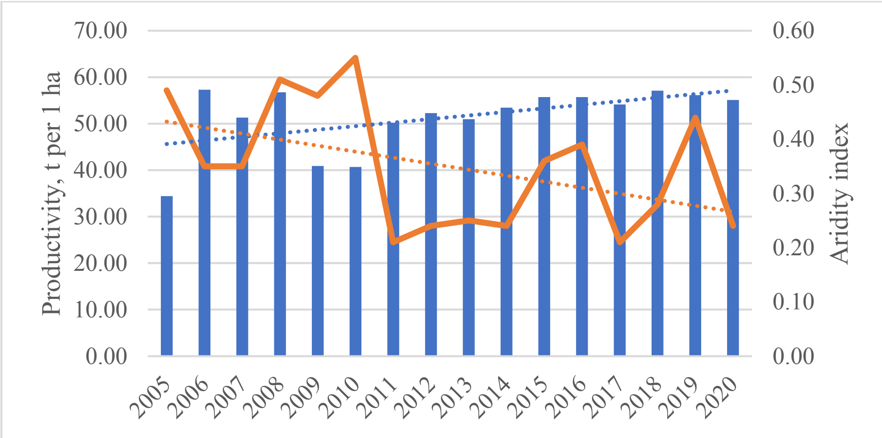


Fig. 3.1.10. Total productivity per 1 ha of arable land and aridity index in Kherson oblast for 2005-2019 (blue – total productivity of 1 ha of arable land; orange – aridity index; dotted lines – trend lines for productivity and aridity index, respectively)

Table 3.1.10

Results of Mann-Kendall and Sen's slope test for aridity index, irrigation water volumes and total productivity of 1 ha of arable land in Kherson oblast for 2005-2019

Statistics	Aridity index	Irrigation water volumes	Total productivity of 1 ha of arable land
alpha	0.05	0.05	0.05
MK-stat	–20	41	71
s.e.	20.06656	20.20726	20.20726
z-stat	–0.94685	1.979487	3.464102
p-value	0.343716	0.047761	0.000532
Trend	no	yes	yes
slope	–0.01	0.74125	43.925
lower	–0.02417	–0.02083	23.65
upper	0.01	1.65125	58.075
Direction of trend	not applicable	↑	↑

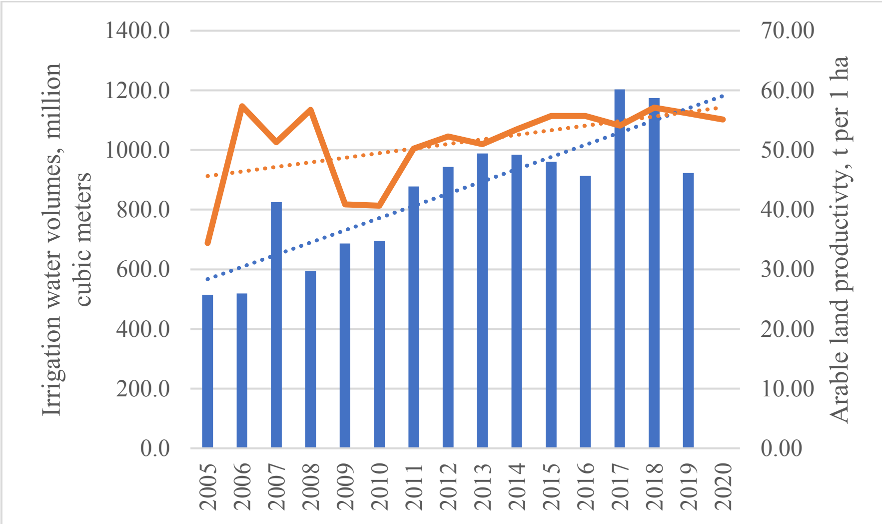


Fig. 3.1.11. Total productivity per 1 ha of arable land and aridity index in Kherson oblast for 2005-2019 (blue – irrigation water volumes; orange – arable land productivity; dotted lines – trend lines for productivity and irrigation water volumes, respectively)

The results of the regression analysis of the multiple relationship between the total productivity of 1 ha of arable land, the aridity index and the volumes of irrigation water use confirmed that the increase in the aridity of the climate has an adverse effect on crop yield in the Kherson region (negative value of the regression coefficient). The regression model has the form as in 3.1.1:

$$TP = 48.1667 - 14.8869AI + 0{,}0096IW \qquad (3.1.1)$$

where: *TP* – total productivity of 1 ha of arable land, t; *AI* – aridity index; *IW* – irrigation water volume, million m^3.

The presented model has reasonable prognostic value, which is confirmed by the values of statistical indices: correlation coefficient – 0.5071; determination – 25.72%; MAPE is 9.9520% (Table 3.1.11) (Moreno et al., 2013).

According to the results of the statistical evaluation (the Durbin-Watson *DW* criterion is close to 2.0), the absence of autocorrelation in the relationship between the total productivity of arable land, the aridity index and the volumes of irrigation water used in the region is proven (Суслов и др., 2005).

Table 3.1.11

Statistics of the model for dependence of total arable land productivity on aridity index and irrigation water use in Kherson oblast for 2005-2019

Regression statistics	Value
R	0.5071
R^2	0.2572
R^2_{adj}	0.1334
R^2_{pred}	0.4013
MSE	42.2402
S	6.4992
$MAPE$, %	9.9520
$PRESS$	956.1653
$PRESS\ RMSE$	7.9840
DW	2.0308
AIC	6.7581
BIC	6.8997
AIC_c	6.8248
HQC	6.7566

Statistical analysis of data for a 15-year period indicates that irrigation is an important and irreplaceable factor for ensuring the sustainable production of plant products in the Kherson region, which had in the past and remains with the status of a zone of risky agriculture due to significant climate aridity, associated with a significant deficit of natural humidification and temporal and spatial instability and uneven supply with natural moisture (Бычков и др., 1987). In view of the above, one of the main priority tasks in the region should be the complete reconstruction of existing irrigation systems and the construction of new ones, including local ones capable of providing high quality irrigation water to small areas. Furthermore, the quality of water for irrigation requires careful study and amelioration, since the parameters of the quality of irrigation water will significantly affect the characteristics of soil fertility, its agro-meliorative state, biological, physical, chemical, mechanical properties, which in turn will determine the parameters of the growth, development and yield formation processes in the crops, and therefore will determine the economic and ecological efficiency of irrigation (Lykhovyd et al., 2019).

3.2. Dynamics and forecasting temperature regime and aridity level in the context of irrigation needs in Ukraine

Studying the temperature regime on the territory of Ukraine is one of the important stages of assessing climatic processes that have a direct impact on agricultural activity.

In recent years, against the background of global climate warming, in many parts of the Earth, an abnormal increase in annual air temperatures has been observed, which is reflected in the productivity and stability of agroecosystems.

A retrospective analysis of data on the average annual air temperature on the territory of Ukraine (including the Donetsk, Luhansk regions and the Crimea) for the period 1753-2020 revealed a clear trend towards a gradual increase in the value of this meteorological index, which has become particularly acute in recent decades (Fig. 3.2.1).

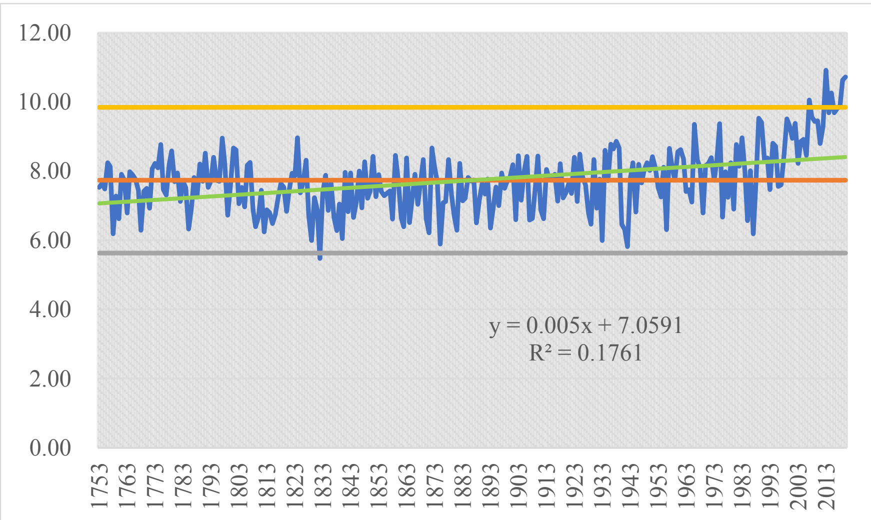


Fig. 3.2.1. Retrospective analysis of the average annual air temperature in Ukraine during 1753-2020 (blue – average annual temperature; red – average for the long-term period; green – trend line; orange – UCL; grey – LCL)

A stable transition of the average annual air temperature in Ukraine over the +9.0ºC has occurred since 2012. The upper control limit is consistently reached and exceeded during 2017-2020 (the average annual air temperature is consistently above +9.8ºC). Since 1998, there has not been a single year with an average annual air temperature in Ukraine below +8.0ºC (the minimum average annual temperature was +8.2ºC in 2003). This indicates a stable trend of climate warming in the country, and therefore, the inevitability of changes in the agricultural sector of production.

Many researchers have established the cyclic nature of changes in the climate at the global and regional scales, and the patterns of periodicity depend on the duration of the period of studying the climate and the geographical area.

For example, cyclic climate fluctuations with a periodicity of 50-70 years were recorded for the level of the hemispheres and the global planetary level (Schlesinger & Ramankutty, 1994; Minobe, 1997; Klyashtorin & Lyubushin, 2005). It is worth saying that similar periods of seasonality of climate change were obtained by analytical retrospective processing of indirect natural climate indicators (for example, by the growth rings of long-living tree species, fluctuations in the number of populations of certain species of fish and animals, etc.) over a very long period of 1,500 years. Hypotheses about 30- and 60-year cycles of change dominate here. In addition, it is interesting that the frequency of climatic changes in different intermediate stages of the 1500-year period is not the same: for example, the frequency of 160 years for the period from the beginning of the 1200s to the end of the 1300s; 33-year cycle for the period from the 1300s to 1700s; the 55-year period is for the period from the 1500s to the 1900s, etc.

At the same time, climatologists at the 1935 (Warsaw) and 1957 (Washington) conferences recommended using 30-year periods to assess dynamic climate characteristics (Klyashtorin & Lyubushin, 2005). This recommendation is consistent with those of Bruckner (who emphasized a 35.5-year cycle) and Bogolepov (who recommended a 33-year period as the most reliable). At the same time, Bogolepov, during the analysis of short-term periods, additionally discovered 11-year and 2.8-3.5-year periods within the 33-year period (Чижевский).

To characterize and assess the dynamics of the global temperature anomaly over a 140-year period, a 13-year moving average was used (Klyashtorin & Lyubushin, 2005). At the same time, it was established that the dynamics of the global temperature anomaly over the past 140 years is characterized by an upward trend with a 60-year seasonality overlap (Klyashtorin & Lyubushin, 2003).

Considering the above, here we applied 12-year seasonality for forecasting changes in climate indices for time series with a duration of about 100 years, and 36- and 60-year seasonality for forecasting time series with a duration of more than 150 years.

For a better idea of the possible consequences of the current temperature trend, it is worth forecasting the temperature regime in the country, at least for the coming years (until 2050). It is technically impossible to predict the development of the temperature regime using the Holt-Winters triple exponential smoothing method with high seasonality (36 and 60 years). The use of artificial neural networks is a promising, but not always justified, method (Vozhehova et al., 2019). Therefore, we consider the best option in this case (the availability of a continuous time series of data for a period of 268 years) to perform mathematical and statistical modeling using the SARIMA method (seasonal autoregressive model based on an integrative moving average) with 36- and 60-year seasonality (Fig. 3.2.2, Fig. 3.2.3).

In addition, the fitting of the accuracy and quality of the developed models were compared according to the Akaike (*AIC*) and Schwartz (*BIC*) criteria, as well as by the value of the mean square error (*MSE*) and standard deviation (*SD*). It was established that the scenario of the development of climatic processes with a forecast seasonality of 36 years is more likely and accurate (Table 3.2.1).

Table 3.2.1

Comparison of the models' quality for average annual air temperature forecasting in Ukraine until 2050 by SARIMA methodology

Indices	36-year seasonality	60-year seasonality
Model coefficients		
const	0.0075	0.0106
phi 1	0.0532	0.1755
theta 1	–0.8957	–0.9160
Phi 1	–0.3008	–0.4356
Theta 1	–0.6278	–0.3426
Statistical criteria and standard deviation		
AIC	–45.5566	–16.9081
BIC	–29.2173	–1.9901
MSE	0.7510	0.8317
SD	1.3907	1.3998

The forecast with a 36-year seasonality makes it possible to say that on the territory of Ukraine in the period 2021-2050, the average annual air temperature will fluctuate within +9.5...11.1°C, and the forecast with a 60-year cyclical component is within +9.5...11.2°C, which is the difference in the temperature curves is not significant (Table 3.2.2).

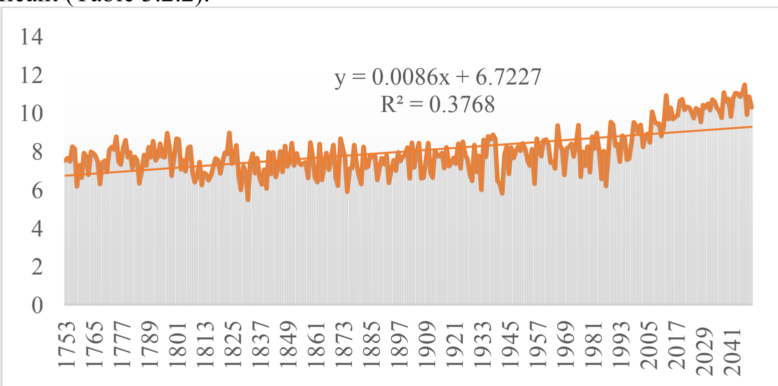


Fig. 3.2.2. Average annual air temperature in Ukraine forecast for the period 1753-2050 (36-year seasonality)

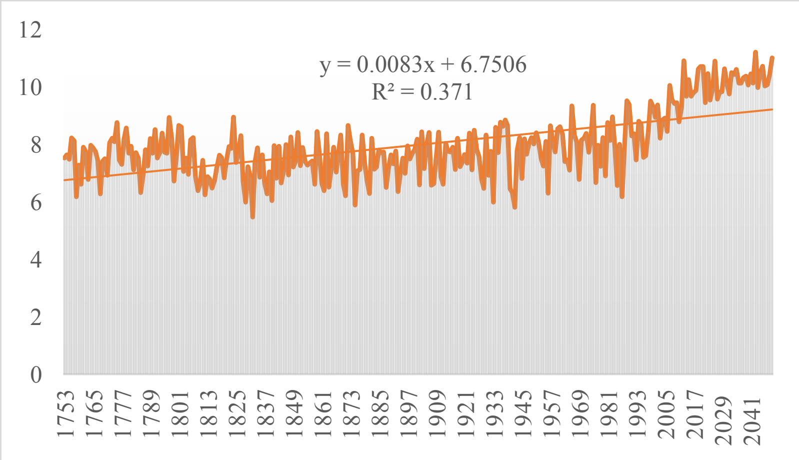


Fig. 3.2.3. Average annual air temperature in Ukraine forecast for the period 1753-2050 (60-year seasonality)

Therefore, in any scenario of the development of the temperature regime, significant warming is expected in the territory of Ukraine, which will inevitably impact agricultural production. It is impossible to unequivocally assess the impact of rising temperatures as positive or negative, since the change of this agrometeorological indicator is almost always accompanied by desirable consequences (for example, the possibility of introducing new heat-loving species and varieties of plants with a long growing season, the possibility of double- and even triple-cropping, etc.), which anyway can significantly shake the stability of plant production (increasing aridity, accelerated development of existing on the territory of the country and the appearance of new harmful organisms and pathogens, reduction of the effectiveness of certain groups of plant protection agents, etc.) according to Боума (2012).

The primary task of the crop production and land reclamation sector in scenarios of climate development with an increase in the temperature regime is to ensure a stable supply of sufficient moisture for the formation of a sustainable, high-quality harvest, which can be implemented in practice only if there is a theoretical basis for assessing the needs for providing artificial humidification in different agroclimatic zones of the country, taking into account the water demand of various crops. For this purpose, it is necessary to reassess the humidification regimes on the territory of Ukraine, considering the current climatic conditions, since the calculations and zoning have lost relevance now.

As it has already been shown in the section 3.1, the most rational assessment of the aridity of the climate allows the calculation of the integrative aridity index. At the same time, it is best to plan about moisture supply in a complex way: both by the value of the aridity index, which is a quantitative indicator of the degree of aridity of the climate (Budyko, 1958), as well as by the indicator of moisture content in the soil. Such an assessment will most accurately reflect the real level of moisture availability of the territory in view of the production of plant products.

Table 3.2.2

Average annual air temperature in Ukraine for 2021-2050 forecasted by SARIMA with 36-year and 60-year seasonality

Year	Average annual air temperature, ºC	
	SARIMA-36	SARIMA-60
2021	10.17	10.72
2022	10.31	9.46
2023	10.28	10.47
2024	10.03	9.55
2025	9.73	9.94
2026	10.25	10.91
2027	10.15	9.58
2028	9.53	9.83
2029	10.42	9.83
2030	10.29	10.64
2031	10.48	10.14
2032	10.15	9.76
2033	10.70	10.51
2034	10.59	10.44
2035	10.27	10.62
2036	10.10	10.14
2037	9.74	10.13
2038	11.06	10.33
2039	10.59	10.38
2040	10.73	10.07
2041	9.80	10.47
2042	10.77	10.13
2043	11.03	11.22
2044	11.01	9.98
2045	10.84	10.51
2046	11.04	10.72
2047	11.47	10.03
2048	9.91	10.08
2049	10.85	10.42
2050	10.30	11.02

The soil moisture regimes on the territory of Ukraine were summarized on satellite monitoring data provided by the Soil Explorer software product. Fig. 3.2.4 displays the prevailing moisture regimes for each region.

According to the data of Soil Explorer and decoding of conventional names by information, provided by Soil Information for Environmental Modeling and Ecosystem Management, four regimes of soil moisture are typical for the territory of Ukraine:

Aridic – soils, which are dry at the depth of the control profile (0-50 cm) for more than half of the cumulative number of days in the year, have a temperature at a depth of 50 cm above 5ºC, partially or fully hydrated for a period of less than 90 days at a temperature at a depth of 50 cm above 8ºC.

Xeric – soils, which are dry at the depth of the control profile (0-50 cm) for at least 45 consecutive days in a period of 4 months after the summer solstice, while being wet for at least 45 consecutive days during the 4-month period following the winter solstice. The average annual temperature of such soils does not exceed +22 ºC.

Udic – soils, which for at least 90 consecutive days do not have any dry part of the control profile (0-50 cm). Such soils are quite moist, characteristic of those types of climate, when evapotranspiration is completely compensated by precipitation or moisture coming into the soil from other sources (for example, from groundwater).

Ustic – soils, which occupy an intermediate position between the Aridic and Udic classes. Usually, such soils, although limited in terms of moisture, can accumulate enough moisture to ensure acceptable growth and development of cultivated plants.

The classification of climatic regimes according to the aridity index is given in Table. 3.2.3 (Colantoni et al., 2015).

Table 3.2.3

Aridity index and climate type

Aridity index (*AI*)	Climate type
<0.05	Extremely arid (EA)
0.05–0.20	Arid (A)
0.20–0.50	Semi-arid (SA)
0.50–0.65	Dry subhumid (DS)
0.65–0.75	Humid (H)
>0.75	Hyper humid (HH)

In accordance with the types of climate and classes of soils according to the moisture regime, a combined method of classifying the territory according to the need for irrigation was developed, while simultaneously considering the requirements for moisture supply of various crops (Table. 3.2.4).

Table 3.2.4

Classification of the territories for irrigation requirements based on the soil moisture class and climate type

Soil moisture class	Climate type	Irrigation requirements
Aridic	SA	Obligatory for most crops
	DS	Obligatory for most crops
	H	Desirable for the crops with high demand for water
	HH	Desirable for the crops with high demand for water
Xeric	SA	Obligatory for most crops
	DS	Desirable for the crops with high demand for water
	H	Desirable for the crops with extremely high demand for water
	HH	No need
Ustic	SA	Desirable for the crops with high demand for water
	DS	Desirable for the crops with extremely high demand for water
	H	No need
	HH	No need
Udic	SA	Desirable for the crops with high demand for water
	DS	Desirable for the crops with extremely high demand for water
	H	No need
	HH	No need

Such crops as millet and sorghum have high drought resistance and can form yields even under moisture deficit conditions, as well as melon crops. Winter and spring cereal crops are examples of the crops with moderate water requirements, grain corn, soybeans require an increased water supply to form high yields, while most vegetables (tomatoes, cucumbers, cabbage), fruits and berry crops, perennial grasses (except sainfoin) have extremely high demand for water supply (Баздырев и др., 2019; Кононюк та ін., 1985).

Due to the independence of the territories from Ukraine and the impossibility of obtaining archival meteorological data for the periods 1991-2020, the climate regime of Donetsk and Luhansk regions was not conducted. The assessment of the climatic regime of the Crimea for the periods after 2014 was carried out according to the data of the Russian Hydrometeorological Center.

Based on the results of the climatic and soil moisture regimes assessment, the maps of aridity and maps of irrigation requirements by the regions of Ukraine were created. The assessment of regional indicators was carried out according to the data of regional hydrometeorological centers. Meteorological data, obtained at regional hydrometeorological stations, can be considered quite representative for each region, as a preliminary study of the maximum amplitude of the deviation of the aridity index within each region of Ukraine at different weather stations testified that they are within 15% and often cannot serve as a criterion for the transition of the region to another aridity group. The results of the study of climate types for different time periods on the territory of Ukraine are presented in the Table 3.2.6.

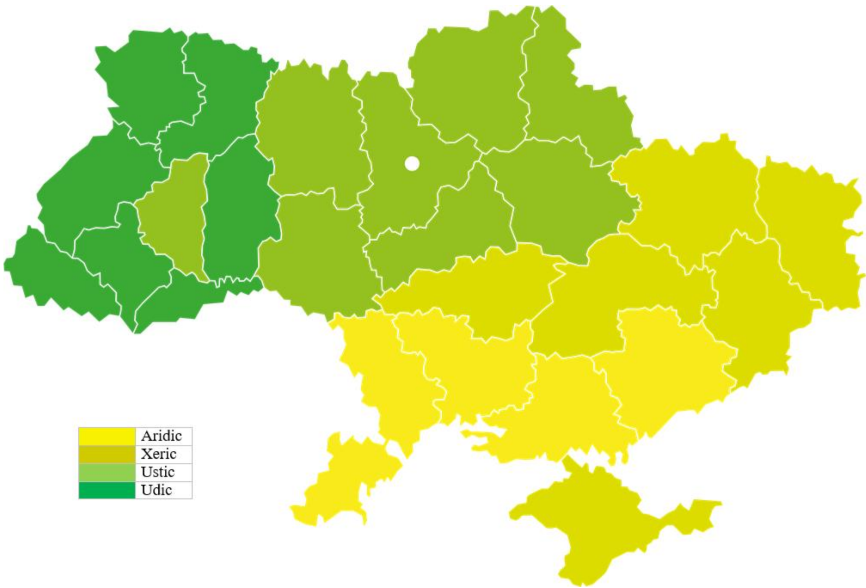


Fig. 3.2.4. Soil classes in the territory of Ukraine according to Soil Explorer surveys

Analysis of the aridity index in dynamics indicates that the most significant changes in its value with the transition of several regions to drier zones in recent years have occurred in the northern and western regions of Ukraine, while southern regions did not change their climatic status. However, the increasing aridity of the climate on the territory of Ukraine as a whole, as well as in each region, is obvious, especially since 2010. This is confirmed by the results of the statistical assessment of the climatic trend of the aridity index for the period 1991-2020 (Table 3.2.7).

Table 3.2.5

Variation of aridity index and aridity level within the regions of Ukraine by the data of regional hydrometeorological centers and stations (1961-1990)

Region (Oblast)	Hydrometeorological stations				Amplitude, %
	Regional center	I	II	III	
Cherkasy	0.67 H	0.72H	0.65H/DS		7.46
Chernivtsi	0.85HH				–
Chernihiv	0.81HH	0.88HH			8.64
Dnipropetrovsk	0.56DS	0.51DS	0.55DS		8.93
Ivano-Frankivsk	0.93HH	0.86HH			7.53
Kharkov	0.57DS	0.64DS	0.62DS		12.28
Kherson	0.40SA	0.41SA	0.38SA		5.00
Khmelnitsky	0.86HH	0.84HH	0.79HH		8.14
Kirovograd	0.56DS	0.63DS	0.59DS		12.50
Kyiv	0.88HH	0.87HH	0.82HH	0.76HH	13.64
L’viv	1.08HH	0.94HH	0.93HH		13.89
Volyn	0.80HH	0.75H/HH	0.87HH		8.75
Mykolaiv	0.47SA	0.52DS	0.42SA		10.64
Odesa	0.45SA	0.51DS	0.45SA	0.46SA	13.33
Poltava	0.60DS	0.63DS	0.68H		13.33
Rivne	0.81HH	0.82HH	0.77HH		4.94
Sumy	0.76HH	0.84HH	0.76HH		10.53
Ternopol	0.90HH	0.88HH			2.22
Zakarpattia	0.90HH	0.73H			18.89
Vinnitsa	0.80HH	0.79HH	0.86HH		7.50
Zaporizhzhia	0.49SA	0.48SA	0.50SA		4.08
Zhytomyr	0.83 HH	0.86 HH	0.90HH		8.43
Crimea	0.54DS	0.36SA	0.42SA	0.53DS	33.33

Mykolaiv, Poltava, Zakarpattia, and the Crimea regions can serve as an exception, where differences in aridity are primarily related to different climatic features of plain and mountainous areas, and in the Crimea – additionally to the features of the climate of the southern coast. Significant deviations on the flat territory are observed only in Mykolaiv and Poltava regions, which are related to the geographical features of the location of hydrometeorological stations (Table 3.2.5).

Table 3.2.6

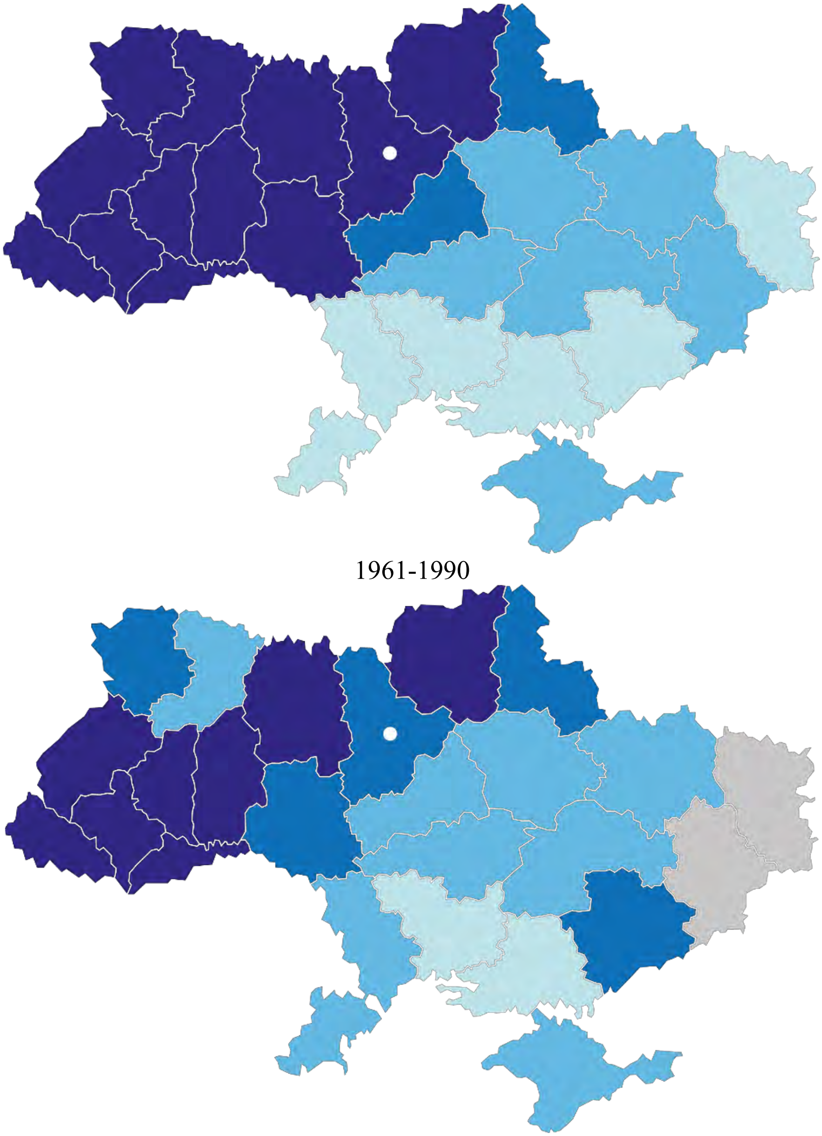
Soil moisture class, aridity index and climate type by the regions of Ukraine for 1961-2020

Region (Oblast)	Soil moisture class	Aridity index (1961-1990)	Climate type (1961-1990)	Aridity index (1991-2020)	Climate type (1991-2020)	Aridity index (1991-2000)	Climate type (1991-2000)	Aridity index (2001-2010)	Climate type (2001-2010)	Aridity index (2011-2020)	Climate type (2011-2020)
Cherkasy	Ustic	0.67	H	0.63	DS	0.95	HH	0.55	DS	0.41	SA
Chernivtsi	Udic	0.85	HH	0.77	HH	1.17	HH	0.71	H	0.43	SA
Chernihiv	Ustic	0.81	HH	0.76	HH	1.15	HH	0.66	H	0.47	SA
Dnipropetrovsk	Xeric	0.56	DS	0.61	DS	0.92	HH	0.57	DS	0.34	SA
Ivano-Frankivsk	Udic	0.93	HH	0.82	HH	1.15	HH	0.79	HH	0.51	DS
Kharkov	Xeric	0.57	DS	0.61	DS	0.91	HH	0.57	DS	0.36	SA
Kherson	Aridic	0.40	SA	0.41	SA	0.46	SA	0.50	HA	0.28	SA
Khmelnitsky	Udic	0.86	HH	0.86	HH	1.34	HH	0.80	HH	0.44	SA
Kirovograd	Xeric	0.56	DS	0.57	DS	0.87	HH	0.55	DS	0.30	SA
Kyiv	Ustic	0.88	HH	0.75	H	1.13	HH	0.65	DS	0.46	SA
L'viv	Udic	1.08	HH	1.02	HH	1.48	HH	0.94	HH	0.63	H
Volyn	Udic	0.80	HH	0.70	H	0.93	HH	0.62	DS	0.54	DS
Mykolaiv	Aridic	0.47	SA	0.44	SA	0.61	DS	0.40	SA	0.31	SA
Odesa	Aridic	0.45	SA	0.61	DS	0.69	H	0.71	H	0.44	SA
Poltava	Ustic	0.60	DS	0.82	HH	0.98	HH	1.04	HH	0.43	SA
Rivne	Udic	0.81	HH	0.73	DS	1.05	HH	0.73	H	0.42	SA
Sumy	Ustic	0.74	H	0.93	HH	1.36	HH	1.01	HH	0.41	SA
Ternopol	Ustic	0.90	HH	0.92	HH	1.23	HH	1.13	HH	0.41	SA
Zakarpattia	Udic	0.90	HH	0.82	HH	1.18	HH	0.74	H	0.55	DS
Vinnitsa	Ustic	0.80	HH	0.73	H	1.13	HH	0.66	H	0.39	SA
Zaporizhzhia	Aridic	0.49	SA	0.68	H	0.82	HH	0.80	HH	0.42	SA
Zhytomyr	Ustic	0.83	HH	1.00	HH	1.32	HH	1.08	HH	0.60	DS
Crimea	Xeric	0.54	DS	0.64	DS	0.84	HH	0.73	H	0.36	SA
Luhansk	Xeric	0.43	SA	–	–	–	–	–	–	–	–
Donetsk	Xeric	0.54	DS	–	–	–	–	–	–	–	–

Table 3.2.7

Results of Mann-Kendall and Sen’s slope analysis for aridity index by the regions of Ukraine on the period 1991-2020

Region (Oblast) Cherkasy	Statistical indices								
	alpha	MK-stat	s.e.	z-stat	p-value	trend	slope	lower	upper
Chernivtsi	0.05	-263	55.94	-4.68	2.82×10^{-6}	↓	-0.0267	-0.0347	-0.0159
Chernihiv	0.05	-261	56.03	-4.64	3.48×10^{-6}	↓	-0.0309	-0.0430	-0.0208
Dnipropetrovsk	0.05	-316	56.02	-5.62	1.88×10^{-8}	↓	-0.0262	-0.0370	-0.0196
Ivano-Frankivsk	0.05	-274	56.02	-4.87	1.10×10^{-6}	↓	-0.0220	-0.0296	-0.0167
Kharkov	0.05	-240	55.98	-4.27	1.96×10^{-5}	↓	-0.0275	-0.0377	-0.0180
Kherson	0.05	-310	56.02	-5.52	3.48×10^{-8}	↓	-0.0236	-0.0314	-0.0180
Khmelnitsky	0.05	-124	55.96	-2.20	2.79×10^{-2}	↓	-0.0069	-0.0129	-0.0007
Kirovograd	0.05	-288	56.02	-5.12	3.01×10^{-7}	↓	-0.0385	-0.0491	-0.0280
Kyiv	0.05	-283	55.99	-5.04	4.74×10^{-7}	↓	-0.0242	-0.0307	-0.0183
L’viv	0.05	-286	55.98	-5.09	3.56×10^{-7}	↓	-0.0294	-0.0375	-0.0218
Volyn	0.05	-258	56.02	-4.59	4.49×10^{-6}	↓	-0.0354	-0.0450	-0.0246
Mykolaiv	0.05	-180	55.98	-3.20	1.39×10^{-3}	↓	-0.0155	-0.0253	-0.0050
Odesa	0.05	-171	55.95	-3.03	2.38×10^{-3}	↓	-0.0100	-0.0167	-0.0033
Poltava	0.05	-141	55.98	-2.50	1.24×10^{-2}	↓	0.0107	-0.0186	-0.0039
Rivne	0.05	-185	56.01	-3.28	1.02×10^{-3}	↓	-0.0253	-0.0380	-0.0139
Sumy	0.05	-241	56.03	-4.28	1.84×10^{-5}	↓	-0.0253	-0.0347	-0.0183
Ternopol	0.05	-315	55.99	-5.61	2.05×10^{-8}	↓	-0.0429	-0.0558	-0.0346
Zakarpattia	0.05	-234	56.04	-4.16	3.22×10^{-5}	↓	-0.0387	-0.0528	-0.0250
Vinnitsa	0.05	-205	56.01	-3.64	2.71×10^{-4}	↓	-0.0229	-0.0309	-0.0129
Zaporizhzhia	0.05	-312	56.04	-5.55	2.87×10^{-8}	↓	-0.0315	-0.0405	-0.0225
Zhytomyr	0.05	-197	56.01	-3.50	4.66×10^{-4}	↓	-0.0183	-0.0259	-0.0105
Crimea	0.05	-262	55.99	-4.66	3.14×10^{-6}	↓	-0.0374	-0.0473	-0.0240
Region (Oblast)	0.05	-253	55.99	-4.50	6.77×10^{-6}	↓	-0.0240	-0.0300	-0.0164
UKRAINE	0.05	-307	56.05	-5.46	4.78×10^{-8}	↓	-0.0262	-0.0315	-0.0218



Figh. 3.2.5. Dynamics of the aridity index in Ukraine for 1961-2020

SA DS H HH

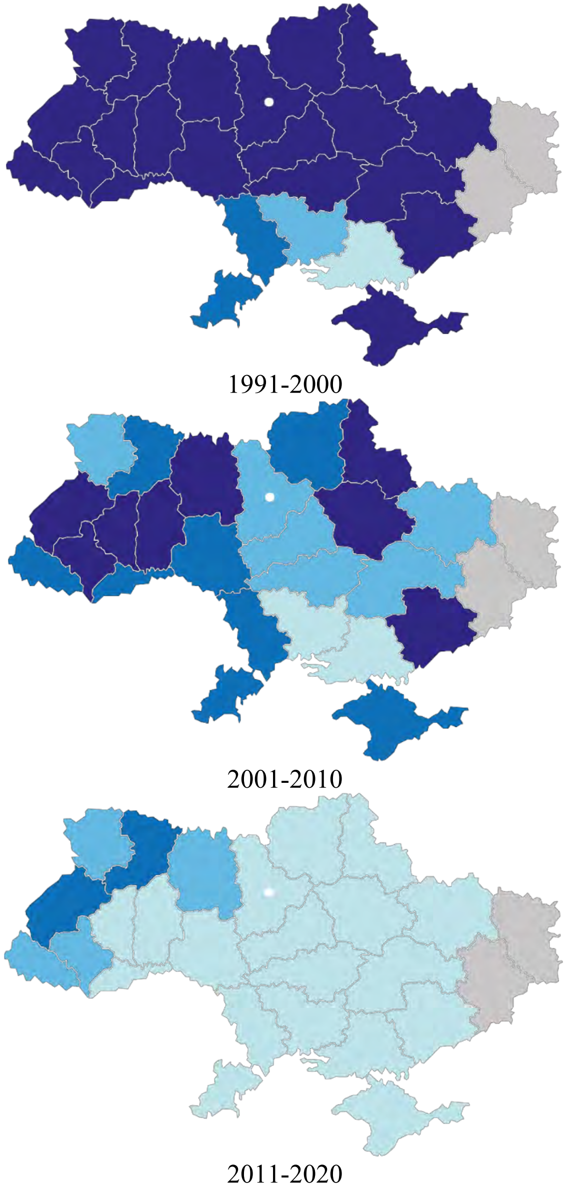


Fig. 3.2.6. Dynamics of the aridity index by the regions of Ukraine for the decades of the period 1991-2020

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Mapping the aridity index over 30-year periods makes it possible to visually assess the degree of climate transformation in Ukraine. The period 1991-2020 is marked by an increase in aridity and a moisture deficit compared to 1961-1990 on the territories of Cherkasy, Vinnitsa, Kyiv, Volyn, Rivne oblasts, while Odesa and Zaporizhzhia regions are characterized by a transition to more favorable zones in terms of the moisture supply.

The dynamics of climatic changes in recent decades can be tracked in more detail by the decades of 1991-2020. If the period 1991-2000 was characterized as favorable in terms of moisture level and most of the territory of Ukraine was in humid and hyper humid zones (excepting Kherson and Mykolaiv regions), then, starting from 2001, there is a period of gradual transformation of the climate to a more arid, which originates in the regions of the central and partly northwestern part of the country. In the period 2011-2020, most of the territory of Ukraine is in the semi-arid zone. except for the territory of certain northwestern regions (Fig. 3.2.6).

The most intense climatic changes over the past 30 years have occurred in Chernihiv, Kharkov, Sumy and Vinnitsa regions (minimum values of statistical indices *MK*-stat < -300 and *p*-value $<10^{-7}$). At the same time, the lowest intensity of climatic changes was in such regions as Kherson, Volyn, Mykolaiv, Odesa, Poltava and Zaporizhzhia oblasts (*MK*-stat > –200, *p*-value > 10^{-5}). The maximum increase in aridity (minimum lower slope values) is observed in such regions of Ukraine as Chernivtsi, Khmelnitsky, L'viv, Sumy, Ternopil, Vinnitsa, Zhytomyr (mainly the northern and western regions of the country), while the minimum dynamics is characteristic of such regions as Kherson, Mykolaiv, Odesa, Zaporizhzhia, Dnipropetrovsk, Volyn regions that is the southern territories of Ukraine do not suffer from an extremely rapid increase in aridity (Table 3.2.7).

Trends in the development of the climatic situation in the regions of Ukraine are presented in Fig. 3.2.7.A-D. A graphic assessment of the dynamics visually confirms the results of the mathematical and statistical assessment and makes it possible to visually assess the degree of intensity of climate change.

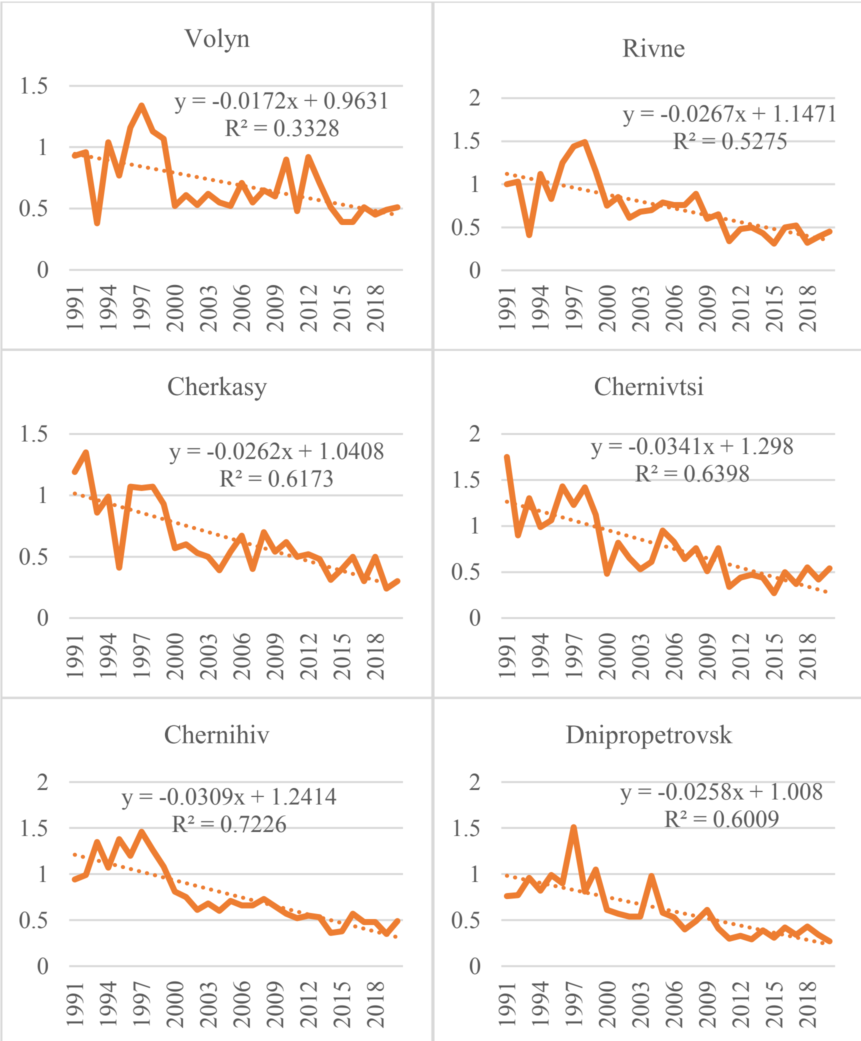

Fig. 3.2.7.A. Trend in the aridity index by the regions of Ukraine for 1991-2020

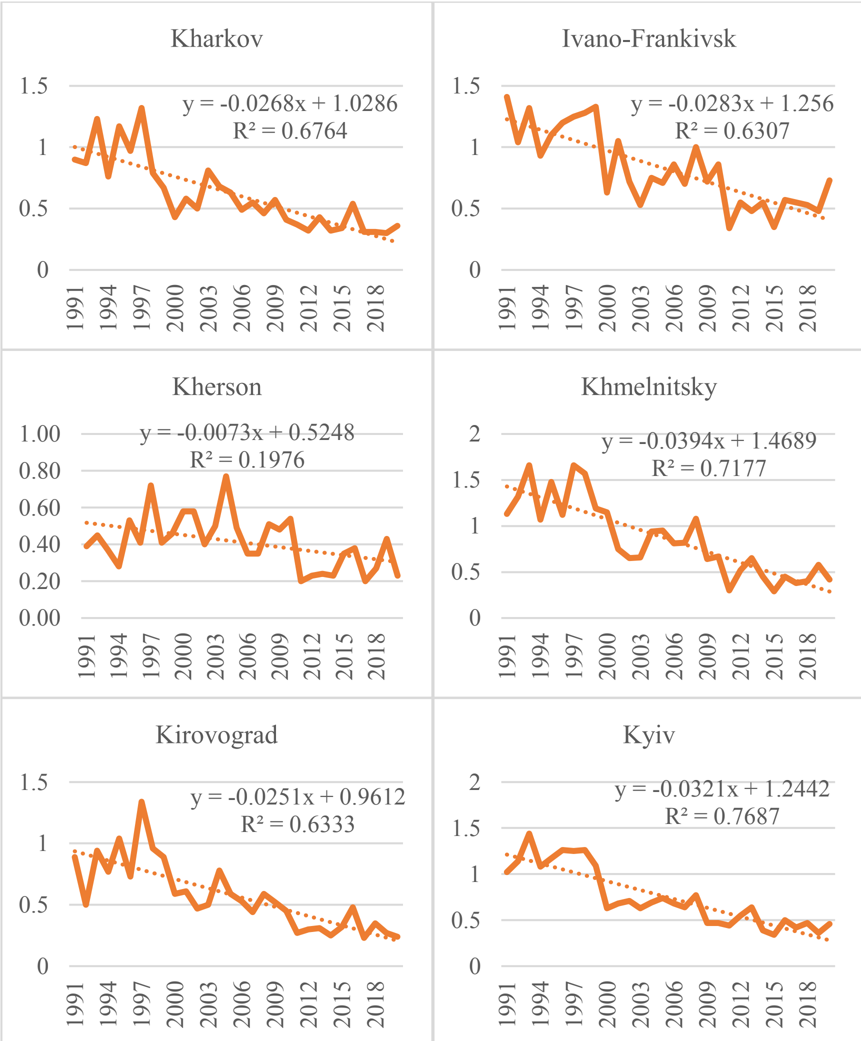

Fig. 3.2.7.B. Trend in the aridity index by the regions of Ukraine for 1991-2020

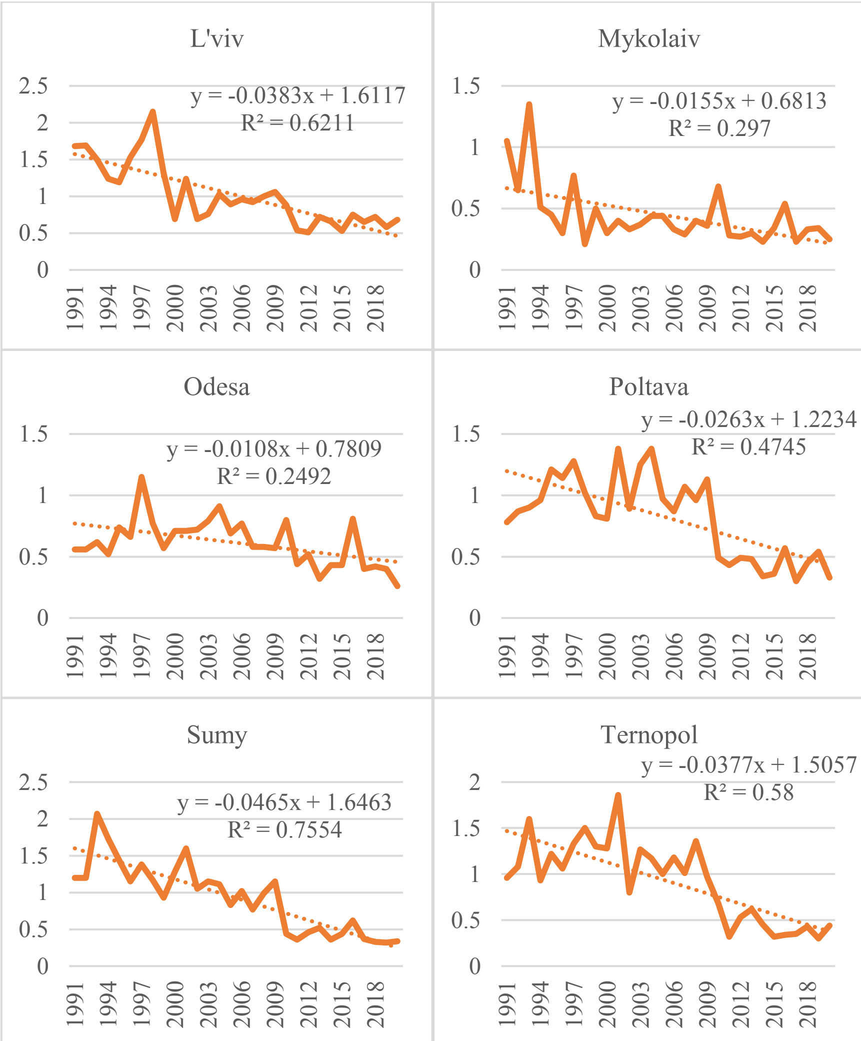

Fig. 3.2.7.C. Trend in the aridity index by the regions of Ukraine for 1991-2020

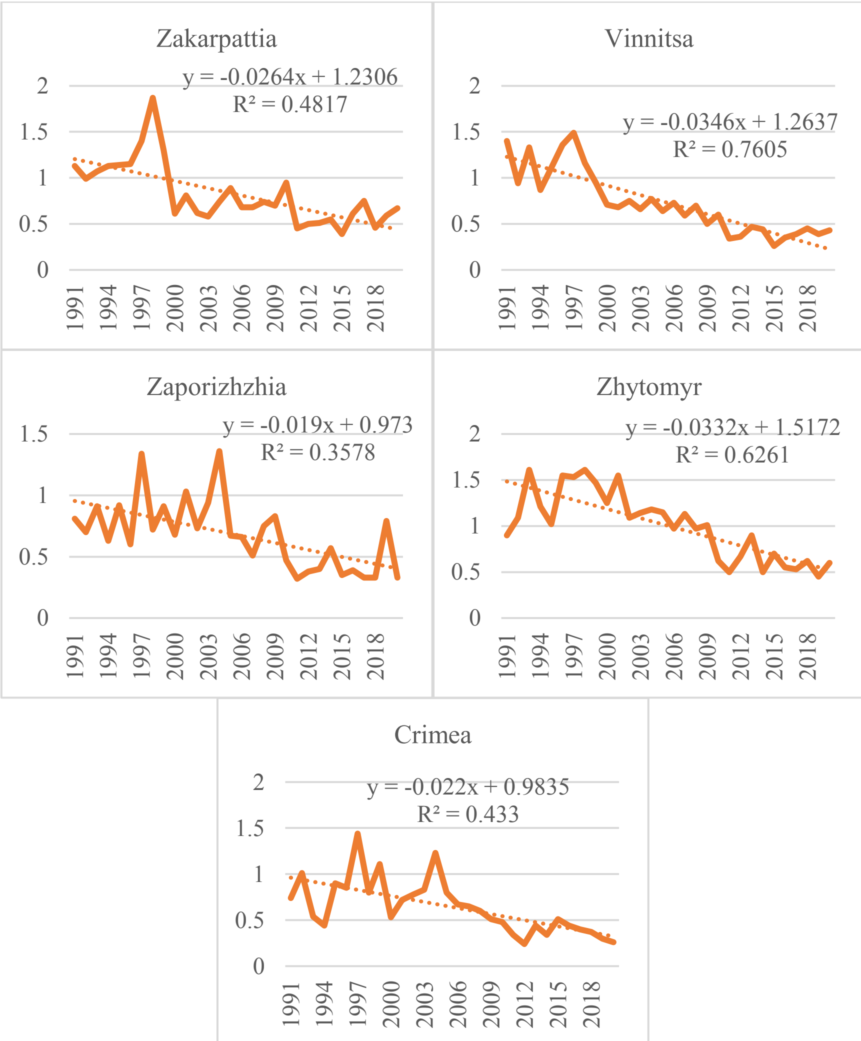

Fig. 3.2.7.D. Trend in the aridity index by the regions of Ukraine for 1991-2020

An interesting and practically valuable additional method of studying the climatic situation and assessing risks in agriculture and crop production is forecasting the possible development of climatic events. The most successful option here will be short-term forecasting using an autoregressive algorithm with floating seasonality, i.e., SARIMA.

Table 3.2.8

Aridity index and climate type by the regions of Ukraine forecasted by SARIMA for 2030 and average for the period 2021-2030

Region (Oblast)	2030	2021–2030
Cherkasy	0.52 DS	0.40 SA
Chernivtsi	0.54 DS	0.44 SA
Chernihiv	0.46 SA	0.41 SA
Dnipropetrovsk	0.40 SA	0.33 SA
Ivano-Frankivsk	0.67 H	0.56 DS
Kharkov	0.33 SA	0.36 SA
Kherson	0.20 SA/A	0.20 SA/A
Khmelnitsky	0.73 H	0.65 DS/H
Kirovograd	0.27 SA	0.27 SA
Kyiv	0.53 DS	0.49 SA
L’viv	0.90 HH	0.83 HH
Volyn	0.55 DS	0.50 DS/SA
Mykolaiv	0.52 DS	0.38 SA
Odesa	0.61 DS	0.58 DS
Poltava	0.69 H	0.63 DS
Rivne	0.42 SA	0.41 SA
Sumy	0.73 H	0.62 DS
Ternopol	0.87 HH	0.78 HH
Zakarpattia	0.70 H	0.62 DS
Vinnitsa	0.59 DS	0.50 DS/SA
Zaporizhzhia	0.55 DS	0.52 DS
Zhytomyr	0.58 DS	0.50 DS/SA
Crimea	0.37 SA	0.28 SA

Forecasting the future development of climate aridity in Ukraine for the period 2021-2030 based on data from 1991-2020 using the SARIMA method with automatic determination of seasonality (which fluctuated within 3-6 years depending on the region) indicates significant fluctuations in the climatic situation in different regions of the country. In most regions of Ukraine the preservation of the climatic situation is likely to be observed, typical for the period 2011-2020, and further progression of aridity is also possible (in particular, in the Kherson and Zhytomyr regions) in some regions (L'viv, Khmelnitsky, Ternopol, Vinnitsa, Poltava, Sumy, Odesa, Zaporizhzhya) one can expect the climate to change to a more humid that will have a favorable effect on the crop production and the reduction of irrigation needs (Table 3.2.8).

The map of the predicted level of the territory of Ukraine humidification level for the period 2021-2030 is presented in Fig. 3.2.8. Compared with the map of the period 2011-2020, a significant increase in moisture availability is noticeable in the West of the country and in certain regions of the South and Northeast.

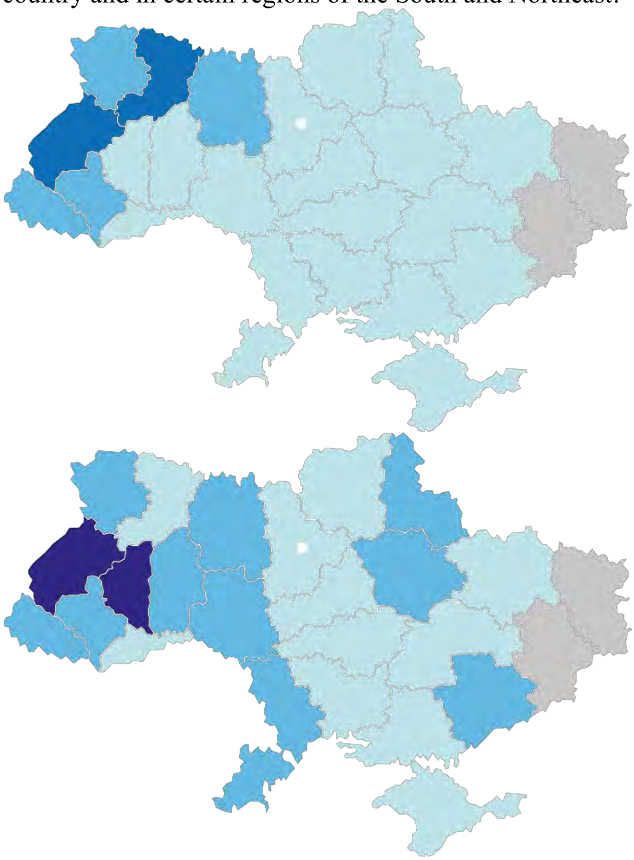

Fig. 3.2.8. Dynamics of aridity index by the regions of Ukraine by the data for 2011-2020 and predicted period 2021-2030

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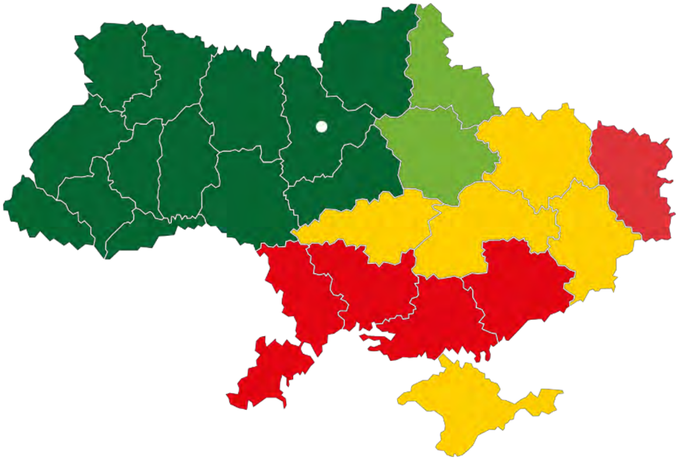
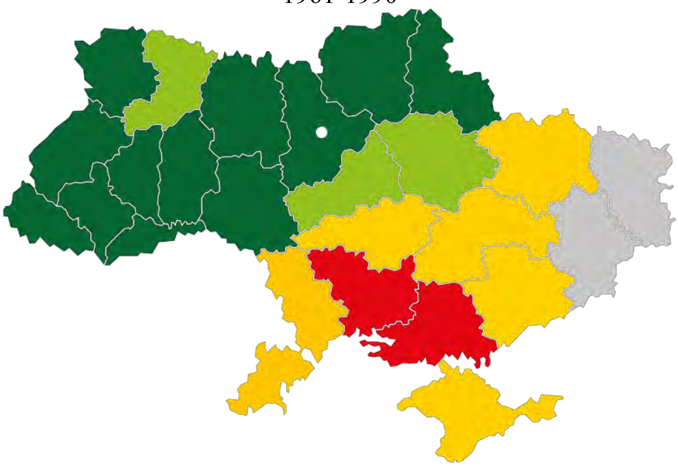


1961-1990



1991-2020

Fig. 3.2.9. Irrigation requirements for different crops by the regions of Ukraine for 30-year periods

Obligatory for most crops

Required for the crops with high water demand

Required for the crops with extremely high demand for water

No need

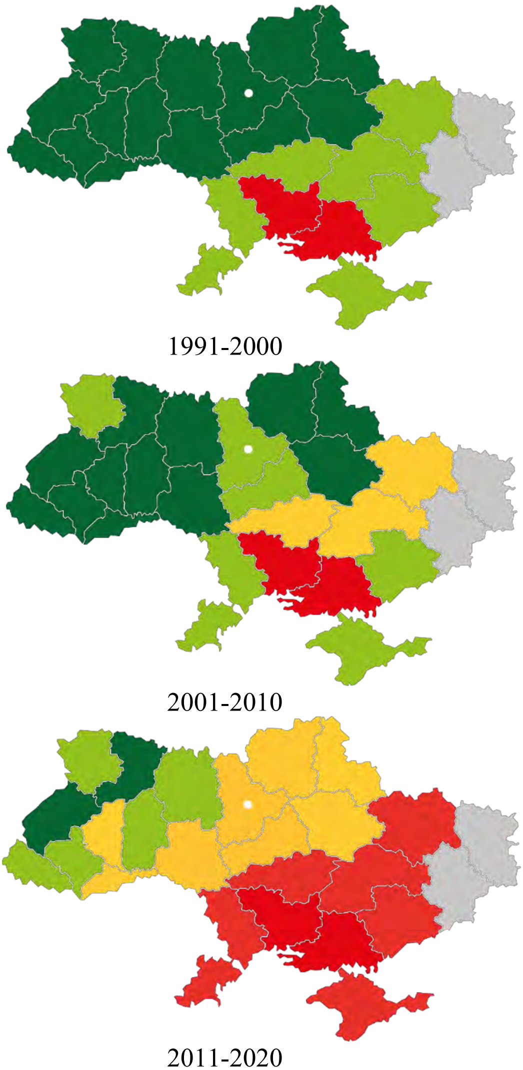


Fig. 3.2.10. Irrigation requirements for different crops by the regions of Ukraine for 10-year periods

Obligatory for most crops
Required for the crops with high water demand
Required for the crops with extremely high demand for water
No need

Compilation of irrigation requirements maps by the regions of Ukraine based on the results of Soil Explorer surveys and the aridity index indicates an increase in the need for artificial water supply to cultivated plants in most of the country. When analyzing 30-year periods (1961-1990 and 1991-2020), the difference is practically imperceptible. only a certain restructuring in the classification of regions (Fig. 3.2.9). The analysis of 10-year periods indicates a gradual increase in irrigation needs in almost all regions of Ukraine since 2001 (Fig. 3.2.10).

Therefore, currently, almost all the regions of Ukraine require irrigation to one degree or another for sustainable crop production, except for a few western regions (L'viv and Rivne regions do not need irrigation, Zhytomyr, Khmelnitsky, Ivano-Frankivsk, Zakarpattia and Volyn regions will need irrigation only for the crops with extremely high and specific needs for moisture supply – for example, some vegetable crops, perennial grasses, grapes, some fruits, and berry crops). Until the 2000s, irrigation was relevant only in the southern and central parts of the country, now it is also relevant for the northern and eastern regions.

Considering the results of forecasting the further dynamics of the aridity level in Ukraine until 2030, the irrigation requirements map for the period 2021-2030 will have the following form (Fig. 3.2.11).

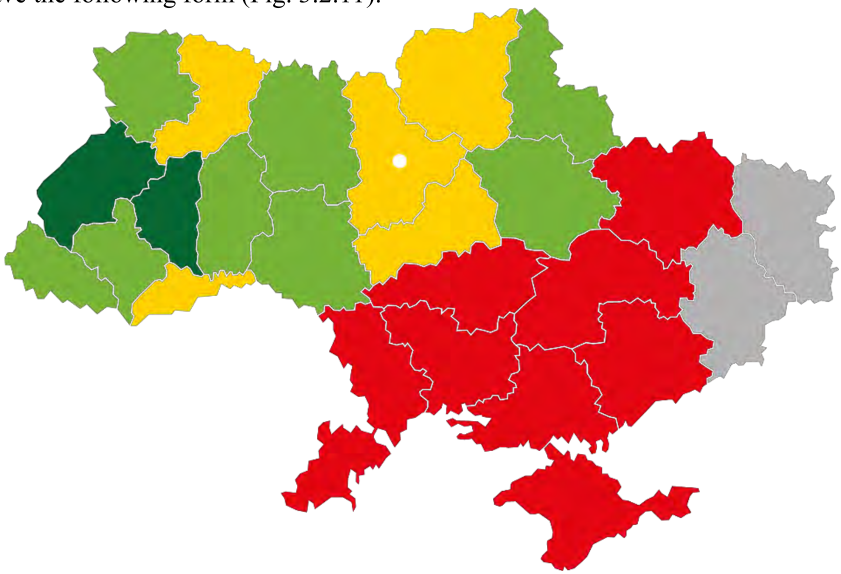


Fig. 3.2.11. Irrigation requirements for different crops by the regions of Ukraine for the forecasted period 2021-2030

Markedly that the level of requirements for artificial humidification for southern and central Ukraine will remain unchanged compared to the current period, but in the West and in the Poltava and Sumy regions, we can expect a decrease in irrigation needs.

However, a significant discrepancy is observed between the actual availability of irrigation systems and the possibilities of providing artificial humidification with real needs for it. And the problem is not only in the lack of irrigation systems, but also in their inadequate technical condition, improper use, as well as the economic and legal aspects of regulating the conduct of reclamation works and the provision of relevant services to agricultural producers, which in aggregate is the main inhibiting factor of active and effective use of available capacities in irrigated agriculture. As of 2019, of 2.17 million hectares of irrigated land in Ukraine, only 532 thousand hectares received water, and this is only 24.5%. Considering the established trends of increasing climatic drought on the territory of Ukraine even under a favorable scenario, more than 50% of the country's territory will require irrigation for effective crop production, and according to some forecasts, up to 70% of arable land in Ukraine will suffer from a lack of moisture by 2050 (Юрченко, 2021). According to some calculations, as of 2016, 18.7 million hectares (60%) of arable land in Ukraine require permanent artificial moistening during the cultivation of field crops to ensure a deficit-free moisture balance, another 4.8 million hectares (15%) are subject to periodic irrigation (Ромащенко та ін., 2020). That is, a total of about 75% of Ukrainian lands require irrigation. Ромащенко та ін. (2015) noted that on the territory of the Steppe, namely on the lands of the Kherson, Mykolaiv, Odesa and Zaporizhzhia regions, profitable cultivation of most crops is possible only under irrigation conditions, which is currently the main factor and driving force for ensuring the growth of agricultural productivity and stable production of high-quality crop production.

According to our calculations for the period 2011-2020, intensive irrigation for all types of crops cultivated in Ukraine (except for certain drought-resistant species, for example, millet) is needed in the territory of 8 regions with a total area of cultivated areas of more than 12 million hectares as of 2019 (excluding cultivated areas in the Crimea). Another 8 regions with a total cultivated area of 9.37 million hectares need moderate irrigation. Only 5 regions with a cumulative cultivated area of 3.44 million hectares can grow field crops without using irrigation, which is required there only for certain crops that are extremely demanding for moisture, and only 2 regions have a sufficient level of moisture for all types of crops (1.29 million ha). So, in 2019, more than 75% of arable land required irrigation, 42.9% of them are intensive (Статистичний щорічник України 2019, 2020), which completely confirms the data of Ромащенко та ін. (2020). So, irrigation requirements are now met at best by 10%. and considering the low level of actual exploitation of existing irrigation systems, then only by 2.5%. This is a catastrophically low level and if measures are not taken to renew the full exploitation of the existing ones (first of all, in the territory of the Kherson, Odesa, Mykolaiv, and Zaporizhzhia regions, where 1,084 thousand hectares or 49.75% of all irrigated lands of Ukraine are now located) and the construction and commissioning of new irrigation systems in the first turn on the territory of the regions that are the most vulnerable to increasing aridity (in the Kirovograd, Dnipropetrovsk, and Kharkov regions, where the actual area of irrigated land is only 198.7 thousand hectares). In the coming decade, Ukraine may experience the negative consequences of climate change and enter a collapse. gradually transforming from a powerful agrarian state into one. which will not be able to fully satisfy internal needs for crop production (Сидоренко та ін., 2016).

So, it is proved that irrigation under modern conditions of climatic transformations is the main means of intensification and stabilization of crop production in Ukraine, not only in its southern regions, which traditionally belonged to the zone of risky farming, but also at the national level.

3.3. Operational reference evapotranspiration assessment as an important precondition for smart irrigation

Rational planning of the irrigation regime is impossible without considering the water balance, i.e., the difference between moisture income and consumption. The main agrometeorological index, which is widely used in international practice and is the basis for determining the amount of moisture consumption, is evapotranspiration. The standard and most accurate method of its installation is the lysimeter method, which involves the field installation of a special complicated tool – a lysimeter – to track the movement of moisture along the soil profile and its direct losses. Calculation methods to determine evapotranspiration and their accuracy are calibrated on the results of lysimeter measurements. The high cost, labor-intensiveness, and need for specialized personnel limit the use of the lysimeter method in scientific research works and do not make it possible to recommend it as the main one for the mass production practice of irrigated agriculture, where the most relevant are the much less expensive and easier-to-implement calculation methods for the indirect determination of evapotranspiration (Kashyap & Panda, 2001).

Now there are several dozens of calculation methods for indirectly establishing the value of potential or reference evapotranspiration (Cruff & Thompson, 1967; Tabari et al., 2013). In this work, we will focus on 16 of them in more detail.

1) Holdridge's method. One of the simplest methods for determining potential evapotranspiration on an annual scale was widely used in climatology (Holdridge, 1959). Calculations are performed according to formula 3.3.1:

$$E = 58.93 \times BT \tag{3.3.1}$$

where: E – annual evapotranspiration, mm; BT – annual biological temperature (it takes into account only positive temperatures above 0ºC, temperatures below 0ºC are taken as 0ºC).

The disadvantage of the technique is the impossibility of using it for operational scheduling of irrigation, as well as the need for calibration. When comparing the results of the assessment of annual evapotranspiration in the Kherson region for the period 1973-2019, calculated according to Holdridge and Penman-Monteith (standardized FAO method, calculations were performed in the ET_o Calculator program), a discrepancy of 37.03% was obtained. With additional calibration of the method using linear regression, the accuracy of the calculations became acceptable - the error was 11.41%. At the same time, the equation changed the coefficient from 58.93 to 96.38 (Вожегова та ін., 2020). Thus, to improve the accuracy of the estimate of annual evapotranspiration, the Holdridge equation must undergo a coefficient refinement procedure for each individual region of Ukraine.

2) Hargreaves method. There are four equations developed for climatic conditions with different levels of humidity. Hargreaves & Samani (1985) offer the following options for calculations (3.3.2):

$$
\begin{aligned}
ET_o &= 0.408 \times 0.0030 \times (T_a + 20) \times (T_{max} - T_{min})^{0.4} \times R_a \\
ET_o &= 0.408 \times 0.0025 \times (T_a + 16.8) \times (T_{max} - T_{min})^{0.5} \times R_a \\
ET_o &= 0.408 \times 0.0013 \times (T_a + 17) \times (T_{max} - T_{min} - 0.0123P)^{0.76} \times R_a \\
ET_o &= 0.408 \times 0.0023 \times (T_a + 17.8) \times (T_{max} - T_{min})^{0.424} \times R_a \qquad (3.3.2)
\end{aligned}
$$

where: ET_o – evapotranspiration, mm/day; P – precipitation, mm; T_a, T_{max}, T_{min} – average, maximum and minimum air temperatures, ºC; R_a – insolation income, MJ/m^2/day.

The Hargreaves method is one of the most common methods of establishing evapotranspiration for the needs of agricultural science. The equation is relatively simple, and there are computer programs and mobile applications that integrate this evapotranspiration estimation technique. However, it has a slightly lower accuracy than the standardized FAO Penman-Monteith method, but at the same time requires a much smaller set of input data, which determines the high popularity of the method among farmers all over the world.

3) Thornthwaite's method. Developed in 1948 to estimate potential evapotranspiration. The equation for the calculation looks like this (3.3.3):

$$e_T = 1.6 \times \left(\frac{10T}{I}\right)^c \qquad (3.3.3)$$

where: e_T – evapotranspiration for 30-day period (daily evapotranspiration cannot be assessed using this methodology), cm; T – average monthly air temperature, ºC; I – heating index; c – cubic function of I.

This technique has a significant drawback – it requires obtaining a specific meteorological index and is not suitable for daily calculations. However, Thornthwaite provided a nomogram to facilitate the determination of evapotranspiration from mean monthly temperatures, as well as tables of approximate heat index values by month and latitude that are relevant to North America (Thornthwaite, 1948). Therefore, an additional limitation is the need for additional calibration of Thornthwaite's data nomograms and tables for the conditions of Ukraine.

4) Lowry-Johnson method. It was developed to estimate annual evapotranspiration. Calculations are made according to the formula (3.3.4):

$$E = 0{,}00185H + 10.4 \quad (3.3.4)$$

where: E – annual evapotranspiration, inches; H – effective heating amount, which is determined as a sum of average daily temperatures above 32ºF.

As it is evident, this method is not suitable for farmers for a number of reasons: it is impossible to calculate daily evapotranspiration; the need to additionally establish the effective heat index in unconventional units of measurement (Lowry & Johnson, 1942).

5) The Blaney-Criddle method. It is interesting primarily because this technique is aimed at calculating the amount of evapotranspiration for different types of cultivated vegetation (reference evapotranspiration). The methodology was developed after a number of field studies and measurements in the territory of the West of the USA. Evapotranspiration is calculated using the formula 3.3.5:

$$E = K\sum\frac{T\times p}{100} \quad (3.3.5)$$

where: E – evapotranspiration for a certain period of plants growth, inches; K – empirical coefficient of water use by plants; p – percentage of insolation relatively to the whole duration of the period; T – average monthly temperature, ºF.

The technique was not widely used in practice because of its narrow specificity. In special tabular appendices to the methodology, Blaney and Griddle provide values of the percentage of duration of sunshine for each month of the year in different latitudes of the West of the United States, as well as values of the crop coefficient (Blaney & Griddle, 1950). However, the evaluation of the calculation method proved its high accuracy and quality of model fit compared to the standard one (Tabari et al., 2013).

6) Hamon's method. In 1961, the scientist formulated a simplified equation for estimating potential evapotranspiration (3.3.6):

$$E_T = CD^2P_t \tag{3.3.6}$$

where: E_T – potential evapotranspiration, inches per day; C – empirical coefficient (Hamon suggested it to be 0.55); D – insolation, hours; P_t – absolute air humidity, sg/m^3.

As one can see, Hamon's method is interesting and practical for use in the agricultural sector, as it allows daily determination of evapotranspiration. However, it is worth admitting that it is not always possible to find the actual values of the duration of sunlight and absolute air humidity (especially in centigrams) to perform calculations. In addition, the empirical coefficient was calibrated by Hamon for US conditions, so in other climates it is likely that additional calibration of its value is required to ensure sufficient accuracy of the calculations (Hamon, 1961).

7) Schendel's method. One of the simplest methods of calculating evapotranspiration, which does not require a large amount of hard-to-reach meteorological data (3.3.7):

$$ET_o = \frac{T_a}{RH} \times 16 \tag{3.3.7}$$

where: ET_o – evapotranspiration, mm/day; T_a – average air temperature, ºC; RH – relative air humidity, %.

This technique is very convenient, but it is significantly inferior in accuracy to other, more complex methods of calculating evapotranspiration (Tabari et al., 2013).

8) The Jensen-Haise method. Developed in 1963 (Jensen & Haise, 1963). The calculations are performed by the equation 3.3.8:

$$ET_o = \frac{C_T \times (T_a - T_x) \times R_S}{\lambda} \tag{3.3.8}$$

where: ET_o – evapotranspiration, mm/day; C_T – temperature constant (it is usually taken as 0.025); T_a – average air temperature, ºC; T_x – standardized correction argument (it is taken as –3); R_s – solar radiation, cal/cm^2/day; λ – latent heat, calories per gran.

The model requires specific input data, in addition, its accuracy is not high, and therefore practical application in agricultural production is limited (Tabari et al., 2013).

9) McGuinness & Bordne (1972) proposed another equation for evapotranspiration assessment (3.3.9):

$$ET_o = \left\{(0.0082 \times T_a - 0.19)\left(\frac{R_S}{1500}\right)\right\} \times 2.54 \tag{3.3.9}$$

where: ET_o – evapotranspiration, mm/day; T_a – average air temperature, ºC; R_s – solar radiation, cal/cm^2/day.

The McGuinness-Bordne equation requires only two input meteorological indices, but according to the results of a study by Tabari et al. (2013) it is distinguished by the lowest accuracy of evapotranspiration estimation (the error reached 59.79% relative to the standard method), so it is not worth recommending it for operational planning of irrigation in agricultural practice.

10) Irmak's method. It is the newest method of determining evapotranspiration, proposed in 2003 (Irmak et al., 2003). The meteorological index is estimated using the formula 3.3.10:

$$ET_o = -0.611 + 0.149 \times R_s + 0.079 \times T_a \qquad (3.3.10)$$

where: ET_o – evapotranspiration, mm/day; T_a – average air temperature, ºC; R_s – solar radiation, cal/cm^2/day.

The method is interesting; however, it differs in average accuracy and requires calibration for specific agro-climatic conditions. It is rarely used in practice.

11) Dalton's method. The oldest method for evapotranspiration assessment was developed back in 1802 (Dalton, 1802). The equation has the following form:

$$ET_o = (0.3648 + 0.07223u) \times (e_s - e_a) \qquad (3.3.11)$$

where: ET_o – evapotranspiration, mm/day: u – windspeed, m/sec; e_s – vapor saturation, GPa; e_a – vapor pressure, GPa.

12) Meyer's method. The method was developed later than Dalton's equation, but has many similarities in the principles of calculating evapotranspiration (Meyer, 1926), and the equation is essentially a modification of that proposed by Dalton (3.3.12):

$$ET_o = (0.375 + 0.05026u) \times (e_s - e_a) \qquad (3.3.12)$$

where: ET_o – evapotranspiration, mm/day: u – windspeed, m/sec; e_s – vapor saturation, GPa; e_a – vapor pressure, GPa.

13) Romanenko's method. In 1961, a Ukrainian researcher developed a unique methodology for estimating evapotranspiration for monthly time periods (Romanenko, 1961). The Romanenko equation does not require specific meteorological input data to perform calculations, and its only drawback is the impossibility of daily estimation of evapotranspiration, which is important for operational planning of irrigation (3.3.13):

$$ET_o = 0.0018 \times (T_a + 25)^2 \times (100 - RH) \qquad (3.3.13)$$

where: ET_o – evapotranspiration, cm/month: T_a – average monthly air temperature, ºC; RH – relative air humidity, %.

In general, Romanenko's method showed high accuracy of estimating evapotranspiration compared to the standard (error of only 11.99%, or 0.28 mm/day), which makes it promising for estimating monthly and annual evaporation (Tabari et al., 2013).

14) Penman method. Further modification of Meyer and Dalton's methods by Penman (Penman, 1948) resulted in the following equation, which, in a modified form, became the basis of the internationally standard Penman-Monteith method (3.3.14):

$$ET_o = 0.35 \times (1 + {}^{0.98}/_{100u}) \times (e_s - e_a) \qquad (3.3.14)$$

where: ET_o – evapotranspiration, mm/day; u – windspeed, m/sec; e_s – vapor saturation, GPa; e_a – vapor pressure, GPa.

In its first version, this approach could not boast of high accuracy of evapotranspiration estimation, however, it turned out to be an extremely important step towards the development of the Penman-Monteith method (Tabari et al., 2013).

15) Penman-Monteith method recommended by FAO. A standard and internationally recognized method of evaluating evapotranspiration. One of the most complicated methods in terms of calculations, which, based on the results of numerous studies, provides the most accurate assessment of the meteorological index. Calculations are made according to the formula 3.3.15:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_a + 273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (3.3.15)$$

where: ET_o – evapotranspiration, mm/day; R_n – pure insolation, MJ/m^2/day; G – soil heat output, MJ/m^2/day; γ – psychrometric constant, kPa/ºC; e_s – vapor saturation, kPa; e_a – vapor pressure, kPa; Δ – slope of the curve of vapor – air temperature, kPa/ºC; T_a – average daily air temperature, ºC; U_2 – average daily windspeed on the height of 2 m, m/sec.

However, the disadvantage of the method, as well as most of the others listed above, is the rather high complexity of calculations in the field without the presence of specific computer programs (for example, ETo Calculator, CROPWAT, etc., where the method is integrated and you only need to enter the fields of the program in the answer meteorological data), especially given the large arrays of meteorological indices that are required to execute them in the corresponding software. Maximum accuracy is achieved due to taking into account in one equation temperature parameters (methods of Thornthwaite, Blaney-Criddle, Schendel, Hargreaves, etc.), radiation balance (methods of Jensen-Hayes, McGuinness-Bordne, Irmak, etc.), as well as the movement of air masses (methods Dalton, Meyer, Penman, Romanenko, etc.).

16) Priestley-Taylor method. Subsequently, scientists sought to simplify the complex method of calculating evaporation. This is how a modification of the standard Penman-Monteith equation appeared, known as the Priestley-Taylor equation (Priestley & Taylor, 1972). A simplified calculation of evapotranspiration is performed according to the formula 3.3.16:

$$ET_o = \alpha \frac{\Delta(R_n - G)}{\lambda(\Delta + \gamma)} \qquad (3.3.16)$$

where: ET_o – evapotranspiration, mm/day; R_n – pure insolation, MJ/m^2/day; G – soil heat output, MJ/m^2/day; γ – psychrometric constant, kPa/ºC; Δ – slope of the curve vapor – air temperature, kPa/ºC; α – empirical constant that accounts vapor pressure deficit; λ – volumetric value of latent heat at vapor formation, 2453 MJ/m^3.

The Priestley-Taylor method generally correlates quite strongly with the standard one, but in certain conditions (for example, in arid and semiarid climates, in the winter period of the year, etc.) the results of evapotranspiration estimation can differ significantly; the cumbersome Penman-Monteith method is an indisputable standard (Akumaga & Alderman, 2019).

Simpler methods of evaluating evapotranspiration usually either do not differ in sufficient accuracy, or require calibration for the conditions of Ukraine, or do not provide an opportunity to evaluate evapotranspiration on a daily basis. Currently, there is practically no alternative to the methodology recommended by FAO. Specialized software for personal computers has been created to simplify the calculation process. But there is still a need to have access to a number of input meteorological indicators, which cannot be obtained at every weather station in Ukraine; in addition, the use of a computer in the field cannot be considered convenient and accessible to all agricultural producers. Of course, there are mobile applications that automatically download up-to-date meteorological data from international servers based on geolocation and perform the Penman-Monteith formula calculation almost instantly. Among such smartphone applications, EVAPO, a free application for Android and iOS smartphones for instant estimation of evapotranspiration using the Penman-Monteith method based on automatically downloaded meteorological data for a selected geolocation from NASA-POWER servers, was developed by the Agrometeorological Research Group of the College of Agriculture and Veterinary Sciences in São Paulo, Brazil. The application has a simple, clear English interface. The user selects the required location on the map or using the built-in quick search, and after a few seconds receives actual evapotranspiration data calculated from NASA-POWER data using the Penman-

Monteith equation. In addition, a historical revision of the calculated values is possible for a period of up to a month from the last date of calculations. To work, the application requires a high-speed stable Internet connection (Fig. 3.3.1).

The study carried out by the developers of the mobile application testified about the good precision of the model calculations (compared to the data obtained at a stationary hydrometeorological station): the correspondence index was 0.67; the coefficient of determination R^2 was 0.72 (good quality of the fit of the model), the mean square error *MSE* was 0.95 mm (Junior et al., 2019).

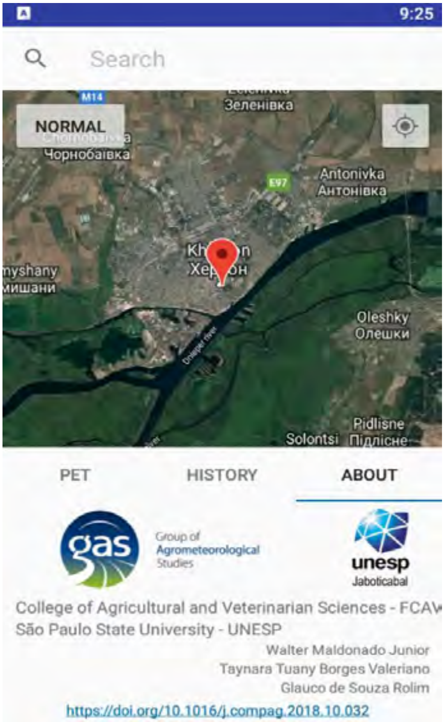


Fig. 3.3.1. Interface of the mobile app for operational evapotranspiration assessment EVAPO

We evaluated the accuracy of evapotranspiration calculations in the EVAPO mobile application in comparison with calculations for the same period based on meteorological data of the Kherson regional hydrometeorological center in the ETo Calculator program (Raes & Munoz, 2009). The research period covered the cold period of 2020 (October-November) and the warm period of 2021 (May-August). As a result of the research, it was established that the calculations performed in the mobile application are not sufficiently accurate (Table 3.3.1), especially for the warmest period of the year, when inaccuracies in the calculations can significantly affect the efficiency and accuracy of the appointment of irrigation dates and rates. The assessment of the model for the entire period (warm + cold) as a whole proved the good quality of the model fit, that is, the calculations in EVAPO well reflect the dynamics of evapotranspiration changes, but the error remained very high - 88.75% - which makes it impossible to directly use the mobile application for operational irrigation planning.

Table 3.3.1

Evaluation of evapotranspiration assessment in the mobile app EVAPO in comparison to ET_o Calculator

Statistical index	Warm period (May-August)	Cold period (October-November)	Total period
R	0.30	0.79	0.93
R^2	0.09	0.63	0.86
MAPE, %	41.43	137.02	88.75

Graphical approximation of the evapotranspiration calculation model indicates the fact of its stable overestimation during evaluation using the EVAPO mobile application in the warm period of the year, while no clear regularity has been established for the cold period (Рис. 3.3.1).

Using the regression analysis of the obtained model data, a calibration model was developed for calculating evapotranspiration in the EVAPO mobile application. The refined calculation will have the form EVAPO × calibration equation. The results of the regression analysis are shown in Table. 3.3.2-3.3.4, according to which the equation for establishing evapotranspiration in EVAPO has the form (3.3.17):

$$ET_o = -0.6121 + 1.3038EVAPO - 0.0664EVAPO^2 \qquad (3.3.17)$$

where: ET_o – evapotranspiration, mm/day; $EVAPO$ – evapotranspiration calculated in the mobile app EVAPO, mm/day.

Table 3.3.2

Regression statistics of the calibration equation for enhancement of EVAPO performance

Statistical index	Value
R	0.9467
R^2	0.8962
R^2_{adj}	0.8941
MSE	0.7009

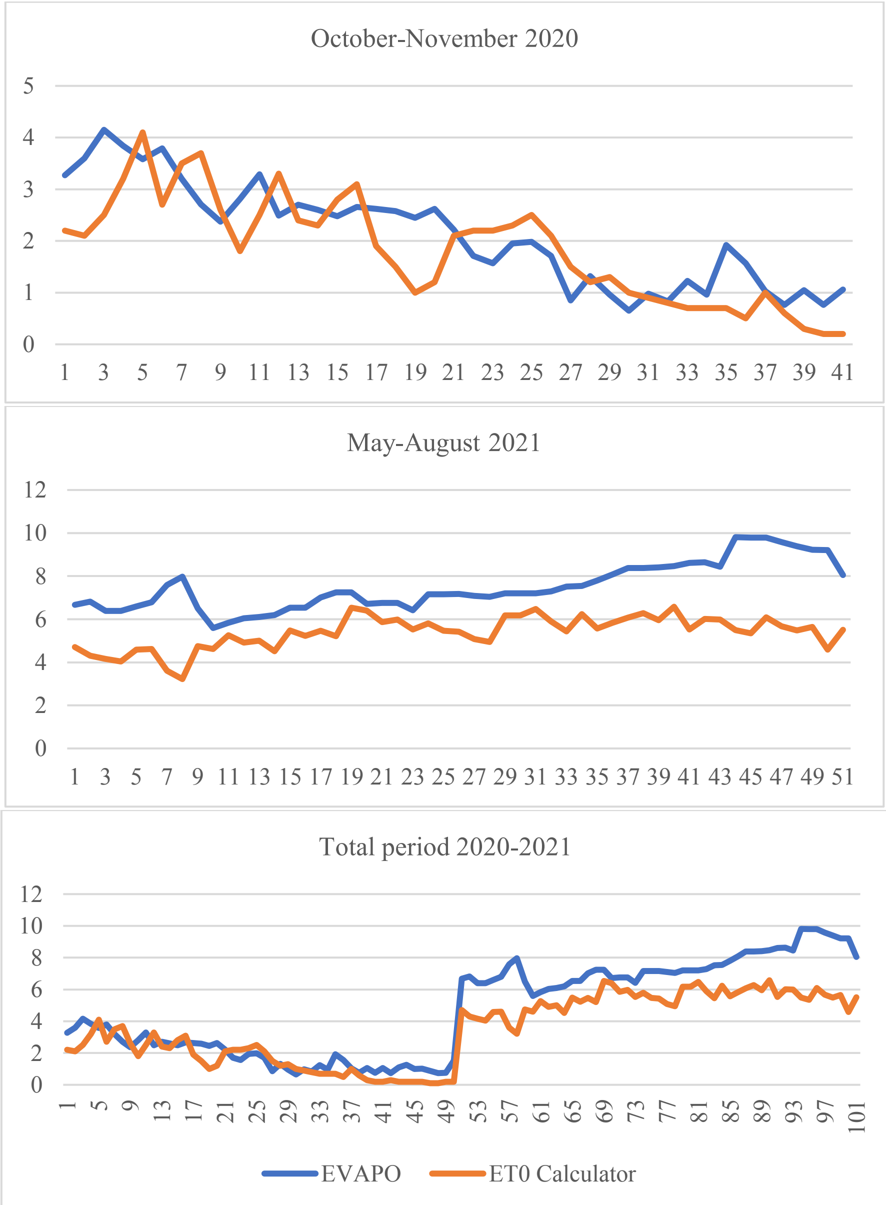


Fig. 3.3.1. Visual approximation of the model for evapotranspiration assessment in the mobile app EVAPO and ET_o Calculator

Table 3.3.3

ANOVA for the calibration equation for the enhancement of EVAPO performance

Index	*d.f.*	*SS*	*MS*	*F*	*p-value*
Regression	2	415.8572	207.9286	423.2344	0
Residuals	98	48.1459	0.4913		
Sum	100	464.0031			

Table 3.3.4

Parameters of the calibration equation (second grade polynomial) for the enhancement of EVAPO performance

Index	*β*	*SE*	*LCL*	*UCL*	*t-stat*	*p-value*
Constant	–0.6121	0.2076	–1.0241	–0.2001	–2.9485	0.0040
EVAPO	1.3038	0.1119	1.0816	1.5259	11.6464	0
EVAPO^2	–0.0664	0.0114	–0.0890	–0.0437	–5.8156	7.5776×10^{-8}

The graph of the approximation of the calibrated model of evapotranspiration calculations in the EVAPO mobile application is presented on Fig. 3.3.2.

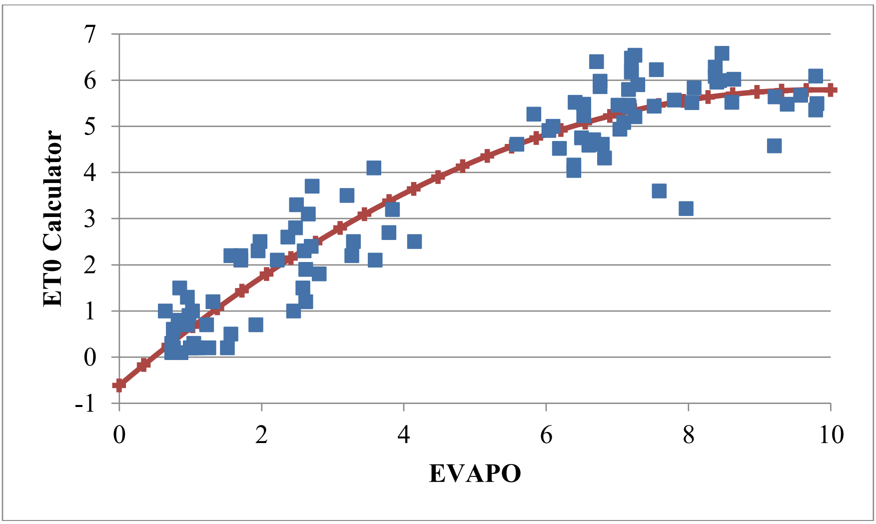


Fig. 3.3.2. Approximation of the calibrated model for the enhancement of EVAPO performance comparing to ET_o Calculator

The results of the statistical evaluation showed a significantly higher accuracy of the evapotranspiration estimation: the *MAPE* of the calibrated model for the study period was 47.52%, or 41.23% less than for the pure estimation in the mobile application. However, this amount of error still does not allow recommending even a calibrated EVAPO application for use in the warm period of the year for setting the timing and rates of irrigation (Лиховид та ін., 2020; Вожегова & Лиховид, 2021).

Therefore, the issue of developing a mathematical model based on the standard Penman-Monteith equation, which would allow to quickly and with sufficient accuracy to determine the amount of evaporation in field conditions, while using a minimum of technical means and scarcely available meteorological indices, is relevant to ensure the rational and maximally productive use of irrigation.

To solve this problem, an array of archival meteorological data was analyzed at regional stations for the period 1971 to 2020 was analyzed to estimate monthly evapotranspiration, calculated according to the standardized FAO Penman-Monteith method using indicators of minimum, maximum and average air temperatures, wind speed, duration of sunshine radiance and relative air humidity, for each of the regions of Ukraine (except Donetsk region and Luhansk region). The analysis was carried out based on the results of the calculations for the period of the year with a temperature above 0 ° C, since the main moisture losses associated with the growth and development of agricultural crops and their irrigation occur during the warm period of the year with positive air temperatures. Empirically, it was established that air temperature has the highest degree of influence on the amount of evaporation, while other meteorological indices are of secondary importance and have a significantly smaller effect on the results of the calculated estimate of evapotranspiration. At the same time, air temperature is the most widely available meteorological indicator, which is reflected in all meteorological data and reports, and therefore is the most convenient and promising input index for operational assessment of evapotranspiration under field conditions. Therefore, based on regression analysis of long-term data on evapotranspiration and average air temperature for each region of Ukraine, mathematical models were developed for estimating evaporation by the value of the latter, which allows determining evaporation based on only one input meteorological indicator. Similar work on simplifying the estimation of evapotranspiration was previously carried out by Rahimikhoob (2010) using the values of minimum, maximum temperature, and incoming solar radiation as input parameters. However, the significant drawback is not so much a larger number of input indices as the use of an artificial neural network, which automatically makes it impossible to derive an equation for calculations. The technique can be considered a derivative of the Hargreaves technique, which requires the same input data to perform calculations (Hargreaves & Samani, 1985). The work of Zanetti et al. (2007) proves the possibility of valid and reliable estimation of evapotranspiration using a neural network only with the input parameters of minimum and maximum air temperatures in the territory of Campus dos Goitacazis, state of Rio de Janeiro, Brazil. In addition, it is important to consider the fact that it is impossible to develop a single approach for estimating evapotranspiration with a limited set of input data because it is impossible to consider such parameters as the elevation of the territory above sea level, the parameters of the movement of air masses and the arrival of insolation, etc. Therefore, the calculation of evapotranspiration based on limited input data must be developed separately for each homogeneous territory in terms of meteorological parameters, in our case - for each separate region of Ukraine. Although it is worth noting the low degree of variation in the dependence of the value of reference evapotranspiration on the value of the average air temperature - the coefficient of variation was 0.0745 (or 7.45%). But the variation of the root mean square error by regions was significant - 62.50% - which makes it impossible to unify the calculation model for the territory of Ukraine as a whole.

The developed mathematical models and basic regression statistics regarding their accuracy and quality of fit are presented in Table. 3.3.5. As can be seen, for each region, the set of input data for building the model was different, which is associated with differences in the temperature regime and the different duration of the warm period of the year in each region. The maximum set of input data was for Crimea (549 pairs), the minimum was for Mykolaiv Oblast (355 pairs).

The models are characterized by sufficiently high accuracy (*MAPE* value in the range of 20-32%) compared to analogues (for example, the EVAPO mobile application with *MAPE* error of 88.75% or 2.8-4.4 times lower without calibration, and *MAPE* 47.52% or 1.5-2.4 times lower – in the case of additional calibration of the estimated value). The maximum value of the mean square error *MSE* (1.62 mm) and the average absolute error in percentage of *MAPE* (31.16%) is recorded for the model of Rivne region, the minimum value of *MSE* (0.29 mm) is recorded for Zakarpattia region, and the minimum value of *MAPE* (20.41 %) – for the Kirovograd region, respectively. In most regions of Ukraine, *MSE* ranges from 0.30 to 0.40.

All the developed models for calculating evapotranspiration based on the value of the mean air temperature have a very high quality of fitting to the reference equation of Penman-Monteith, which confirms the value of the predicted coefficient of determination in the range of 0.90-0.98. The analysis of the developed mathematical models made it possible to establish that the maximum increase in evapotranspiration with increasing air temperature can be expected in the Rivne, Kirovograd, Dnipropetrovsk regions and the Steppe zone of Crimea. While minimal changes can be expected in Odesa, Kyiv, Zakarpattia, and Volyn regions.

It is important that the models created by regression analysis consider the regularities of the conjugate change in the parameters of wind speed, air humidity, solar energy input and other parameters of the full Penman-Monteith equation for automatic assessment of the probable set of effects of the above meteorological factors on the level of evapotranspiration at a certain temperature (according to *p*-value < 0.05).

Table 3.3.5

Mathematical models for evapotranspiration (mm) assessment in the regions of Ukraine using the average air temperature T (ºC)

Region (Oblast)	Equation	*MAPE*	*R*	R^2_{pred}	*N*	*MSE*
Cherkasy	0.2413×T	23.95%	0.98	0,96	413	0,48
Chernivtsi	0.2438×T	23.61%	0.98	0,97	475	0,35
Chernihiv	0.2461×T	21.72%	0.99	0,97	413	0,31
Dnipropetrovsk	0.2609×T	20.87%	0.99	0,98	429	0,37
Ivano-Frankivsk	0.2534×T	24.12%	0.98	0,96	442	0,39
Kharkov	0.2401×T	21.33%	0.99	0,98	431	0,31
Kherson	0.2473×T	31.13%	0.98	0,96	477	0,62
Khmelnitsky	0.2537×T	22.62%	0.99	0,97	426	0,34
Kirovograd	0.2654×T	20.41%	0.99	0,98	426	0,35
Kyiv	0.2262×T	23.77%	0.99	0,97	457	0,31
L'viv	0.2466×T	24.31%	0.98	0,96	467	0,35
Volyn	0.2212×T	26.71%	0.98	0,96	406	0,35
Mykolaiv	0.2424×T	28.96%	0.98	0,96	355	0,60
Odesa	0.2138×T	30.71%	0.98	0,97	535	0,35
Poltava	0.2388×T	22.36%	0.99	0,97	417	0,33
Rivne	0.3023×T	31.16%	0.95	0,90	438	1,62
Sumy	0.2540×T	20.97%	0.99	0,98	398	0,31
Ternopol	0.2562×T	22.49%	0.98	0,97	424	0,34
Zakarpattia	0.2248×T	25.44%	0.99	0,97	515	0,29
Vinnitsa	0.2573×T	22.42%	0.99	0,97	449	0,34
Zaporizhzhia	0.2499×T	26.46%	0.99	0,97	447	0,40
Zhytomyr	0.2362×T	26.60%	0.98	0,96	427	0,46
Crimea (except for coastal and mountainous regions)	0.2711×T	24.02%	0.99	0,97	549	0,46
Coefficient of variation *CV*	0.0745					0.6250

In addition, the validation of mathematical models was performed on data that were not included in the training array (data of average monthly evapotranspiration in the regions of Ukraine, calculated according to the Penman-Monteith method, for the year 2021). The results are shown in the Table 3.3.6.

In the validation group of data, the coefficients of correlation and determination ranged from 0.92 to 0.98 and 0.84 to 0.95, respectively (minimum – for L'viv region, maximum – for Mykolaiv region), which indicates a high quality of model curve fitting. The average absolute error of *MAPE* for most regions of Ukraine was within 10-20%, the maximum was for Zhytomyr region (26.24%) and the minimum for Mykolaiv region (8.96%). Thus, the validation of evapotranspiration calculation models proves their high quality and accuracy since the calculation errors on the validation dataset were even lower than on the training dataset. Therefore, the developed mathematical models can be recommended for use in agricultural science and practice.

Table 3.3.6

Validation of the mathematical models for evapotranspiration assessment by the regions of Ukraine using average air temperature (for the meteorological data of 2021)

Region (Oblast)	*MAPE*	*R*	R^2	*N*
Cherkasy	13.45%	0.97	0.94	9
Chernivtsi	15.43%	0.94	0.89	9
Chernihiv	16.81%	0.97	0.94	9
Dnipropetrovsk	12.90%	0.97	0.95	9
Ivano-Frankivsk	18.25%	0.93	0.86	9
Kharkov	12.51%	0.97	0.95	9
Kherson	15.04%	0.96	0.93	10
Khmelnitsky	16.60%	0.95	0.90	9
Kirovograd	12.69%	0.97	0.94	9
Kyiv	18.64%	0.95	0.90	9
L'viv	19.07%	0.92	0.84	9
Volyn	15.07%	0.94	0.89	9
Mykolaiv	8.96%	0.98	0.95	9
Odesa	20.31%	0.95	0.90	11
Poltava	15.71%	0.96	0.92	9
Rivne	23.34%	0.94	0.89	9
Sumy	17.90%	0.97	0.94	9
Ternopol	17.03%	0.95	0.90	9
Zakarpattia	24.08%	0.94	0.88	11
Vinnitsa	15.87%	0.97	0.94	9
Zaporizhzhia	15.04%	0.96	0.93	9
Zhytomyr	26.24%	0.93	0.87	9
Crimea (except for coastal and mountainous regions)	18.01%	0.96	0.92	11

Validation of the mathematical models developed for daily periods for 2021weather data, performed at typical weather stations of the main agroclimatic zones of Ukraine according to the classification of Полупан та ін. (2003), indicates a reasonable level of the models' reliability, which largely depends on the zone. The maximum precision is observed for the Steppe regions of the country, whereas the calculations for the Forest zone have significantly lower predictive and simulation accuracy (Table 3.3.7).

Table 3.3.7

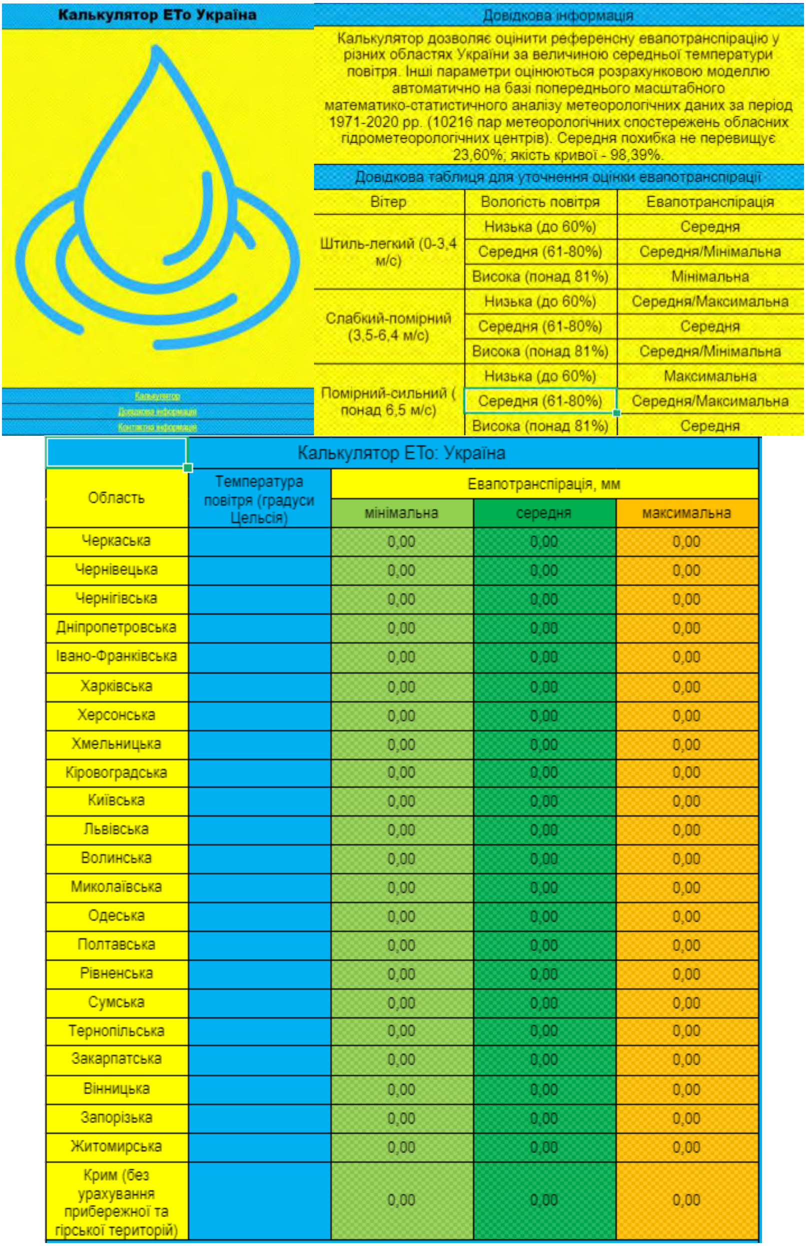
Validation of the mathematical models for evapotranspiration assessment by the major agro-climatic zones of Ukraine using average air temperature (for the meteorological data of the typical meteorological stations recorded in 2021)

Agroclimatic zone	*MAPE*	*R*	R^2	*N*
Dry Steppe	18.58%	0.93	0.86	322
Southern Moderately Dry Steppe	18.07%	0.93	0.87	321
Northern Steppe	20.69%	0.92	0.84	300
Forest Steppe	20.86%	0.91	0.83	303
Polissia	22.22%	0.92	0.86	299
Forest	25.50%	0.91	0.82	325

It is obvious that the accuracy and quality of the estimated evapotranspiration depends on the location by geographic latitudes: calculations made for southern latitudes are much more accurate than those made for northern latitudes. The more northerly the calculation geographical point is, the lower the accuracy of the meteorological index estimate is.

For greater convenience of evaluating evapotranspiration in field conditions, a free online application "ETo Calculator Ukraine" was created in the format of an electronic interactive table based on the Zoho processor (Fig. 3.3.3). The calculator allows you to estimate evapotranspiration in the selected region or regions of Ukraine by filling in cells with the value of the average air temperature, has a simple and clear working interface like a Microsoft Excel spreadsheet processor.

The "Help" menu provides a brief description of the essence and accuracy parameters of the method, provides material for the correct interpretation of the results of evapotranspiration assessment (minimum, average, or maximum value) taking into account such parameters as wind speed (0-3.3 m/s - calm light wind; 3.4-5.4 m/s - weak wind; 5.5-7.9 m/s - moderate wind according to the Beaufort scale described by Monmonier (2005)), as well as air humidity level (<50% - low; 51-59% - reduced; 60-70% - normal; 71-89% - increased; >90% - high) (Ecology. Handbook), which additionally affect the level of evaporation according to the pattern - higher wind speed results in higher probability of the maximum value of evapotranspiration, while this pattern is reversed for relative air humidity. The application «ETo Calculator Ukraine» is free to access via https://sheet.zohopublic.eu/sheet/published/7290q9c2bb51e88ed4acaa80c46db53bfb9f0 for online computations.



Калькулятор ETo Україна

Калькулятор
Довідкова інформація
Контактна інформація

Довідкова інформація

Калькулятор дозволяє оцінити референсну евапотранспірацію у різних областях України за величиною середньої температури повітря. Інші параметри оцінюються розрахунковою моделлю автоматично на базі попереднього масштабного математико-статистичного аналізу метеорологічних даних за період 1971-2020 рр. (10216 пар метеорологічних спостережень обласних гідрометеорологічних центрів). Середня похибка не перевищує 23,60%; якість кривої - 98,39%.

Довідкова таблиця для уточнення оцінки евапотранспірації

Вітер	Вологість повітря	Евапотранспірація
Штиль-легкий (0-3,4 м/с)	Низька (до 60%)	Середня
	Середня (61-80%)	Середня/Мінімальна
	Висока (понад 81%)	Мінімальна
Слабкий-помірний (3,5-6,4 м/с)	Низька (до 60%)	Середня/Максимальна
	Середня (61-80%)	Середня
	Висока (понад 81%)	Середня/Мінімальна
Помірний-сильний (понад 6,5 м/с)	Низька (до 60%)	Максимальна
	Середня (61-80%)	Середня/Максимальна
	Висока (понад 81%)	Середня

Калькулятор ETo: Україна

Область	Температура повітря (градуси Цельсія)	Евапотранспірація, мм		
		мінімальна	середня	максимальна
Черкаська		0,00	0,00	0,00
Чернівецька		0,00	0,00	0,00
Чернігівська		0,00	0,00	0,00
Дніпропетровська		0,00	0,00	0,00
Івано-Франківська		0,00	0,00	0,00
Харківська		0,00	0,00	0,00
Херсонська		0,00	0,00	0,00
Хмельницька		0,00	0,00	0,00
Кіровоградська		0,00	0,00	0,00
Київська		0,00	0,00	0,00
Львівська		0,00	0,00	0,00
Волинська		0,00	0,00	0,00
Миколаївська		0,00	0,00	0,00
Одеська		0,00	0,00	0,00
Полтавська		0,00	0,00	0,00
Рівненська		0,00	0,00	0,00
Сумська		0,00	0,00	0,00
Тернопільська		0,00	0,00	0,00
Закарпатська		0,00	0,00	0,00
Вінницька		0,00	0,00	0,00
Запорізька		0,00	0,00	0,00
Житомирська		0,00	0,00	0,00
Крим (без урахування прибережної та гірської територій)		0,00	0,00	0,00

Fig. 3.3.3. Interface of the online app for evapotranspiration assessment «ETo Calculator Ukraine»

In addition, a mobile version of the application for smartphones based on the Android OS – Evapotranspiration Calculator (Fig. 3.3.4) is additionally available for download in the Play Market. The application is trilingual (Ukrainian, English, Russian) and has an intuitive interface and help for the correct interpretation of calculation results.

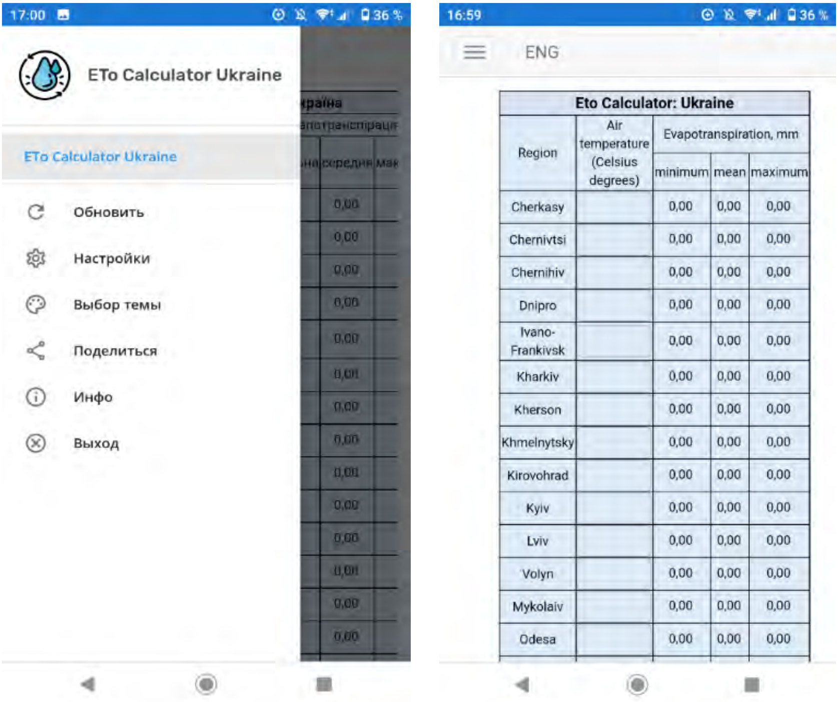


Fig. 3.3.4. Interface of the mobile app Evapotranspiration Calculator (Ukraine)

Conclusions to Chapter 3

1. The analysis of time series of weather conditions in the Kherson region confirms the existence of certain risks to the increase in the aridity of the climate in the region. Thus, the results of forecasting the climate aridity index in the region until 2050 indicate the possibility of the territory transitioning to an extremely arid one – the index will be 0.22. Given the growing aridity in the Kherson region, irrigation will become more and more important for stabilizing plant products, which is confirmed by the results of the analysis of the level of productivity of arable land in the region in recent years against the backdrop of increasing air temperature and

evaporation. It has been proven that one in the fundamental factors of ensuring the stability of the production of the main agricultural crops in the region is the increase in the use of irrigation water, since artificial humidification allows to neutralize the negative impact of the arid climate. In the future, it is necessary to increase irrigation capacities in the region due to the reconstruction of previously built and construction of new irrigation systems at the local and regional level.

2. The increase in the average annual air temperature on the territory of Ukraine as a whole, which is especially clearly visible in the last decade, has been proven. It is predicted that in the period 2021-2050, the average annual temperature on the territory of Ukraine may reach +11.1-11.2ºC. In order to assess the current and prospective regimes of irrigation on the territory of Ukraine, a combined methodology for the classification of the territory according to the need for irrigation was developed, taking into account the requirements for moisture supply of various agricultural crops. Based on the results of the assessment of climate regimes and soil moisture regimes, aridity maps and maps of irrigation needs by regions of Ukraine for different time periods were created for a convenient spatial assessment of climate changes and their impact on the state's moisture supply. The most dynamic climatic changes over the past 30 years occurred in Chernihiv, Kharkov, Sumy, and Vinnitsa regions, the lowest intensity of climatic changes was noted in Kherson, Volyn, Mykolaiv, Odesa, Poltava, and Zaporizhzhia regions. The strongest increase in aridity is observed in regions of Ukraine as Chernivtsi, Khmelnitsky, L'viv, Sumy, Ternopol, Vinnitsa, Zhytomyr (mainly the northern and western regions of the country), while less intense dynamics are characteristic of regions such as Kherson, Mykolaiv, Odesa, Zaporizhzhya, Dnipropetrovsk and Volyn regions, that is, the southern territories of Ukraine. Forecasting the further development of climate aridity in Ukraine for the period 2021-2030 based on data from 1991-2020 shows that while in most regions of Ukraine there is a likely trend toward preservation of the climatic situation typical for the period 2011-2020, as well as a further progression of aridity (in particular, in the Kherson and Zhytomyr regions), in some regions (L'viv, Khmelnitsky, Ternopol, Vinnitsa, Poltava, Sumy, Odesa, Zaporizhzhia regions) we can expect the climate to change to a more humid and favorable one. Analysis of 10-year periods indicates a gradual increase in irrigation needs in almost all regions of Ukraine since 2001. Today, almost all regions of Ukraine, except for a few western regions, have a need for irrigation to one degree or another for stable crop production (L'viv and Rivne regions do not need irrigation, Zhytomyr, Khmelnitsky, Ivano-Frankivsk, Zakarpattia and Volyn regions need irrigation for growing crops with high and specific needs for moisture supply). If until the 2000s, white irrigation was relevant only in the territory of the southern and central regions of the country, then today it is also relevant for the northern and eastern regions. At the moment, irrigation needs in Ukraine are met by 10%, and taking into account the low level of actual operation of irrigation systems, by 2.5%. This is a catastrophically low level, so it is necessary to take measures to restore the

full exploitation of existing ones (first of all, in the territory of Kherson, Odesa, Mykolaiv, Zaporizhzhia regions, where 1,084,000ha or 49.75% of all irrigated lands of Ukraine) and the construction and commissioning of new irrigation systems primarily in the territories of the regions most vulnerable to increasing aridity (in the Kirovograd, Dnipropetrovsk, Kharkov regions, where the actual area of irrigated land is only 198.7 thousand hectares).

3. Determination of evapotranspiration is a necessary prerequisite for rational management of crop irrigation regimes and optimization of irrigation water use. To date, scientists and specialists from all over the world have developed several dozen different methods of indirect calculation estimation of both potential and reference evapotranspiration for different time intervals and using various agrometeorological indices as input parameters. FAO standardized as a reference equation of Penman-Monteith, and several software products were developed and implemented to perform calculations in automatic mode on a computer – ETo Calculator, CROPWAT. However, the need for a large amount of hard-to-reach input meteorological data makes the Penman-Monteith method not always possible and convenient to use. Mobile applications, for example, EVAPO, designed to quickly determine evapotranspiration based on geodata using cloud services and meteorological servers, do not differ in high accuracy. By means of mathematical analysis based on the assessment of the array of complete meteorological data for the regional stations of Ukraine in the period 1971-2020, simplified models for estimating reference evapotranspiration were developed based on the Penman-Monteith method using the values of the average air temperature as the main input parameter (others are estimated conjugated according to temperature changes). Statistical analysis and validation of the models based on the data of 2021 proved their sufficiently high quality and accuracy, the possibility of implementation in agricultural science and practice. To simplify calculations and provide additional reference information, an online application "ETo Calculator Ukraine" has been developed based on the Zoho spreadsheet cloud processor and is available to a wide audience interested in estimating reference evapotranspiration by temperature regime. Additionally, for the greater convenience of owners of devices based on Android OS, the Evapotranspiration Calculator has been developed with an intuitive interface for evaluating the reference evaporation rate.

CHAPTER 4
AGRICULTURAL LAND USE AND CROP PRODUCTION PRACTICES IN THE CONTEXT OF GLOBAL WARMING

4.1. Greenhouse gases, ozone, and global warming

Global climate warming is a gradual increase in the temperature of the surface layer of the atmosphere and the world ocean, which, according to scientists, began in the middle of the twentieth century. According to the data from the Intergovernmental Panel on Climate Change (IPCC), the air temperature in the surface zone during the period 1900-2000 increased by 0.74±0.18ºC. It is believed that the most likely reason for the increase in global temperature in the 20th and 21st centuries is a rapid increase in the concentration of greenhouse gases (GHG) in the atmosphere (Rose et al., 1984), which at a certain stage causes the appearance of the so-called "greenhouse effect", which has been known since 1827 and was studied by a number of scientists who discovered the potential ability of a number of atmospheric gases, when they reach a certain concentration, retain thermal radiation and contribute to the accumulation of thermal energy in the surface layer. Carbon dioxide CO_2, nitrogen oxide N_2O, methane CH_4 are considered the main greenhouse gases. Recently, halogenated organic compounds, sulfur hexafluoride SF6, belong to the GHG category. However, the greatest role in the formation of the greenhouse effect and related changes in climate and weather phenomena belongs, according to scientists, to CO_2 emissions with a share of influence reaching 80% (Lashof & Ahuja, 1990). In addition, more and more attention is paid to the climate-forming effect of the less studied in terms of the impact on global warming of gases, such as, for example, ozone. In addition to GHG and ozone, aerosols remaining in the atmosphere, changes in land use, changes in solar activity, volcanic activity, etc., have a significant contribution to climate change (Wallington et al., 2009).

Experts emphasize that the mechanisms of natural cooling of the atmosphere, related to the regulation of solar radiation and the activity of volcanoes, are no longer able to effectively regulate the climate, especially since the beginning of the 1950s. The reason for this is the intensification of anthropogenic activity, which leads to GHG emissions into the atmosphere. The rapid increase in the rates and volumes of GHG emissions into the atmosphere because of anthropogenic activity under various scenarios of process development (mainly, under different degrees of intensity of GHG emissions from the industrial and agricultural spheres of the economy) predicts a further increase in the average global air temperature to +1.1...6.4ºC at the end of the XXI century. At the same time, global warming, according to scientists, is a process that cannot be stopped, at least within the next 80-100 years, because even with absolutely zero emissions, the accumulation of GHG in the atmosphere now reaches values such that it is impossible to expect restoration of thermal balance in the surface air layer (Haldar, 2011).

Currently, there is no consensus on the prospects for the further development of global warming, the factors affecting it, and the levers for regulating and restraining the process. Only the fact of the existence of the problem of excessive accumulation of thermal energy remains indisputable. Thus, the analysis of data on the average annual global air temperature over the past 271 years (Fig. 4.1.1) shows the existence of a clear trend towards a stable transition of the average annual temperature above +8ºC starting from 1908 (1907 is the last year for the period 1750-2020 with a temperature below +8ºC, which was +7.95ºC), and a stable transition above the +9ºC occurred 86 years later - in 1994 (1993 is the last year with an air temperature below +9ºC – +8.87ºC). It is worth noting that the modal (the one that occurs most often in the data set) air temperature for the studied period is +8.22ºC, and the medians (average temperatures) for 50-year periods (the last period is 21 years) are: 1750-1799 – +8.22ºC; 1800-1849 – +7.89ºC; 1850-1899 – +8.13ºC; 1900-1949 – +8.48ºC; 1950-1999 – +8.80ºC; 2000-2020 – +9.60ºC. It is noticeable that the median global average annual temperature has started to increase since the period after 1950, which coincided with the rapid development of industry, the beginning of the so-called third industrial revolution (Соловйов, 2017).

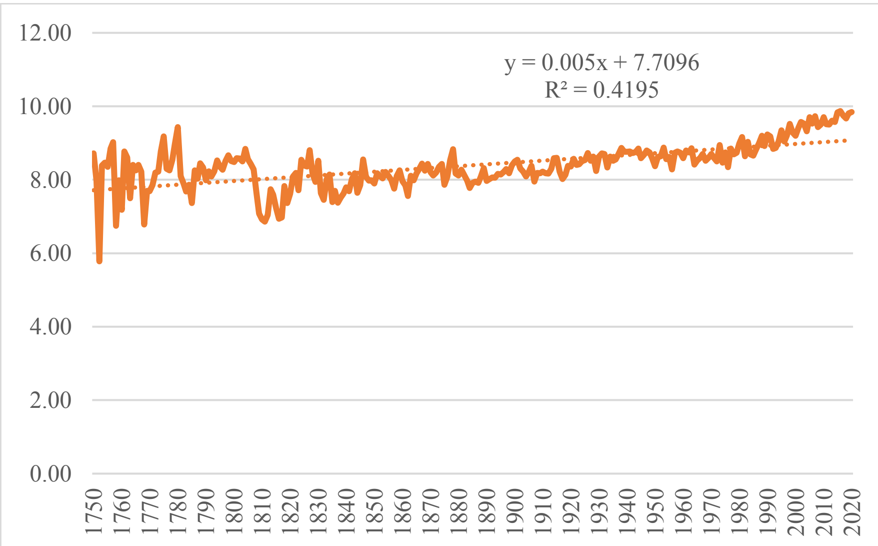


Fig. 4.1.1. Dynamics of global average annual air temperature in Celsius degrees for the period 1750-2020

Solving the issue of finding the causes and features of the influence of atmospheric factors on the process of climate change is necessary, since only a correct understanding of these laws can give impetus to the development of rational measures to control the process of changing meteorological conditions. The need to solve this problem as quickly as possible to ensure sustainable development of agricultural production, as one of the most vulnerable to climatic stresses and changes in the economic sectors, which is an integral component of the food security system (Cline, 2008), is especially acute. The purpose of our research is to establish the nature and strength of the relationship between the concentration of GHG and ozone in the atmosphere with the process of a gradual increase in air temperature, to establish the peculiarities of the regulation of the temperature regime of the planet due to changes in the composition of atmospheric air, the role of each GHG in climate changes, and on the basis of the results obtained to propose effective mechanisms of resistance to global warming in modern conditions.

The analysis of data on the global average annual temperature of the surface layer and the composition of the atmosphere for the period 1750-2020 demonstrated the presence of a clear trend towards a gradual increase in temperatures and GHG concentrations (the concentration of the main GHGs is expressed in *ppm* and *ppb*, the ozone concentration is in *DU*, Dobson Units), which is shown in Fig. 4.1.2-4.1.6 (for the concentration of ozone and the area of the ozone hole in million km2, calculations were made for the period 1979-2020). At the same time, negative trends towards a decrease in ozone concentration and an increase in the ozone hole were noted (Table 4.1.1).

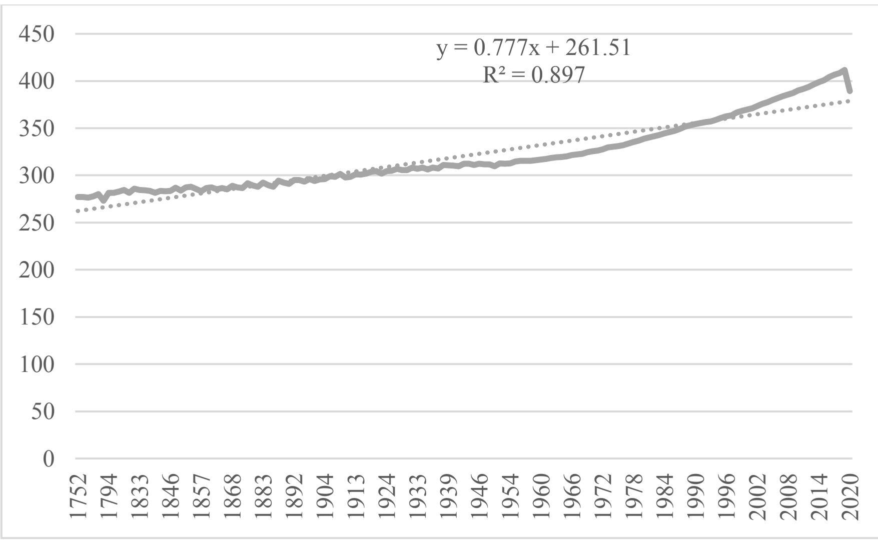


Fig. 4.1.2. Dynamics of CO_2 concentration (ppm) in the atmosphere for the period 1750-2020

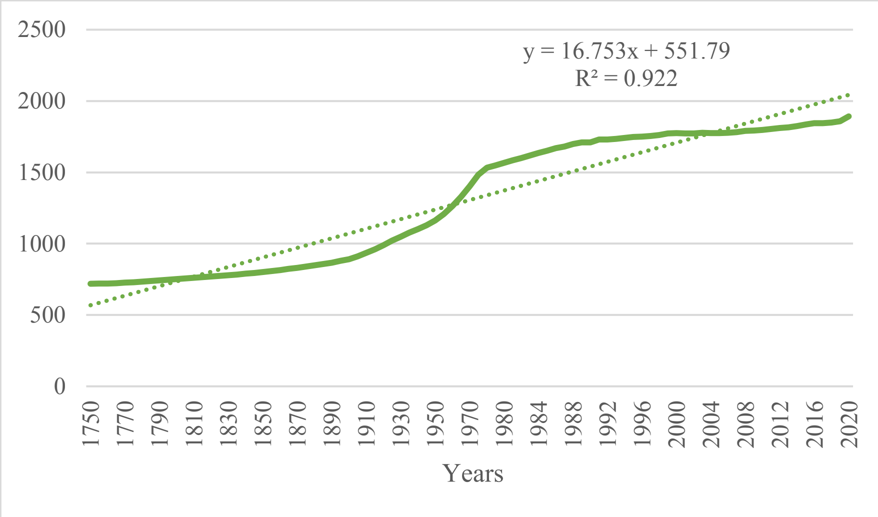


Fig. 4.1.3. Dynamics of CH_4 concentration (ppb) in the atmosphere for the period 1750-2020

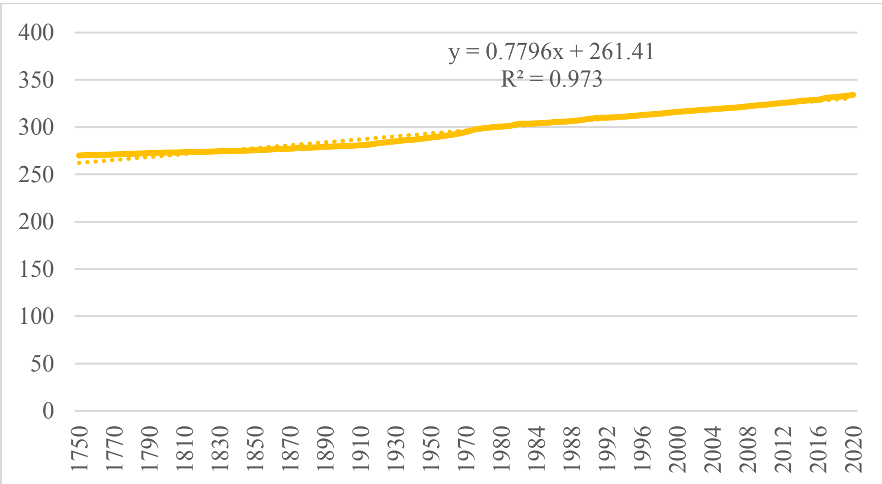


Fig. 4.1.4. Dynamics of N_2O concentration (ppb) in the atmosphere for the period 1750-2020

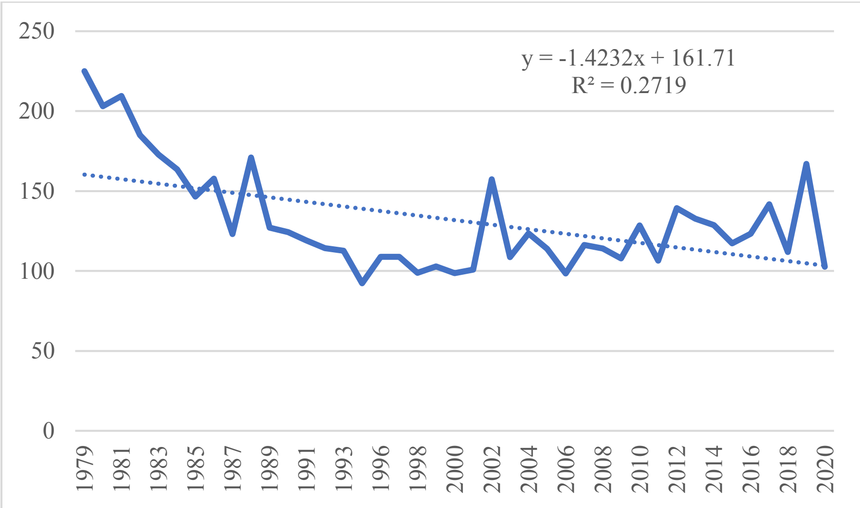


Fig. 4.1.5. Dynamics of ozone O_3 concentration (DU) in the atmosphere for the period 1979-2020

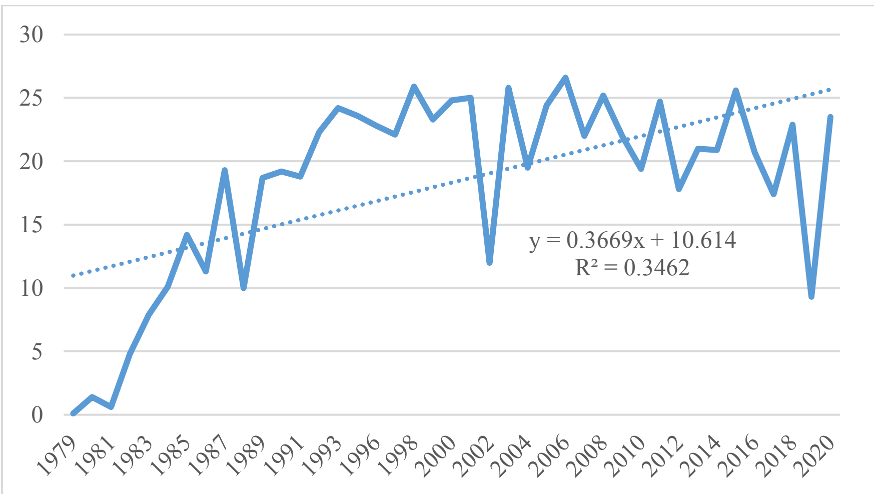


Fig. 4.1.6. Dynamics of the ozone hole area (million square kilometers) for the period 1979-2020

Table 4.1.1

Results of Mann-Kendall and Sen's slope test for global average air temperature and greenhouse gases concentration for the period1750-2020

Statistical indices	Greenhouse gases concentration				Air temperature	Ozone hole
	CO_2	N_2O	CH_4	O_3		
alpha	0.05	0.05	0.05	0.05	0.05	0.05
MK-stat	10732	3916	3902	-239	18316	295
s.e.	621.53	282.18	282.18	89.03	1491.16	89.03
z-stat	17.27	13.87	13.82	–2.67	12.28	3.30
p-value	8.55×10^{-67}	9.09×10^{-44}	1.81×10^{-43}	0.0075	1.13×10^{-34}	9.59×10^{-5}
trend	yes	yes	yes	yes	yes	yes
slope	0.6758	0.7865	15.9271	–1.2686	0.0055	0.3460
lower	0.6143	0.7625	14.4635	–2.2286	0.0047	0.1286
upper	0.7439	0.8135	17.0567	–0.275	0.0063	0.5368
Direction of trend	↑	↑	↑	↓	↑	↑

In addition, trends were determined regarding a very important, in our opinion, parameter of influence on the climate of the planet, the area of the ozone hole. An ozone hole is an area with an ozone concentration of less than 220 *DU* between the earth's surface and space (NASA, 2021). The hole was first recorded and described in the scientific literature in 1985 (Farman & Gardiner, 1985), and it remains a kind of *terra incognita* for modern science. The role of the ozone hole in climate regulation, particularly in the Southern Hemisphere, is beyond debate (Son et al., 2009; Solomon, 2019), as is the impact of significant ozone depletion on biological entities such as plants and animals that sensitive to an increase in the amount of incoming short-wave ultraviolet radiation (Mayer, 1992; Björn, 1996; Sinha et al., 1999; Xiong & Day, 2001). Although it is believed that the ozone hole is a product of irrational human activity, it is predicted that, under a favorable scenario, we can expect its complete recovery from 2068 if measures are taken to reduce the emissions of ozone-depleting substances and the number of spacecraft launched into Earth orbit (Newman et al., 2006). However, the role of ozone hole size in global climate regulation may be underestimated by the scientific community, although this understanding is widespread among the public, such as the student community (Kilinc et al., 2008). It is worth noting that even skeptics recognize the need to restore the ozone layer and the ozone hole due to the great importance of ozone concentration in ensuring global environmental sustainability (Fang et al., 2019).

According to the results of statistical calculations, a tendency was established to increase the area of the ozone hole with a simultaneous decrease in the presence of ozone in the atmosphere. Thus, it is hypothetically possible to assume that GHGs can be an additional reason for the decrease in the protective properties of the atmosphere because the decrease in ozone concentration and the increase in the area of the ozone hole make the Earth less protected against the penetration of the ultraviolet spectrum of solar radiation, which negatively affects ecosystems (Gotz, 1951). In recent years, it has been proven that the decrease in ozone concentration is closely related to human use of certain chemical compounds that have a destructive effect on ozone in the air, mainly aerosols and cooling agents (Bolaji & Huan, 2013). Therefore, anthropogenic activity leads not only to an increase in the concentration of GHG, but also to the destruction of the protective layer of the Earth's atmosphere.

Correlation analysis of the relationships between the concentration of the studied greenhouse gases and air temperature, as well as between the area of the ozone hole and air temperature, proved the existence of close relationships (Table 4.1.2).

Table 4.1.2

Correlation between the greenhouse gases and ozone concentrations, ozone hole area and global air temperature

Statistical indices	CO_2	N_2O	CH_4	O_3	Площа озонової діри
R	0.8366	0.8630	0.8351	–0.3964	0.4675
R^2	0.6999	0.7447	0.6975	0.1572	0.2186

In addition, we determined the degree of negative impact of excessive concentration of the main greenhouse gases on the preservation of the ozone layer and the "healing" of the ozone hole (Table 4.1.3).

Table 4.1.3

Correlation between the greenhouse gases, ozone concentrations, and ozone hole area

Statistical indices	CO_2	N_2O	CH_4
Ozone hole area			
R	0.5327	0.5605	0.7377
R^2	0.2838	0.3141	0.5444
Ozone concentration			
R	–0.4563	–0.4957	–0.6991
R^2	0.2082	0.2457	0.4888

It is interesting that the most popularized and present in the maximum concentration in the atmosphere carbon dioxide takes only the second place in determining the increase in global air temperature, while the first place is occupied by nitrogen oxide, and the third place by methane. A sufficiently strong directly proportional correlation dependence ($R > 0.69$) was established between the increase in the GHG concentration and the increase in global air temperature. Therefore, the main concern of the scientific community and practitioners at this stage should not be CO_2, but N_2O, which is reliably (the confidence interval of the calculations is 95%) the most dangerous from the climatological point of view. At present, it has already been proven that the emission of nitrogen oxide can be no less dangerous than the emission of carbon dioxide (Crutzen et al., 2007), and our results only confirm this hypothesis. The level of nitrogen oxide and methane emissions cannot be neglected, focusing all attention only on carbon dioxide as the most common GHG, because such an approach will not give the desired results in the policy of reducing the risks of a rapid increase in global air temperature, which was proven by the scientific work of Mosier et al. (2003).

A moderately weak degree of correlation was established for the pairs "ozone concentration – global air temperature" and "ozone hole area – global air temperature" ($|R| = 0.40\text{-}0.47$). That is, the decrease in the concentration of ozone in the atmosphere, the depletion of the ozone layer and the increase in the ozone hole area partially (determination within the range of 15-22%) determine the increase in global air temperature and to some extent can be considered additional levers of atmospheric promotion of the further development of global warming along with the main greenhouse gases. Therefore, it is worth considering maintaining and renewing the optimal concentration of ozone in the atmosphere, which can be achieved by reducing emissions of ozone-depleting substances (primarily aerosols, cooling agents, methane, etc.), which can be achieved in the field of agricultural production by reviewing current practices in the production of plant products. Although most scientists are skeptical about the role of the ozone layer in global warming and even claim the opposite ideas, namely that ozone increase in the concentration in the atmosphere will cause not a decrease but an increase in air temperature, we have evidence that the destruction of the ozone layer and an increase in the size the ozone hole may be one of the reasons for the increase in global air temperature, and restoring the concentration of ozone in the atmosphere and closing the ozone hole will make it possible to reduce the rate of temperature increase (Abdullah et al., 2017).

In addition, a strong inverse correlation was established between the concentration of ozone in the atmosphere and the area of the ozone hole (R –0.9770, R^2 0.9546), which indicates that it is impossible to hope for the "healing" of the latter if there is not the problem of restoring enough ozone in the atmosphere has been solved.

Regarding the role of greenhouse gases in the formation of the ozone layer, a medium degree of association with ozone concentration and ozone hole area is found for carbon dioxide and nitrogen oxide, while a strong association is found for methane. Therefore, methane has the greatest negative impact on the ozone layer, while carbon dioxide has the least impact among the studied greenhouse gases. Thus, one of the links of additional influence on the improvement of the atmospheric composition of the air, which can potentially lead to a significant restraint on the further development of global warming, is the struggle to minimize methane emissions into the atmosphere from industry and agricultural activities. An important stage of work in this direction is the determination of the influence of the main practices of crop production and the characteristics of land use on the emission level of each GHG to determine the strategic directions of reducing their emissions into the atmosphere from the agrarian sector of the economy. According to the results of studies, the most important factors in regulating GHG emissions in the agricultural sector include the method of soil tillage and the depth of plowing (Bayer et al., 2012; Abdalla et al., 2013), application rates and types of fertilizers and pesticides used (Johnson et al., 2012; Zhang et al., 2016), intensification of agricultural technology due to the involvement of high-energy machines and tractors (Neue et al., 1996).

The regression model of the global air temperature dependence on the concentration of greenhouse gases, ozone, and the ozone hole area, which helps better understanding of the processes in formation of the temperature regime depending on the composition of the atmosphere, has the form (4.1.1):

$$GAT = 0.0010CH_4 + 0.0167N_2O + 0.0045CO_2 + \\ + 0.0109OHA + 0.0036O_3 \qquad (4.1.1)$$

where: *GAT* – global air temperature, ºC; CH_4, N_2O, CO_2, O_3 – concentrations of the corresponding greenhouse gases (*ppb* for nitrogen oxide and methane, *ppm* for carbon dioxide, *Dobson Units* for ozone); *OHA* – ozone hole area, million km^2.

The statistics of the model are given in Table. 4.1.4. The results of the calculation of accuracy and reliability criteria indicate the high performance of this model and its high predictive level, autocorrelation is almost absent.

The simulation results indicate that the maximum contribution to global warming in the period 1979-2020 was made by the concentration of nitrogen oxide (R 0.0167) and the area of the ozone hole (R 0.0109), while methane played a minimal role in the accumulation of heat in the surface layer of the Earth's atmosphere (R 0.0010). The content of carbon dioxide and ozone in atmospheric air are moderately significant climate-forming factors for this period.

Table 4.1.4

Statistics for the model of global air temperature dependence on the concentrations of greenhouse gases and ozone, as well as the ozone hole area (for the period 1979-2020)

Statistical index	Value
R	0.9999
R^2	0.9997
R^2_{adj}	0.9997
R^2_{pred}	0.9996
MSE	0.0288
S	0.1698
$MAPE$, %	1.4915
$PRESS$	1.3536
$PRESS\ RMSE$	0.1817
DW	1.7642
AIC	–0.5944
BIC	–0.3854
AIC_c	–0.5537
HQC	–0.5183

Therefore, the basis of the strategy to combat global warming on the planet is the minimization of nitrogen oxide emissions and diminishment of the ozone hole area.

4.2. Influence of crop production and agricultural land use practices on the process of climate change

Agriculture is the branch of the economy that is most susceptible to climate change. Working with natural ecosystems, productivity of which and ability to ensure food security largely depends on the adaptation of cultivated species and agricultural technologies to environmental changes, makes the agricultural sector extremely vulnerable to climate stressors. Most scientists agree that global climate change will have an increasingly powerful impact on the productivity of the agricultural sector and will change the priority areas of crop and livestock development (Rosenzweig & Colls, 2005; Xue et al., 2019; Lal, 2020). The territory of Africa, Arab countries (Middle East), India, and South America were considered the main regions that will suffer from a decrease in the yield of agricultural crops according to early simulation models (1994-2010), while recent studies on modeling crops productivity under climate change indicate that these territories will most likely be supplemented by Australia, New Zealand, the Far East, and Central America (Wheeler & von Braun, 2013). Some countries (mainly located in North America, Northern Europe and Central Asia) are expected to benefit somewhat from global warming, while the vast majority of agricultural land will suffer from unstable crop production due to natural moisture deficits, weather instability and adverse weather events (droughts, floods, downpours, hailstorms, etc.), which, accompanied by destructive anthropogenic activity, will lead to drastic changes in the appearance of the Earth's natural and artificial ecosystems (Hughes et al., 2018; Prăvălie, 2018; Ito et al., 2020). In addition, food security will be complicated by the rapid increase in the world population (Godfray et al., 2010).

At the same time, scientists claim that agriculture is to some extent responsible for increasing the pace of global warming (Javeed et al., 2021). Animal husbandry and intensive crop production are believed to be among the main factors affecting climate through their effects on the concentration of greenhouse gases (GHG) in the atmosphere. Modern intensive cultivation technologies, especially those that use energy-intensive machinery, large amounts of fertilizers and pesticides, are to blame for a significant share of total anthropogenic greenhouse gas emissions, especially against the background of irrational land use and deforestation (Adger & Brown, 1994). Therefore, we are observing a global tendency to reduce the number of livestock, transition to organic farming and energy-saving technologies within the framework of the so-called climate-oriented (or climate-smart) agriculture. However, the claim that the agricultural sector is to blame for climate deterioration requires evidence, as it is not clear whether the significant contribution of agricultural production to global greenhouse gas emissions is as large as it is believed to be, and whether the transition to a climate-oriented, energy-saving and organic one will really be beneficial. agriculture.

As a result of summarizing the statistical data of the main agricultural indicators characterizing the intensity of agrotechnologies in crop production, generalized data were obtained (Table 4.2.1). The results of the trend calculation indicate that there are statistically significant trends toward an increase in the application of pesticides and all types of fertilizers, simultaneously with a sharp increase in the use of tractors (which is evident from the increase in their number per unit area), which is closely related to modern technical progress and industrialization. At the same time, no significant and reliable trend was found in the share of arable land out of the total area of agricultural land (although there is a trend of increasing absolute values of agricultural land and arable land), indicating a certain stabilization of the situation in the field of agricultural land use. In general, the presence of positive trends in all the indices studied indirectly indicates the gradual intensification of crop production with the simultaneous extensive development of land use, which, given the simultaneous strong trend towards global deforestation and the reduction of areas under forest plantations of natural and artificial origin, is clearly one of serious problems of ensuring environmental stability in the future (Table 4.2.2).

Global GHG emissions are summarized in Table 4.2.3. It is obvious that the total emissions of all greenhouse gases, except N_2O, tend to increase. However, the total GHG emissions from crop production are practically unchanged. At the same time, there is a tendency to increase emissions of N_2O and CH_4 from crop production, and the situation with N_2O emissions is critical, as it shows a tendency to increase not only in absolute volumes, but also in share of total emissions from all sources of anthropogenic activity (i.e. is a significant and significant factor in the deterioration of the ecological and climatic situation), while the share of other GHG emissions from crop production in the total volume of emissions is decreasing. The results of the calculations on the identification and assessment of trends in the changes in GHG emissions are shown in Table 4.2.4. A graphic presentation of the share of crop production is shown in Fig. 4.2.1, where the maximum impact of the agricultural production sector on nitrogen oxide emissions is clearly visible, while the emission of carbon dioxide due to modern systems of conservation agriculture, which takes into account the need for carbon sequestration and the preservation of soil organic matter due to the transition to new soil cultivation systems and methods cultivation of cultivated plants is currently the smallest and in the near future with the further development of climate-smart agriculture will decrease further due to the reduction of the absolute volumes of CO_2 emissions into the atmosphere, which are now actually stable with a slight downward trend.

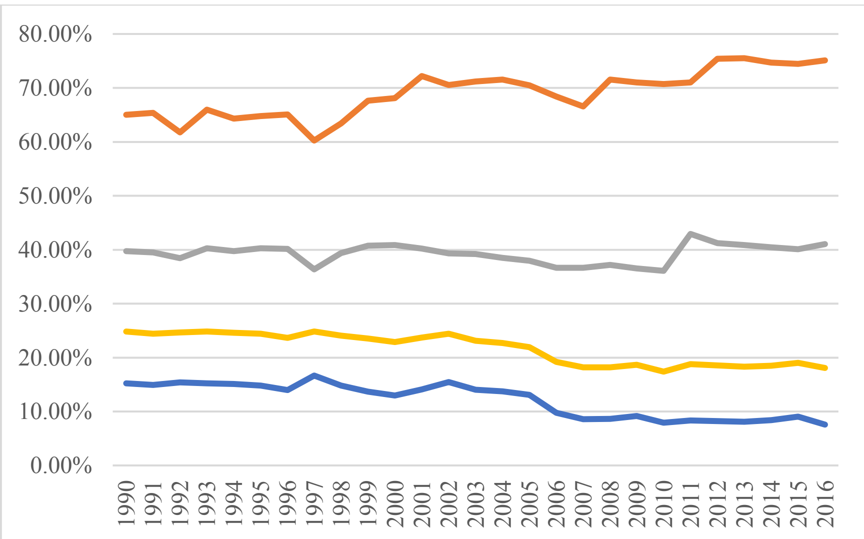


Fig. 4.2.1. Crop production share in global greenhouse gases emissions for the period 1990-2016 (blue – carbon dioxide; red – nitrogen oxide; grey – methane; orange – GHG in total)

Analysis of the relationship between greenhouse gas emissions and land use and crop production practices showed that the closest relationship was established between greenhouse gas emissions and forest areas. R^2 is 0.8758, i.e., the level of determination is 87.58% (Table 4.2.5). Forests are the main regulators of the concentration of carbon-containing gases CO_2 and CH_4 and absorb a large share of emissions of these gases even before they accumulate in the atmosphere, while the emission of nitrogen oxide N_2O remains outside the control of forests. The slightest effect on total GHG emissions is observed for nitrogen fertilizers (R^2 0.0603, or 6.03 % of the determination), while tractor use has the second strongest relationship after forests with total GHG emissions with R^2 at 0.1607 or 16.07% of determination. In third place are the arable land (13.90% of the determination), followed by the amount of pesticide use. The use of nitrogen fertilizers (96.61% determination) is the largest driver of the increase in N_2O emissions, along with the level of tractor use (96.04% determination) and the volume of pesticides applied (96.36% determination). Methane emissions are most dependent on the intensity of the use of tractors and nitrogen fertilizers (78.61 and 76.13% of determination, respectively), and demonstrate moderate ties with crop production practices and land use. The smallest strength of connection is established for carbon dioxide CO_2, the volume of emissions of which is not regulated by any of the studied factors even by 45%. Only the forest area showed a very strong inverse relationship with the level of CO_2 emissions (89.56% of the determination), indicating a potentially strong regulatory role of forests in controlling the concentration of this greenhouse gas. Nitrogen fertilizers have the lowest impact on greenhouse gas emissions among mineral fertilizers, and phosphorus fertilizers have the highest impact. Land use practices are currently not of decisive importance in reducing greenhouse gas emissions, as the relationship between them is weak and the overall level of determination ranges from 1-14%. All the investigated factors of crop production and land use are negatively correlated with CO_2 emissions; therefore, modern crop production cannot be blamed for increasing the concentration of this greenhouse gas. The areas of forests and artificial forest plantations have a negative, inverse correlation with all GHGs (minimal – with the concentration and emissions of nitrogen oxide), which indicates the potential benefits of reforestation in terms of regulating their concentration in the atmosphere.

Table 4.2.1

Main agricultural indices to assess the intensity of agrotechnologies and land use practices (averaged for 1990-2016; for mineral fertilizers – 1990-2014)

Year	Pesticide use, Mt	Mineral fertilizers use, Mt				Forests, % to dryland	Land use, million km^2			Tractors per 100 km^2
		N	P	K	Total		Agricultural lands	Arable lands (%)	Arable land	
1990	2.29	77.18	35.97	24.68	137.83	31.62	40.67	10.86	4.42	2871.39
1991	2.26	75.63	35.24	23.73	134.60	31.57	40.78	10.89	4.44	2861.02
1992	2.32	73.66	31.19	20.49	125.34	31.62	46.81	10.82	5.06	2777.25
1993	2.39	72.39	28.96	19.13	120.48	31.57	47.29	10.83	5.12	2737.66
1994	2.54	72.43	29.57	20.05	122.05	31.51	47.51	10.81	5.14	2806.56
1995	2.69	78.36	30.66	20.66	129.68	31.46	47.56	10.80	5.14	2765.46
1996	2.79	82.59	31.10	20.89	134.58	31.40	47.66	10.74	5.12	2941.39
1997	2.92	81.32	33.29	22.58	137.19	31.33	47.87	10.77	5.16	2983.00
1998	2.98	82.81	33.31	22.04	138.16	31.28	48.01	10.80	5.19	3059.67
1999	3.09	84.92	33.29	22.10	140.31	31.22	48.05	10.80	5.19	3101.80
2000	3.06	80.79	32.43	21.69	134.91	31.17	48.11	10.77	5.18	3063.87
2001	3.03	82.18	33.07	22.59	137.84	31.14	48.08	10.75	5.17	3126.42
2002	3.07	82.59	34.55	26.62	143.76	31.10	47.96	10.71	5.14	3100.99
2003	3.16	86.58	36.99	28.41	151.98	31.07	47.82	10.76	5.15	3094.17
2004	3.34	89.02	38.59	30.83	158.44	31.03	47.92	10.78	5.17	3372.58
2005	3.42	89.45	38.82	29.60	157.87	31.00	47.93	10.82	5.19	3262.61
2006	3.46	91.96	39.78	30.45	162.19	30.97	47.82	10.75	5.14	3306.22
2007	3.75	96.08	41.68	33.45	171.21	30.95	47.80	10.74	5.13	3375.73
2008	3.79	95.57	37.62	32.21	165.40	30.92	47.76	10.76	5.14	3538.84
2009	3.71	97.64	38.36	28.38	164.38	30.90	47.64	10.74	5.12	3559.42
2010	3.96	100.79	42.95	33.21	176.95	30.87	47.62	10.70	5.10	3555.38
2011	4.05	104.35	45.41	34.88	184.64	30.84	48.73	10.76	5.24	3664.95
2012	4.09	106.28	45.47	34.35	186.10	30.82	48.8	10.83	5.29	3625.30
2013	4.05	107.08	45.69	35.50	188.27	30.79	48.77	10.85	5.29	3832.14
2014	4.11	108.94	46.70	37.65	193.29	30.77	48.91	10.91	5.34	3906.30
2015	4.06	–	–	–	–	30.74	48.62	10.99	5.34	3923.22
2016	4.09	–	–	–	–	30.72	48.63	10.99	5.34	3966.78
Trend	↑	↑	↑	↑	↑	↓	↑	No trend	↑	↑

Table 4.2.2

Results of Mann-Kendall and Sen's slope test for main agricultural indices to assess the intensity of agrotechnologies and land use practices

Statistical indices	Pesticide use	Nitrogen fertilizers	Phosphorus fertilizers	Potassium fertilizers	Fertilizers in total	Forests, %	Agricultural lands	Arable lands, %	Arable lands	Tractors per 100 km^2
alpha	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
MK-stat	327	259	215	222	252	-347	178	-19	181	307
s.e.	47.95	42.81	42.81	42.82	42.82	47.95	47.96	47.80	47.97	47.97
z-stat	6.80	6.03	4.99	5.16	5.86	-7.22	3.69	-0.38	3.75	6.38
p-value	1.05×10^{-11}	1.67×10^{-9}	5.75×10^{-7}	2.45×10^{-7}	4.57×10^{-9}	5.35×10^{-13}	2.24×10^{-4}	0.71	1.75×10^{-4}	1.78×10^{-10}
trend	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
slope	0.08	1.54	0.76	0.80	3.06	–0.04	0.06	-8.3×10^{-4}	0.01	48.71
lower	0.07	1.34	0.55	0.58	2.51	–0.04	0.04	–0.01	0.01	42.13
upper	0.08	1.79	0.87	0.88	3.43	–0.03	0.09	4×10^{-3}	0.01	53.47
Trend	↑	↑	↑	↑	↑	↓	↑	–	↑	↑

Table 4.2.3

Greenhouse gases emissions and crop production share in them, Mt (1990-2016)

Year	Global emissions in total, Mt				Crop production emissions, Mt				Crop production share, %			
	CO_2	N_2O	CH_4	Total	CO_2	N_2O	CH_4	Total	CO_2	N_2O	CH_4	Total
1990	22.72	2.95	6.67	32.34	3.46	1.92	2.65	8.03	15.23	65.02	39.74	24.83
1991	23.19	2.91	6.71	32.81	3.46	1.90	2.65	8.01	14.92	65.40	39.50	24.42
1992	22.47	3.08	6.85	32.39	3.46	1.90	2.63	7.99	15.40	61.77	38.41	24.67
1993	22.72	2.85	6.50	32.07	3.46	1.88	2.62	7.96	15.23	65.99	40.29	24.82
1994	22.88	2.96	6.62	32.45	3.46	1.90	2.63	7.99	15.12	64.30	39.74	24.62
1995	23.37	2.98	6.56	32.91	3.46	1.93	2.64	8.03	14.80	64.79	40.26	24.40
1996	24.10	3.01	6.55	33.66	3.37	1.96	2.63	7.96	13.98	65.07	40.14	23.65
1997	24.24	3.24	7.21	34.69	4.04	1.95	2.62	8.61	16.67	60.24	36.33	24.82
1998	24.15	3.12	6.68	33.95	3.57	1.98	2.63	8.18	14.78	63.44	39.37	24.09
1999	24.46	2.96	6.50	33.92	3.34	2.00	2.65	7.99	13.66	67.66	40.75	23.56
2000	25.15	2.92	6.48	34.56	3.26	1.99	2.65	7.90	12.96	68.13	40.89	22.86
2001	25.37	2.79	6.59	34.74	3.58	2.01	2.65	8.24	14.11	72.17	40.20	23.72
2002	25.92	2.85	6.79	35.56	4.01	2.01	2.67	8.69	15.47	70.53	39.32	24.44
2003	27.17	2.84	6.83	36.84	3.82	2.02	2.68	8.52	14.06	71.20	39.23	23.13
2004	28.44	2.91	7.09	38.44	3.91	2.08	2.73	8.72	13.75	71.55	38.52	22.69
2005	29.40	2.97	7.28	39.64	3.84	2.09	2.76	8.69	13.06	70.47	37.93	21.92
2006	30.38	3.10	7.62	41.09	2.97	2.12	2.79	7.88	9.78	68.39	36.62	19.18
2007	31.28	3.26	7.70	42.24	2.69	2.17	2.82	7.68	8.60	66.56	36.64	18.18
2008	31.99	3.03	7.64	42.67	2.76	2.17	2.84	7.77	8.63	71.57	37.16	18.21
2009	31.53	3.07	7.78	42.38	2.89	2.18	2.84	7.91	9.17	71.03	36.53	18.67
2010	33.15	3.12	7.93	44.20	2.62	2.21	2.86	7.69	7.90	70.74	36.08	17.40
2011	34.27	3.15	8.01	45.44	2.85	2.24	3.44	8.53	8.32	71.02	42.92	18.77
2012	34.79	2.97	8.37	46.13	2.86	2.24	3.45	8.55	8.22	75.42	41.22	18.53
2013	34.96	2.94	8.34	46.24	2.83	2.22	3.41	8.46	8.10	75.51	40.89	18.30
2014	35.23	3.00	8.48	46.71	2.96	2.24	3.43	8.63	8.40	74.67	40.45	18.48
2015	35.24	3.05	8.66	46.95	3.19	2.27	3.47	8.93	9.05	74.43	40.07	19.02
2016	35.38	3.05	8.55	46.98	2.68	2.29	3.51	8.48	7.57	75.08	41.05	18.05
Trend	↑	No trend	↑	↑	↓	↑	↑	No trend	↓	↑	No trend	↓

Table 4.2.4

Results of Mann-Kendall and Sen's slope test for greenhouse gases emissions and crop production share in them

Statistical indices	Global emissions in total				Crop production emissions				Crop production share			
	CO_2	N_2O	CH_4	Total	CO_2	N_2O	CH_4	Total	CO_2	N_2O	CH_4	Total
alpha	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
MK-stat	337	76	250	331	–136	323	283	59	–251	221	–1	–255
s.e.	47.97	47.96	47.96	47.97	47.67	47.87	47.68	47.93	47.97	47.97	47.97	47.97
z-stat	7.00	1.56	5.19	6.88	–2.83	6.73	5.91	1.21	–5.21	4.59	0	–5.30
p-value	2.48×10^{-12}	0.12	2.08×10^{-7}	6.01×10^{-12}	0.01	1.74×10^{-11}	3.34×10^{-9}	0.23	1.87×10^{-7}	4.51×10^{-6}	1	1.19×10^{-7}
trend	yes	no	yes	yes	yes	yes	yes	no	yes	yes	no	yes
slope	594.90	4.08	91.06	683.25	–0.03	0.02	0.02	0.02	3.33×10^{-3}	4.59×10^{-3}	-1.1×10^{-6}	-3.02×10^{-3}
lower	521.65	–1.3	71.90	598.80	–0.04	0.02	0.01	–0.01	4.16×10^{-3}	3.27×10^{-3}	-1.36×10^{-3}	-3.76×10^{-3}
upper	654.71	10.29	115.00	760.11	–0.01	0.02	0.03	0.03	2.39×10^{-3}	0.01	7.01×10^{-4}	-2.13×10^{-3}
Trend	↑	↑	↑	↑	↓	↑	↑	–	↓	↑	–	↑

Table 4.2.5

Results of correlation analysis between greenhouse gases emissions and current practices of crop production and land use (data of 1990-2016; for mineral fertilizers – 1990-2014)

Crop production and land use practices	Correlation coefficient (R)				Coefficient of determination (R^2)			
	CO_2	N_2O	CH_4	GHG	CO_2	N_2O	CH_4	GHG
Pesticide use	–0.65	0.98	0.82	0.33	0.4223	0.9636	0.6648	0.1092
Nitrogen fertilizers use	–0.64	0.97	0.87	0.28	0.4105	0.9491	0.7610	0.0782
Phosphorus fertilizers use	–0.67	0.98	0.87	0.25	0.4498	0.9661	0.7613	0.0603
Potassium fertilizers use	–0.60	0.92	0.87	0.31	0.3598	0.8531	0.7582	0.0967
Total use of fertilizers	–0.58	0.94	0.81	0.30	0.3319	0.8783	0.6613	0.0887
Forests	–0.95	–0.23	–0.85	–0.94	0.8956	0.0507	0.7142	0.8758
Agricultural lands area	–0.19	0.50	0.38	0.30	0.0376	0.2476	0.1472	0.0908
Arable lands	–0.22	0.54	0.48	0.37	0.0483	0.2928	0.2295	0.1390
Tractors use	–0.64	0.98	0.89	0.40	0.4141	0.9561	0.7861	0.1607

The results of the multiple regression analysis made it possible to establish the degree of change in GHG emissions and their individual types depending on the intensity of agrotechnology at different degrees of implementation of each of the factors studied of crop production and land use characteristics. Mathematical models were developed for the calculation of the design of emissions, which have the following form (4.2.1-4.2.4):

$$CO_2 = -0.6209X_1 - 0.0704X_2 + 0.0697X_3 + 0.0218X_4 - 0.0210X_5 + \\ + 0.1143X_6 + 0.1990X_7 + 0.0008X_8 \quad (4.2.1)$$

$$N_2O = 0.1378X_1 + 0.0019X_2 + 0.0010X_3 + 0.0019X_4 + 0.0443X_5 + \\ + 0.0300X_6 - 0.3218X_7 + 6.2363E\text{-}05X_8 \quad (4.2.2)$$

$$CH_4 = 0.3896X_1 + 0.0268X_2 + 0.0407X_3 - 0.0170X_4 - 0.0454X_5 - \\ - 0.2097X_6 + 2.3326X_7 + 2.8326E\text{-}05X_8 \quad (4.2.3)$$

$$GHG = -0.8727X_1 - 0.0417X_2 + 0.1114X_3 + 0.0067X_4 - 0.0221X_5 - \\ - 0.0653X_6 + 2.2098X_7 + 0.0009X_8 \quad (4.2.4)$$

where: X_1 – pesticide use, Mt; X_2 – nitrogen fertilizers use, Mt; X_3 – phosphorus fertilizers use, Mt; X_4 – potassium fertilizers use, Mt; X_5 – forest area, %

to dryland; X_6 – agricultural land area, million km^2; X_7 – arable land area, million km^2; X_8 – number of tractors in use per 100 km^2 of agricultural land.

Table 4.2.6

Statistics of the regression models for greenhouse gases emissions depending on crop production and land use practices

Statistics	Model			
	CO_2	N_2O	CH_4	GHG in total
R	0.9967	0.9999	0.9995	0.9995
R^2	0.9934	0.9998	0.9989	0.9991
R^2_{adj}	0.9906	0.9998	0.9985	0.9987
R^2_{pred}	0.9873	0.9997	0.9974	0.9982
MSE	0.1090	0.0002	0.0128	0.0926
S	0.3302	0.0143	0.1131	0.3044
MAPE, %	6.6583	0.4614	2.6673	2.4994
PRESS	3.5502	0.0066	0.5186	2.9397
PRESS RMSE	0.3768	0.0163	0.1440	0.3429
DW	1.0781	1.6176	1.4279	1.3381
AIC	0.8757	–5.3998	–1.2662	0.7132
BIC	1.2659	–5.0098	–0.8761	1.1032
AIC_c	1.2147	–5.0610	–0.9274	1.0520
HQC	0.9840	–5.2916	–1.1580	0.8213

Statistical indices of the models confirming their high accuracy and reliability (at $p<0.05$ or 95% confidence interval) are given in Table 4.2.6. The nitrogen oxide emission model is characterized by the highest accuracy (*MAPE* is 0.4614%), the carbon dioxide emission model is the least accurate (*MAPE* is 6.6583%). At the same time, the presence of autocorrelation can be assumed only for the model with carbon dioxide, since the Durbin-Watson DW criterion approaches 1.0 (Суслов и др., 2005).

According to the results of mathematical modeling, it was established that an increase in the amount of pesticide application by 1 Mt reduces GHG emissions by 872.7 thousand tons; an increase in the amount of nitrogen fertilizer application by 1 Mt contributes to a decrease in total GHG emissions by 41.7 thousand tons; the use of 1 Mt of phosphorus and potassium fertilizers leads to an increase in GHG emissions by 111.4 and 6.7 thousand tons, respectively; an increase in the area of forest plantations by 1% and agricultural land by 1 million km^2 will help reduce GHG emissions by 22.1 and 65.3 thousand tons, respectively; the expansion of arable land by 1 million km^2 will contribute to the growth of GHG emissions by 2.2098 Mt; each additional tractor per 100 km^2 of agricultural land leads to an increase in GHG emissions by 0.9 thousand tons.

It is worth noting that, according to the GHG fractions, almost all agricultural practices and land use lead to an increase in nitrogen oxide emissions, which, as mentioned earlier, is the main problem of the modern agricultural sector, which occupies the lion's share of the total emissions of this greenhouse gas from all branches of the modern economy. Thus, it is worth reducing the pressure on the environment by reducing the amount of use of outdated pesticides, as well as volatile forms of mineral fertilizers and those forms that are potentially able to decompose under the action of soil microflora in the process of denitrification and high temperatures to volatile N_2O. We are primarily talking about urea and calcium cyanamide and, to a lesser extent, about solutions of urea-ammonium nitrate (UAN). Also, an important agrotechnical measure of preventive nature is the prevention of anaerobic processes in the soil, as well as soil salinization, which always leads to an increase in the processes of denitrification and the emission of volatile nitrogen oxide from the soil surface. Therefore, it is worth performing alkalized soil liming, creating a favorable and well ventilated soil structure, especially in the upper layer, avoiding excessive compaction, the appearance of a soil crust due to irrigation with mineralized water and irrational soil cultivation, as well as avoiding high single doses of nitrogen fertilizers (more than 250-300 kg/ha of the active substance), which leads to an increase in the loss of gaseous nitrogen up to 35-40% (Минеев, 2004; Євпак, 2007; Господаренко, 2018).

Rational preservation and reproduction of forest resources, rational use of pesticides and agricultural land play a major role in curbing the growth of carbon dioxide and methane emissions. It is very important to use as little energy-consuming tractors as possible and to reduce the intensity of their use, which can be achieved by reducing the required number of passes of machine-tractor units on the field, that is, due to the mass introduction of combined units for soil cultivation, sowing, and fertilizers into the production of plant products.

Paustian et al. (1997) suggested that current carbon conservation technologies and efforts to reduce carbon emissions from soils are effective, but we must recognize that these emissions account for only 3-6% of total GHG emissions, so this direction cannot be considered as the main one at this stage.

However, it is important to remember that in the pursuit of reducing carbon emissions, some agricultural practices, while reducing CO_2 emissions, simultaneously increase N_2O emissions. For example, the practice of no-till (zero tillage), which is recognized as the most effective carbon conservation during tillage, contributes to a significant reduction of carbon dioxide emissions, but at the same time, in some types of soil, this tillage technology leads to a significant increase in emissions N_2O, which also leads to an increase in the concentration of dangerous GHGs in the atmosphere (Rochette et al., 2008; Abdalla et al., 2013). However, this issue requires more detailed further study, as there is evidence of a positive effect on the amount of nitrogen oxide emissions from the soil due to conservation tillage (Chatskikh, & Olesen, 2007). In our view, this is highly dependent on the machines and implements used to cultivate the soil, as well as the properties of the soil itself and weather conditions (Rochette, 2008). In addition, it may depend on the cultivated crop and the intensity of the nutrition system, since it has been proven that the activity of soil respiration strongly depends not only on the depth of plowing, but also on the nutrient regime of the soil and its meliorative state (Lykhovyd & Lavrenko, 2017).

The current trend towards deforestation (of particular concern is the gradual destruction of Amazon forests as one of the most large-scale and influential in terms of ensuring ecological and climatic stability at the global level) and the deterioration of the quality of care for artificial forest plantations is one of the biggest threats to global ecological stability and lead to significant disruptions in biodiversity and climate (Houghton et al., 2015). Currently, very little attention is paid to forest conservation and promoting afforestation, although this strategy may be one of the most effective in solving the problems of modern climatology (Nilsson & Schopfhauser; Islam & Rahman, 2015). Additionally, afforestation provides a huge number of other positive effects, making it an effective and simple tool for comprehensive environmental improvement (Korkanç, 2014; Kamal et al., 2019).

The current practice of using agricultural land seems to be far from optimal, but it does not require an urgent review, especially given the fact of the gradual transition to climate-smart technologies in agriculture (climate-oriented agriculture), which are aimed at further reducing CO_2 emissions. The main goal of modern land use is to maintain arable land at an ecologically safe level since an increase in arable land will mean an increase in GHG emissions and an increased risk of desertification. An optional development option should include strategies to increase the productivity of arable land unit by performing a thorough analysis of land use and implementing various models of land use transformation, taking into account the most promising areas of both economic and environmental benefit (Yin et al., 2017).

In addition, forecasting (using the Holt-Winters triple exponential smoothing method) of the level of GHG emissions from the production of plant products and the characteristics of land use was performed, considering two scenarios: the development of the industry will continue without changes, and also according to the scenario of restoration of forest plantations to the level of 32.00% land area (slightly higher than the level of 1990). The forecast is made until 2050 at a 95% confidence interval, with a 9-year seasonality (the forecast is based on a 27-year period). Forecast statistics are given in the Table 4.2.7.

Table 4.2.7

Statistics for forecasting greenhouse gases emissions depending on crop production and land use practices by 2050 in the scenario of taking no steps for the situation improvement

Statistics	Value for each forecast input							
	Pesticide	N fertilizer	P fertilizer	K fertilizer	Agric. land area	Arable land area	Forest area	Tractors in use
p	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
α	0.13	0.90	1.00	0.75	0.90	0.90	0.75	0.75
β	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00
γ	0.00	0.10	0.00	0.00	0.10	0.10	0.25	0.00
MASE	1.21	1.00	1.59	1.27	0.59	0.75	0.36	1.05
SMAPE	0.03	0.02	0.05	0.05	0.01	0.01	0.00	0.02
MAE	0.11	2.31	2.09	1.74	0.33	0.05	0.02	73.99
RMSE	0.12	2.72	2.51	2.10	0.48	0.06	0.02	79.30

The results of the forecast established that the level of GHG emissions from activities related to the crop production will gradually increase, and by 2050 it will reach 9.35 Mt, i.e., 0.82 Mt more than in 2016 (Fig. 4.2.2).

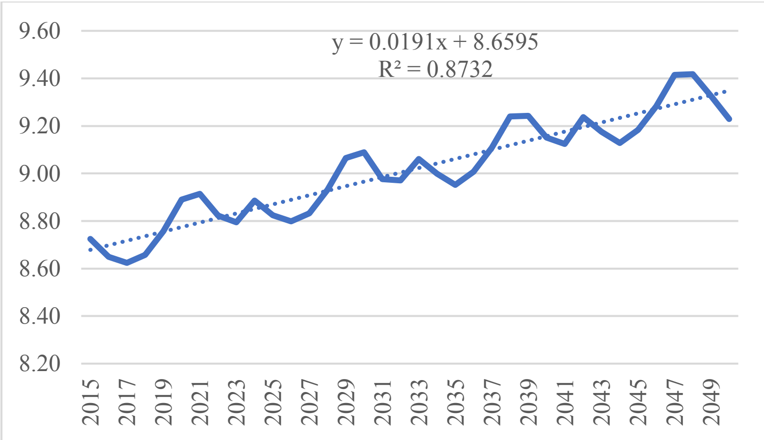


Fig. 4.2.2. Greenhouse gases emissions forecast (in Mt) depending on the activity connected with crop production (the scenario of no steps is taken)

If by 2050 the forest area will gradually be restored to the level of 32.00% of the dryland, while maintaining the development of other practices of crop production and land use without changes (since it is quite difficult to predict and program changes in the policy of using pesticides and agrochemicals, as well as predict the degree of development of combined machine-tractor units, in contrast to afforestation, which can be artificially and purposefully created), the forecast will have the same form, but by 2050 the emission of GHG will reach the mark of 9.30 Mt, that is, it will be by 0.05 Mt lower. In the same case, if the area of forest plantations is intensively increased to 35.00% by 2050 due to mass afforestation and greening urban landscapes, the creation of park systems, the system of forest amelioration and creation of forest shelter belts along the fields, renewal and maintenance in proper condition of natural and artificial forest areas with fast-growing species of trees, emissions of 9.23 Mt can be expected, even under the absence of improvements in agricultural technologies and land use practices. If at the same time it is possible to restrict the growth of arable land and agricultural land at the level of 2016, then we can reduce the increase in GHG emissions from the agricultural sector to 8.51 Mt by 2050 (Fig. 4.2.3).

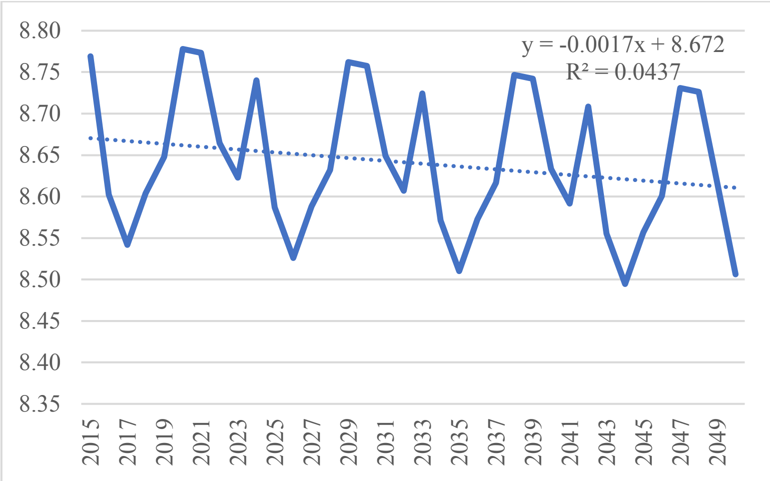


Fig. 4.2.3. Greenhouse gases emissions forecast (in Mt) depending on the activity connected with crop production (the scenario of 35% afforestation, agricultural lands area maintenance at the level of 2016)

Thus, the significant positive role of afforestation and forest amelioration in overcoming the current environmental crisis associated with GHG emissions into the atmosphere is confirmed, which, accompanied by rational land use, will allow maintaining the growth of GHG emissions even under the conditions of further intensification of crop production.

At the same time, by making efforts to restrain the rapid growth of the number of tractors in use per 100 km^2 of agricultural land and keeping their number at the level of 4,000 units, with high reliability (confidence interval of the forecast is 95%, R^2 is 0.9395), it is possible to achieve a significant reduction in GHG emissions from crop production – up to 7.14 Mt by 2050 (Fig. 4.2.4).

In addition, it is worth considering the possibility and rationality of the mass introduction of GMOs into the practice of plant production. Brookes & Barfoot (2018) claim that the introduction of GM varieties and hybrids of crops resistant to pests and diseases into production can significantly reduce the amount of pesticide use, leading to a significant reduction in GHG emissions. Of course, improving the climatological situation is an important task of modern science, but it is worth paying attention to the fact that to date there are not enough large-scale scientific studies that would convince about the food and ecological safety of GM crops. Currently, the issue of the safety of GMOs is quite controversial; transgenic plants have both their supporters and opponents, and the arguments of the latter are not always less convincing and testify to the violation of natural biodiversity, the death and mutation of natural species of insects and plants, the destruction of natural ecological food chains in ecosystems in areas where GM crops are grown, emergence of new superweeds as a result of natural mutations in crops of transgenic crops, accumulation of glyphosate and derivative compounds in soil and natural water bodies, etc. While the indisputable advantages of GM technologies include increasing the productivity of agroecosystems, reducing the pesticide load, improving agricultural technology, reducing GHG emissions and climate pressure (Dale et al., 2002; Brookes & Barfoot, 2006; Waltz, 2009; Carpenter, 2010; Helander et al., 2012; Bain et al., 2017).

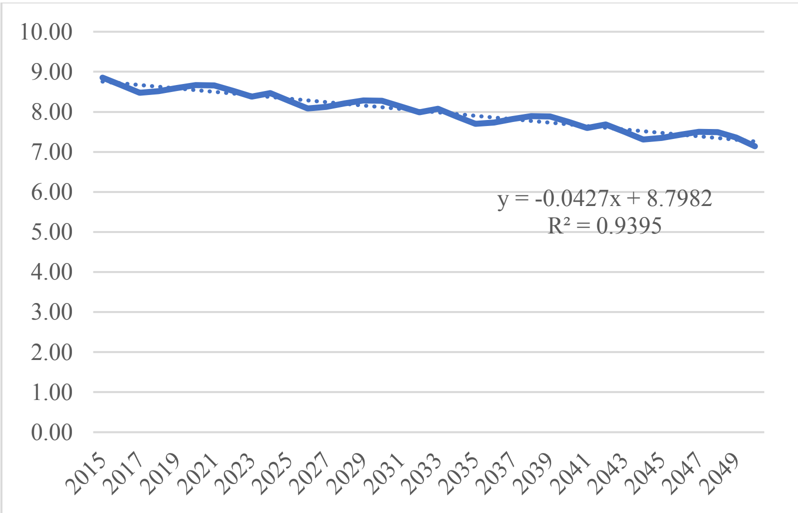


Fig. 4.2.4. Greenhouse gases emissions forecast (in Mt) depending on the activity connected with crop production (the scenario of 35% afforestation, agricultural lands area maintenance at the level of 2016, and cutting tractors use to the level of 4000 pcs. per 100 km²)

4.3. Afforestation as an effective measure of climate regulation and agricultural land productivity increase

The forest is an integral and very valuable part of the biosphere, it is a unique natural ecosystem that unites organisms from the kingdoms of plants, animals, and fungi. Modern anthropogenic activities, together with adverse natural factors, have led to a significant decrease in the areas covered by various types of forests in the world. In recent decades, forests and their adjacent ecosystems have been significantly damaged due to the rapid growth of the world population and the many-fold increase in the man-made load. It is expected that the anthropogenic load on forests has not yet reached its peak, and it will continue to increase, which will lead to an even greater decrease in the area of forests, deterioration of conditions for afforestation, and the ecological conditions of the biosphere as a whole (Kimmins, 2004; Newton, 2007), because forests are one of the valuable and important regulators of the microclimate and are a habitat for many species of plants and animals of wild nature (Hunter & Hunter Jr., 1999).

One of the main concerns associated with intensive deforestation is its connection with current global climate change – a significant increase in the global average surface air temperature, which, as we pointed out earlier, is mainly due to increased GHG concentrations (Ramanathan, 2007), which, in its turn, negatively affects agriculture and food security due to an increase in the frequency of adverse natural phenomena such as drought, downpours, hail, hurricane winds, leads to an aggravation of the shortage of high-quality fresh water, deterioration of soil fertility, and, as a result, crop losses (Arnell et al., 2019). As is known, forests can effectively control the concentration of carbon-containing greenhouse gases (CO_2 and CH_4) in the atmosphere (Houghton et al., 2015). Therefore, an important task of modern science is to assess the role of forests in limiting global warming both on a global and local scale, as well as to determine the response of the main agricultural crops to deforestation and related changes in the microclimate.

The purpose of the study is to determine the relationship between the world area of forests of natural and artificial origin and global air temperature, as well as the relationship between the area of forest plantations and the productivity of agricultural crops at local levels (state and regional) to provide justification for the use of measures aimed at reconstruction of disturbed, maintenance of existing and creation of new objects of the forest fund, or to support the hypothesis that these measures are not necessary, as some scientists claim (Wang et al., 2015).

Deforestation is closely related to ineffective control of the concentration of carbon-containing greenhouse gases, as it was already proved above in section 4.2, and to the increase in global air temperature. The practice of destroying forest plantations can be one of the important reasons for intense climate changes, especially if we consider the relationship between the area of forest massifs and air temperature, where the correlation coefficient is -0.85, and the determination is 72.25% (Fig. 4.3.1).

There is a natural relationship between forest areas and climate change: climate change to some extent causes a natural decrease in forest area (due to fires, accelerated development and spread of phytopathogens and phytophagic organisms under conditions of global warming), but at the same time additional forest destruction is one of the causes of further climate changes and their intensification both on a local and on a planetary scale (Seidl et al., 2017).

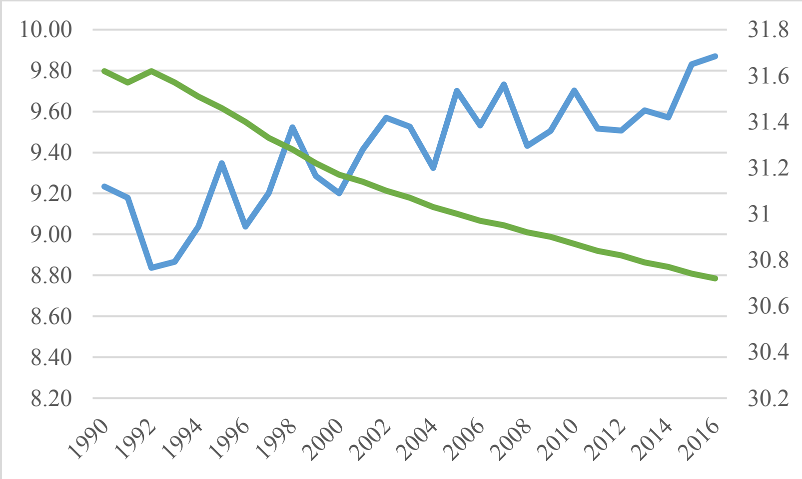


Fig. 4.3.1. Forest area and global air temperature for 1990-2016 (blue line – air temperature, ˚C; green line – forest area, % to dryland)

However, some researchers still claim that the effect of afforestation on mitigating the consequences of global warming is not obvious, and its effectiveness depends on the area of afforestation, the most promising of which is the tropical region of the Earth, while the effects of reforestation may not be sufficiently effective and justified in high latitudes and temperate climates (Bala et al., 2007). At the same time, there is another opinion, which confirms the results of our research, that further massive deforestation will inevitably lead to an increase in the negative impact of global warming and a simultaneous deterioration of the conditions for conducting agricultural activities (Lawrence & Vandecar, 2015). Furthermore, deforestation also negatively affects the properties of soil cover, water bodies, biodiversity, leading to a change in the global ecological balance not only in the areas of deforestation, but also in adjacent territories (Houghton, 1990; Прокопенко та ін., 2018). For example, the adverse impact of deforestation on soils is their over-compaction, reduction in the content of organic substances, and deterioration of chemical and mechanical properties (Hajabbasi et al., 1997).

The impact of forests is not limited to the mentioned above. Forests of both artificial and natural origin as a powerful microclimate regulation factor have a significant impact on the productivity of agroecosystems and on the yield of crops. This fact is confirmed by a local study of the dynamics of the area of artificial forest plantations and the productivity of agricultural crops in the Kherson region for the period 2001-2019.

Thus, over a 20-year period, the area of forest plantations in the Kherson region increased from 151.1 to 154.7 thousand hectares, or by 2.38% (according to the data of the regional office of the State Statistical Service). Despite the relatively small increase, the trend towards reforestation in the region is significant, which is confirmed by the results of statistical data processing (Table 4.3.1).

Table 4.3.1

Results of Mann-Kendall and Sen's slope test for the forest area and total yields of crops in Kherson oblast

Statistical indices	Forest area	Total yields per 1 ha
alpha	0.05	0.05
MK-stat	150	13
s.e.	28.06	20.21
z-stat	5.31	0.59
p-value	1.10×10^{-7}	0.55
trend	yes	no
slope	0.0833	0.2790
lower	0.0667	–0.5483
upper	0.1000	0.9814
Direction of trend	↑	No trend

At the same time, the productivity of 1 ha of arable land, expressed in the total average yield of the main types of crops (namely: cereals, legumes, sunflower, sugar beets, potatoes, vegetables, fruit and berry crops, grapes) according to the results of statistical analysis, remains at relatively stable level (Table 4.3.2).

Regression analysis of the relationship between arable land productivity and forest supply of the region testifies about weak correlation between these parameters (R is 0.31; R^2 is 0.0961). Therefore, it is impossible to claim that afforestation of Kherson oblast will grant significant increase in crops yield. Mathematical equation of the model is as follows 4.3.1:

$$Y = -220.6983 + 1.7941FA \tag{4.3.1}$$

where: Y – total yields (productivity) per 1 ha of arable land, ton; FA – forest area in the region, thousand ha.

Table 4.3.2

Forest area and total yields of major crops in Kherson oblast for 2001-2019

Year	Forest area, thousand ha	Total productivity per 1 ha, ton
2001	151.1	N/A
2002	151.1	N/A
2003	151.1	N/A
2004	151.3	N/A
2005	151.4	74.01
2006	151.4	57.34
2007	151.4	51.33
2008	151.4	56.75
2009	151.5	40.91
2010	152.0	40.69
2011	152.0	50.22
2012	152.0	52.26
2013	152.0	50.98
2014	152.1	53.46
2015	152.1	55.70
2016	152.1	55.72
2017	152.1	54.12
2018	153.8	57.09
2019	154.7	56.15

Table 4.3.3

Statistics of the regression model for the productivity of 1 ha of arable land in Kherson oblast depending on the area of forest in the region

Statistical indices	Value
R	0.3100
R^2	0.0961
R^2_{adj}	0.0208
R^2_{pred}	0.1256
MSE	28.8043
S	5.3670
MAPE, %	7.4379
PRESS	430.4283
PRESS RMSE	5.5448
DW	1.2712
AIC	6.3300
BIC	6.4213
AIC_c	6.3538
HQC	6.3215

It is worth recognizing the low prognostic reliability of the proposed equation (the predicted $R^2 pred$ is only 0.1256, which even against the optimal background of the absolute average error of 7.4379% indicates an insufficient level of model fit quality and its correspondence to the real course of productive processes), which relates to a weak connection between the studied factors (Table 4.3.3). Relatively high values of the calculated information criteria of the model testify to this indirectly.

While the local impact of forest plantations on the productivity of arable land is low in the Kherson region (determination <10%), the situation in the case of performing a similar analysis for the territory of Ukraine is the opposite. The results of the assessment of trends for 1990-2019 (according to the data of the State Statistical Service of Ukraine, covered in the Statistical Yearbooks) showed that there is a clear and reliable tendency to increase the area of forest plantations on the territory of Ukraine (thanks to rational work on afforestation and protection of forest plantations on the state level), and to the growth against this background of the productivity of agricultural land (Table 4.3.4). Correlation analysis of the relationship between the total productivity of arable land and the country's supply of forest plantations indicates the presence of a moderately strong correlation between these parameters (R is 0.69; R^2 is 0.4792). Based on the regression analysis of the data, a mathematical model of the relationship between the productivity of 1 hectare of Ukrainian arable land and the level of afforestation of the territory of the country was developed (Table 4.3.5). Autocorrelation is present in the model (Суслов и др., 2005), i.e., the time component plays a certain role in the forecast.

Table 4.3.4

Results of Mann-Kendall and Sen's slope test for the area of forests and total yields of crops in Ukraine

Statistical indices	Forest area	Total yield per q ha
alpha	0.05	0.05
MK-stat	191	189
s.e.	35.41	35.46
z-stat	5.37	5.30
p-value	8.04×10^{-8}	1.15×10^{-7}
trend	yes	yes
slope	0.0269	3.5967
lower	0.0164	3.0175
upper	0.0400	3.9792
Direction of trend	↑	↑

Table 4.3.5

Statistics of the regression model for yields per 1 hectare of arable land in Ukraine depending on the area of forest

Statistical indices	Value
R	0.6923
R^2	0.4792
R^2_{adj}	0.4532
R^2_{pred}	0.4046
MSE	287.9001
S	16.9676
$MAPE$, %	18.5010
$PRESS$	6583.5731
$PRESS\ RMSE$	17.2989
DW	0.4737
AIC	8.5870
BIC	8.6862
AIC_c	8.5961
HQC	8.6104

Mathematical model for Ukraine has reasonable prognostic accuracy according to the values of R^2_{pred} and *MAPE* within 10-20% (Moreno et al., 2013), and looks as follows (4.3.2-4.3.3):

$$Y = -505.5704 + 35.3499FA \tag{4.3.2}$$

where: Y – total yields (productivity) per 1 ha of arable land, tons; FA – forest area in the country, % to the total dryland area.

$$Y = -505.5704 + 5.8565FA \tag{4.3.3}$$

where: Y – total yields (productivity) per 1 ha of arable land, tons; FA – – forest area in the country, thousand km^2.

Thus, it can be stated that the productivity of a unit of agricultural land of Ukraine is determined by 40-45% by the level of its supply with high-quality forest plantations of natural or artificial origin. Currently, unfortunately, the supply of a unit of planted area with forests in Ukraine is insignificant, while there is no tendency to increase this indicator (Tables 4.3.6-4.3.7).

For comparison, we will provide data on the ratio of forest supply per 1 hectare of arable land in some other countries of the world (FAOSTAT): Netherlands

– 0.36; France – 0.41; Poland – 0.59; Great Britain - 0.68; Spain – 1.21; USA – 2.17. So, the situation with afforestation in Ukraine is far from the best. In the near term, to ensure agro-ecological stability and sustainable development of the agrarian sector of the economy, it is worth intensifying afforestation measures while simultaneously reducing the arable land area to achieve the ratio of forest supply per 1 ha of arable land at the level of 0.50-0.60. For this (under the conditions of maintaining the cultivated area at the level of 27 thousand ha) it is necessary to plant 28.1-55.1 thousand km^2 of forest, including a forest strip along the fields.

Table 4.3.6

Forest area and total yields of major crops in Kherson oblast for 1990-2019

Year	Forest area, thousand km^2	Total yields per 1 ha of arable land, ton	Croplands, thousand ha	Forest supply coefficient
1990	96.64	69.39	32406	0.30
1995	97.84	52.25	30963	0.32
2000	99.05	53.27	27173	0.36
2001	99.23	51.64	27928	0.36
2002	99.35	53.22	27539	0.36
2003	99.47	60.04	25081	0.40
2004	99.59	66.05	26752	0.37
2005	99.78	69.04	26044	0.38
2006	99.71	71.14	25928	0.38
2007	99.65	72.32	26060	0.38
2008	99.59	84.19	27133	0.37
2009	99.53	81.87	26990	0.37
2010	99.47	76.54	26952	0.37
2011	99.71	94.18	27670	0.36
2012	99.96	97.58	27801	0.36
2013	100.14	100.99	28239	0.35
2014	100.38	111.79	27239	0.37
2015	100.62	106.25	26902	0.37
2016	100.86	111.78	27026	0.37
2017	106.78	111.61	27585	0.39
2018	106.78	120.77	27699	0.39
2019	106.90	110.55	28001	0.38

Thus, the task of afforestation, maintenance of the quality of existing and reconstruction of disturbed forest areas should become strategic for Ukraine to ensure a better ecological environment, maintain the stability of ecosystems, guarantee a stable increase in the productivity of agricultural production, ensure climate stability, and preserve biological diversity in the state.

Table 4.3.7

Results of Mann-Kendall and Sen's slope test for croplands area and their supply with forests in Ukraine

Statistical indices	Croplands	Croplands supply with forests
alpha	0.05	0.05
MK-stat	19	67
s.e.	35.46	35.46
z-stat	0.51	1.86
p-value	0.61	0.06
trend	no	no
slope	14.5556	0.0010
lower	–78.4286	-5.4×10^{-5}
upper	107.3333	0.0028

Unfortunately, the world scientific community pays very little attention to the study of the mutual influence of forest plantations and agroecosystems, there is a small number of studies devoted to the direct and indirect influence of forests on the production of plant products, so it is difficult for us to cite the results of other domestic or foreign scientists for support or refutation the results of our scientific work. To support and explain the results of our work, we can cite the scientifically proven statement that forests take a direct part in the formation of soil fertility, the preservation and distribution of water resources, the regulation of weather phenomena, the protection of adjacent territories from the adverse effects of natural and anthropogenic factors, etc. (Pearce, 2001; Ivanova et al., 2017), and all this collectively affects the productivity of agricultural crops. Deforestation has also been proven to be one of the reasons for the decline in the productivity of agricultural crops that are entomophilous and require pollinating insects to form a quality crop, most of which have lost their natural habitat located in forests (De Marco & Coelho, 2004). Forest reclamation measures play an important role in the fight against desertification and land degradation (Movchan, 2017), and it has also been proven that forest plantations are a guarantor of improving the ecological and economic stability of the agricultural sector (Протас та ін., 2008). Thus, forests are a natural, ecologically safe factor for improving the productivity of agricultural crops and, in our opinion, their role in agricultural production and ensuring the ecological stability and sustainability of ecosystems in the context of global climate change will continue to increase.

Conclusions to Chapter 4

1. Analysis of the average annual global air temperature for the period 1750-2020 demonstrated the presence of a clear trend towards a gradual increase in temperatures. Reliable trends towards an increase in the concentration of the main greenhouse gases in the atmosphere, an increase in the area of the ozone hole, as well as a trend towards a decrease in the concentration of ozone were revealed. It has been established that carbon dioxide has a secondary role in the increase in global air temperature, while nitrogen oxide is the most influential. A strong directly proportional correlation dependence ($R > 0.69$) was established between the increase in the concentration of the investigated greenhouse gases and the increase in global air temperature. The decrease in the concentration of ozone in the atmosphere, the depletion of the ozone layer and the increase in the ozone hole area partially determine the further increase in global air temperature and are additional reasons for the worsening of the climate situation. We have proposed a mathematical model for forecasting the global air temperature based on indicators of the concentration of GHG and ozone in the atmosphere, as well as from the area of the ozone hole, which has high reliability: R^2pred is 0.9996; *MAPE* is 1.4915%. The simulation results additionally confirmed that the maximum contribution to global warming in the period 1979-2020 was the concentration of nitrogen oxide and the area of the ozone hole. The main attention should be paid to the control of the emission of nitrogen oxide into the atmosphere, as well as to the restoration of the natural mechanism of thermoregulation due to the ozone layer.
2. There is a tendency to increase emissions of N_2O and CH_4 from crop production, and the situation with N_2O is critical, as there is a tendency to increase not only absolute, but also relative emissions of this GHG from crop production. Currently, the agricultural sector is the main source of nitrogen oxide emissions (over 75% share), while carbon dioxide emissions due to modern farming systems are minimal (less than 8% share). A strong correlation was established between emissions and accumulation of GHG and the area of forest plantations (R^2 is 0.8758). Forests are the main regulators of the concentration of carbon-containing gases CO_2 and CH_4 in the atmosphere. According to the results of mathematical modeling, it was established that an increase in the amount of pesticide application by 1 million tons reduces GHG emissions by 872.7 thousand tons; an increase in the amount of nitrogen fertilizer application by 1 million tons contributes to a decrease in total GHG emissions by 41.7 thousand tons; the use of 1 million tons of phosphorus and potash fertilizers leads to an increase in GHG emissions by 111.4 and 6.7 thousand tons, respectively; an increase in the area of forest plantations by 1% and agricultural land by 1 million km^2 will help reduce GHG emissions by 22.1 and 65.3 thousand tons, respectively; the expansion of arable land by 1 million km^2 will contribute to the growth of GHG emissions by 2.2098 million tons; each additional tractor per 100 km^2 of agricultural land leads to an increase in GHG emissions by 0.9 thousand tons.

It is worth reducing the loads on the environment by reducing the amount of use of outdated pesticides, as well as volatile forms of mineral fertilizers and those forms that are potentially able to decompose under the action of soil microflora in the process of denitrification and high temperatures to volatile N_2O (urea, calcium cyanamide, solutions of urea-ammonia nitrates, etc.). It is important to prevent the development of anaerobic processes in the soil, their alkalinization. It is necessary to perform liming of alkaline soils, avoid compaction and the appearance of soil crust, avoid high single doses of nitrogen fertilizers (more than 250-300 kg/ha of active substance). The results of the forecast established that without taking measures, the level of GHG emissions from crop production will reach 9.35 million tons by 2050, and thanks to rational practices of afforestation and reducing environmental pressure, it is possible to achieve a reduction of GHG emissions from the industry by 7.14 million tons by 2050.

3. The practice of deforestation is a significant factor in the intensification of climate change, which is confirmed by the close inverse correlation between global air temperature and the area of forests: the correlation coefficient is -0.85, and the determination is 72.25%. In addition, we have proven the significant role of forest plantations in regulating the productivity of agricultural crops on the territory of Ukraine. The mathematical model of the total productivity of 1 ha of Ukrainian arable land, depending on its availability of forests, has high reliability and good predictive accuracy, which is confirmed by the results of statistics: R^2pred is 0.4046 with a *MAPE* value of 18.5010%. In the period 1990-2019, the ratio of arable land coverage with forest plantations in Ukraine is within 0.3-0.4 without a tendency to increase.

CHAPTER 5
REMOTE SENSING IN AGROECOLOGICAL MONITORING AND MODERN AGRICULTURAL PRACTICE

5.1. Flora monitoring on regional scale using remote sensing data

Space investigation, increasing the number of artificial satellites and equipping them with special sensors gave impetus to the development of a new field of science and technology – remote sensing of the Earth. Satellite monitoring is a modern field that is experiencing steep and rapid development, finding application in many fields of science, primarily in geography, geology, ecology, etc. The possibilities of remote sensing have also found their practical application in the field of agriculture, where, in combination with information technologies and modern technical means, they are implemented in mapping and management of land and water resources, agroecological monitoring, modeling and forecasting of the conditions of natural and anthropogenic flora, as well as in precision agriculture systems (Kustas & Norman, 1996; Herold et al., 2002; Rogan & Chen, 2004; Marsett et al., 2006; Morales et al., 2008; Martínez-López et al., 2014).

Remote sensing is a valuable source of data for fast and highly accurate monitoring of the conditions of both natural and anthropogenic phytocenoses, regardless of their spatial characteristics. The main means of assessing the state of vegetation based on satellite monitoring data are vegetation indices, which are obtained by processing various spectral ranges of space images of the Earth's surface. There are more than 150 vegetation indices, but only a limited number of them are used in practice, primarily normalized difference (NDVI) and enhanced (EVI) vegetation indices (Білинський & Книш, 2021).

The normalized difference vegetation index is one of the oldest and most used vegetation indices in agroecological science. Proposed at the end of the 20th century (Rouse et al., 1974), it remains to this day the main index used in precision agriculture systems. Sometimes NDVI data is supplemented with other vegetation indices, most often – EVI. The latter is an improved version of NDVI, less sensitive to distortions due to the reflection of light from the soil surface, to atmospheric distortions, as well as errors related to the structure of the green cover (Matsushita et al., 2007; Jiang et al., 2008).

Monitoring and control of the conditions of vegetation is an important component of ecological research aimed at the reproduction and preservation of biodiversity. Seasonal and multi-year observations of the state of the flora make it possible to establish the patterns of reactions of the plant world to anthropogenic activity and climate change. Of course, direct observations and measurements remain the most accurate way of obtaining information about the condition of plants. However, the use of spatial satellite indices of vegetation makes it possible to quickly assess the general state of the flora in large areas, which is practically very difficult, expensive, or impossible at all using direct on-Earth methods (Kim et al., 2010).

The aim of the study was to establish the annual and multi-year dynamics of vegetation indices, the strength and direction of the influence of climatic factors on the vegetation of the Kherson region (both natural and artificial) by studying the regularities of the relationship between NDVI and EVI with air temperature and precipitation for a better understanding of the response of the regional flora to climatic changes.

Like any biological system, flora has its own specific dynamics of fluctuations over time (Tsimring, 2014). The annual seasonal dynamics of vegetation conditions is well known and, at first glance, obvious. Thus, the native population of the Kherson region knows that grass begins to grow in early spring, trees bloom in late spring and summer, fruits appear in late summer and autumn, and at the end of autumn the gradual aging and death of most plants occurs, except for evergreens. This knowledge is based on life experience, and therefore reflects the processes of the dynamics of the state of the flora, although accurately and in an understandable form, but often not precisely enough, in an axiomatic format, and therefore cannot be integrated into the processes of scientific knowledge of the world. Based on the results of the generalization of data on NDVI and EVI by region for the period 2012-2021, the main seasonal patterns of growth and development of vegetation in the region were established (Fig. 5.1.1).

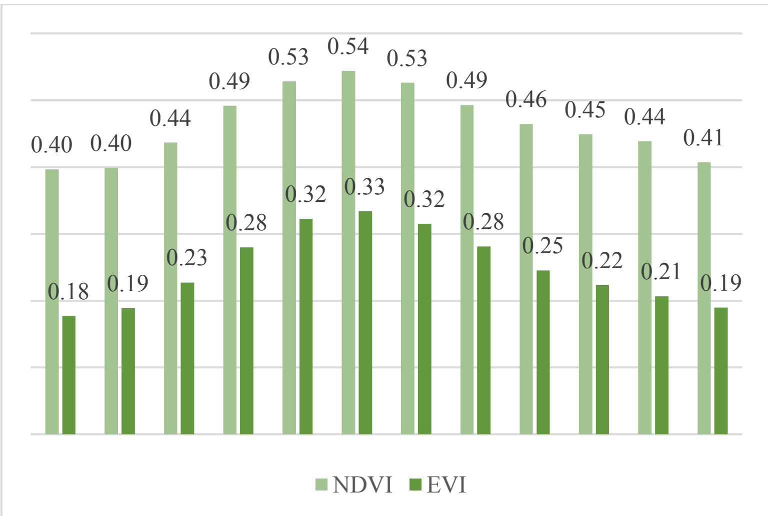


Fig. 5.1.1. Annual dynamics of NDVI and EVI on the regional scale for Kherson oblast from January to December (averaged for 2012-2021)

It was established that the vegetation indices in the region reach their peak values (which means the maximum intensity of growth processes, the maximum level of green cover and the greatest vitality of natural and artificial plantations) in the period from May to July: NDVI is 0.53-0.54, EVI is 0.32-0.33. Undoubtedly, this is connected not only with the cyclical nature of the growth and development of natural flora, but also with the fact that the growth and development of the major crops cultivated in the region is characterized by the maximum intensity during this period. The winter period (December – February) is characterized by the minimum values of the vegetation indices (NDVI is 0.40-0.41, EVI is 0.18-0.19), which, however, do not reach the values that are typical for bare soil. This is due to the presence of evergreen plants (for example, pine forests located in Oleshshia district), as well as thaws, when even in the winter period of the year we observe the growth of green grassy vegetation. The spring period (March – May) is characterized by a rapid increase in the intensity of growth and development of flora in the region, which confirms a significant leap in the values of vegetation indices: from 0.40 to 0.53 for NDVI (+32.50%) and from 0.19 to 0.32 for EVI (+68.42%). The peak of growth processes for the flora of the Kherson oblast coincides with the summertime (June – August), when the values of the spatial indices of vegetation reach 0.49-0.54 for NDVI and 0.28-0.33 for EVI. The maximum values of the vegetation indices are the month of June (0.54 and 0.33 for NDVI and EVI, respectively). From July and especially from August, the vegetation enters a period of gradual senescence, which lasts throughout the autumn period (September – November) and reaches its peak in January (the lowest values of NDVI and EVI on average for the annual period are 0.40 and 0.18, respectively). The dynamics of the decrease in vegetation indices since the end of summer can be closely related to the fact of the end of the growing season, the death of green biomass and the harvesting of the main agricultural crops grown in the region.

It is interesting that the results of the study of the seasonal dynamics of the growth and development of vegetation in the Kherson region, based on satellite data, fully confirm the information provided by the Agrometeorological Service of the Kherson region, based on long-term observations, that the end of the growing season in the region usually happens in November, and its beginning is usually recorded in March (Ушкаренко, 1994).

The study of the long-term dynamics of the flora conditions in the Kherson region shows that there is a sustainable trend towards an increase in the intensity of vegetation growth and an improvement in its general condition, which is confirmed by a gradual increase in the value of the vegetation indices (Fig. 5.1.2, 5.1.3). At the same time, it is worth noting the fact that the vegetation index EVI turns out to be more sensitive and shows a much higher rate of linear dynamics to increase compared to NDVI.

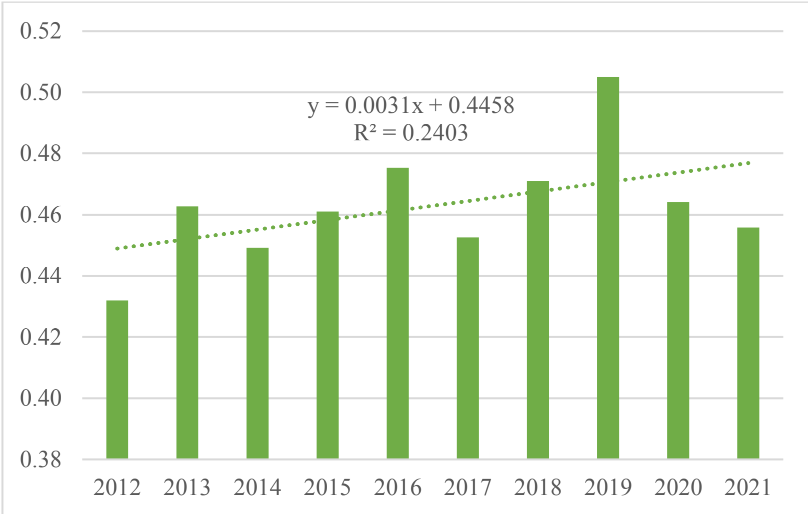


Fig. 5.1.2. Long-term dynamics of flora conditions in Kherson oblast by NDVI for the period 2012-2021

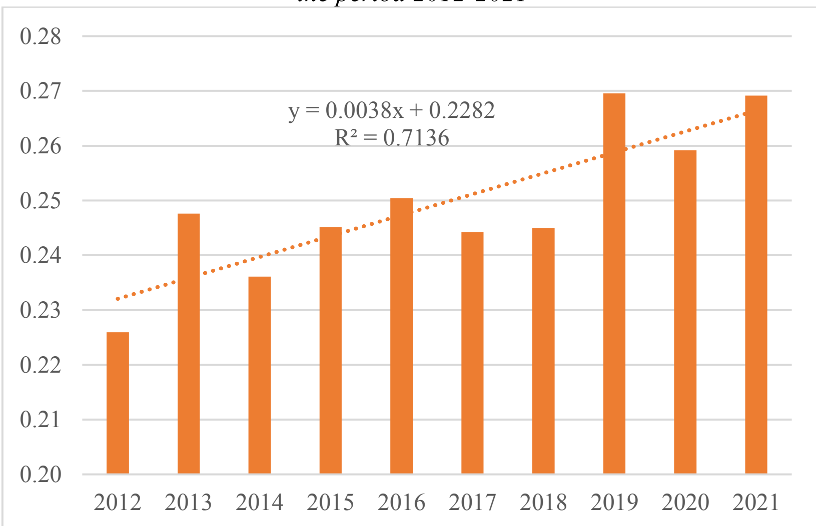


Fig. 5.1.3. Long-term dynamics of flora conditions in Kherson oblast by EVI for the period 2012-2021

The established dynamics in vegetation indices requires the search for reasons, one of which can be put upon the change in climatic features in the region. However, the analytical work was subject to data sets on the continuous vegetation cover of the Kherson region, including anthropogenic arrays of agrophytocenoses, and therefore the hypothesis of the connection of established patterns with the development of agricultural technologies cannot be rejected. To clearly determine the degree of influence of climatic factors (primarily, average annual air temperature and amount of precipitation) on the state of vegetation in the region, we performed a statistical regression analysis of the relationships between the values of vegetation indices and meteorological indicators for the period 2012-2021 (Tables 5.1.1, 5.1.2).

Table 5.1.1

Results of the regression analysis between average annual air temperature, precipitation and average annual NDVI in Kherson oblast for the period 2012-2021

Regression statistics	Index value
Correlation coefficient (*R*)	0.7477
Standard deviation (*SD*)	0.0144
Mean square error (*MSE*)	0.0002
Coefficient of determination (R^2)	0.5591
Adjusted R_{adj}^2	0.4331
Root mean square error (*RMSE*)	0.0190
Mean average percentage error (*MAPE*)	2.30
Regression model coefficients	
Slope	–0.1915
A (for average annual air temperature)	0.0485
B (for annual precipitation)	0.0002

Table 5.1.2

Results of the regression analysis between average annual air temperature, precipitation and average annual EVI in Kherson oblast for the period 2012-2021

Regression statistics	Index value
Correlation coefficient (*R*)	0.6257
Standard deviation (*SD*)	0.0121
Mean square error (*MSE*)	0.0001
Coefficient of determination (R^2)	0.3915
Adjusted R_{adj}^2	0.2176
Root mean square error (*RMSE*)	0.0162
Mean average percentage error (*MAPE*)	3.84
Regression model coefficients	
Slope	–0.0790
A (for average annual air temperature)	0.0232
B (for annual precipitation)	0.0001

According to the results of the mathematical evaluation, a significantly higher sensitivity to meteorological factors was established for the normalized differential vegetation index, which confirms the higher values of the regression statistics indicators: correlation and determination coefficients, as well as the average absolute error. However, both regression models (for both NDVI and EVI) describe the average strength of the relationship between climate parameters and vegetation indices in the region. The models are presented here (5.1.1-5.1.2):

$$NDVI = -0.1915 + 0.0485\mathrm{T} + 0.0002R \quad (5.1.1)$$

$$EVI = -0.0790 + 0.0232\mathrm{T} + 0.0001R \quad (5.1.2)$$

where: T – average annual air temperature, ºC; R – annual precipitation, mm.

The assessment of the relationship between climatic parameters and vegetation indices for the growing season made it possible to establish the following regularities. First, it is interesting that in this case the NDVI is more sensitive to dynamic changes in the vegetation conditions, while the EVI is more sensitive to annual dynamic assessments (Fig. 5.1.4, 5.1.5).

In addition, it was established that the response of vegetation indices to the climatic factor also shows the completely opposite to the average annual intensity of the dependence of vegetation indices on meteorological indicators. Thus, during the assessment of the relationship between the weather conditions of the growing season and the value of the vegetation indices, it was established that the NDVI did not respond to the climatic factor at all, as evidenced by the value of the coefficient of determination less than 0.30 and the negative value of the adjusted coefficient of determination (Dodge, 2008), while the EVI showed a higher sensitivity to meteorological conditions than the annual mean estimate (Tables 5.1.3, 5.1.4).

Another fact that attracts attention is the change in the direction of the influence on the vegetation indices of air temperature: if the regression coefficient had positive (>0) values when assessing the average annual dynamics, then the assessment within the growing season indicates a negative effect of the increase in temperature on the vegetation of the region (regression coefficients <0). For precipitation, the direction of influence is the same for different periods of assessment, the strength of the influence decreased during the assessment for the growing season.

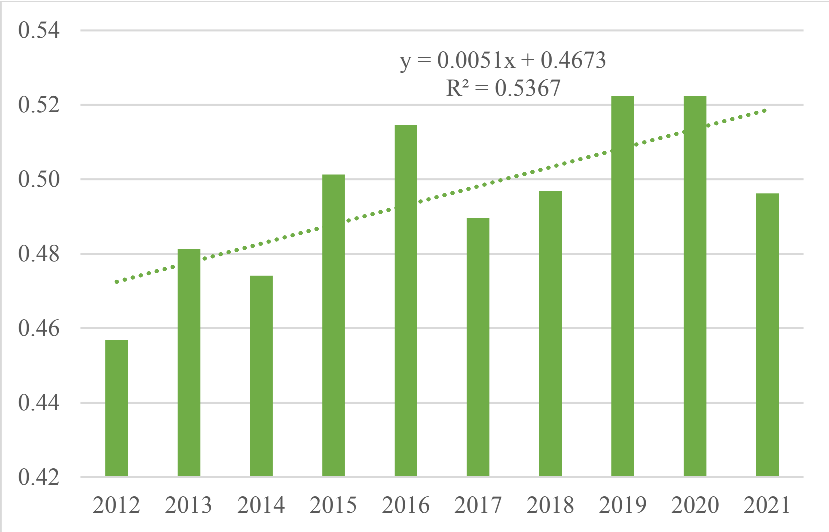


Fig. 5.1.4. Long-term dynamics of vegetation conditions in Kherson oblast by the average NDVI in the growing season of 2012-2021

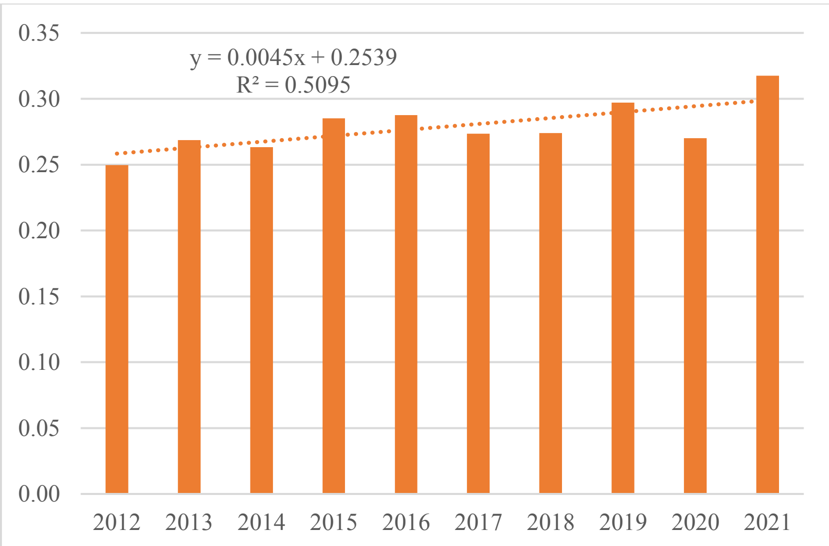


Fig. 5.1.5. Long-term dynamics of vegetation conditions in Kherson oblast by the average NDVI in the growing season of 2012-2021

According to the results of the regression analysis, equations of the following form were developed for the models of the dependence of vegetation indices on meteorological factors in the growing season (Eq. 5.1.3-5.1.4):

$$NDVI = 0.4728 - 0.0001\mathrm{T} + 8.4001 \times 10^{-5} R \quad (5.1.3)$$
$$EVI = 0.5220 - 0.0159\mathrm{T} + 8.1239 \times 10^{-5} R \quad (5.1.4)$$

where: T – average annual air temperature, ºC; R – annual precipitation, mm.

Table 5.1.3

Results of the regression analysis between average air temperature, precipitation and average NDVI in Kherson oblast in the growing season for the period 2012-2021

Regression statistics	Index value
Correlation coefficient (*R*)	0.2743
Standard deviation (*SD*)	0.0231
Mean square error (*MSE*)	0.0005
Coefficient of determination (R^2)	0.0752
Adjusted R_{adj}^2	–0.1890
Root mean square error (*RMSE*)	0.0277
Mean average percentage error (*MAPE*)	3.13
Regression model coefficients	
Slope	0.4728
A (for average annual air temperature)	–0.0001
B (for annual precipitation)	8.4001×10^{-5}

Table 5.1.4

Results of the regression analysis between average air temperature, precipitation and average EVI in Kherson oblast in the growing season for the period 2012-2021

Regression statistics	Index value
Correlation coefficient (*R*)	0.7844
Standard deviation (*SD*)	0.0134
Mean square error (*MSE*)	0.0002
Coefficient of determination (R^2)	0.6154
Adjusted R_{adj}^2	0.5055
Root mean square error (*RMSE*)	0.0151
Mean average percentage error (*MAPE*)	3.49
Regression model coefficients	
Slope	0.5220
A (for average annual air temperature)	–0.0159
B (for annual precipitation)	8.1239×10^{-5}

The normalized difference vegetation index is a simple and most widely used vegetation index in precision agriculture systems (Oliver, 2010), but many scientists have questioned the possibility of its use for establishing and predicting dynamic changes in flora (Koslowsky, 1993; Hobbs, 1997; Elmore et al., 2000). The enhanced vegetation index is considered more reliable, distortions of its value mainly depend on the topography and to a lesser extent on the characteristics of the atmosphere and soil cover (Matsushita et al., 2007). Despite the sufficiently close movement of the curve of changes of both researched vegetation indices in the annual dynamics, the results of the study indicate that the value of NDVI is almost twice as high as the value of EVI, which is especially clearly visible for the winter period of the year, which is confirmed in the works of other scientific groups that blame for this on the imperfection of the estimation of plant cover parameters in conditions of a high value (>3.0) of the leaf area index LAI, as well as a clear dependence on the angle of sunlight income and the content of chlorophyll in the plant tissue (Lillesaeter, 1982; Huete et al., 1999; Lange et al. ., 2017). It is worth noting that the value of NDVI is significantly less variable over the years than EVI (Table 5.1.5). Perhaps this factor explains the insufficient information of the normalized difference vegetation index in the description of dynamic annual changes in the flora of the Kherson region. Regarding the degree of the variability of vegetation indices by month of the year, it was established that a higher level of variability of the value of the enhanced vegetation index is also observed here, and a growth pattern is also observed in the coefficient of variation of the values of both vegetation indices in the cold period (October – March) of the year is also observed. (Table 5.1.6).

The higher efficiency of EVI for assessing the conditions of agricultural land was confirmed by the research of Lijun et al. (2008). However, there is evidence of a lower efficiency of EVI-based models to predict the state of vegetation cover. For example, a study by Eduarda et al. (2007) and Li et al. (2010) demonstrated the significant advantage of NDVI-based vegetation condition modeling and mapping. Here it is worth noting that a distinctive feature of our research is the search for the connection of spatial indices of vegetation with climatic parameters, and it is in this respect that a significant advantage of the improved vegetation index was established. In addition, regression models suggest that EVI can be more accurately predicted by meteorological indicators, making this index more suitable to predict the state of vegetation under climate change.

Table 5.1.5

Coefficients of variation for the vegetation indices NDVI and EVI in Kherson oblast for the period 2012-2021

Period	Vegetation index	
	NDVI	EVI
Annual	0.04	0.05
Growing season	0.04	0.07

Table 5.1.6

Coefficients of variation for the vegetation indices NDVI and EVI in Kherson oblast on the monthly basis for the period 2012-2021

Month	Vegetation index	
	NDVI	EVI
January	0.10	0.14
February	0.10	0.12
March	0.09	0.12
April	0.08	0.13
May	0.07	0.13
June	0.06	0.12
July	0.06	0.09
August	0.08	0.07
September	0.09	0.07
October	0.10	0.11
November	0.12	0.17
December	0.17	0.20

Thus, according to the established regularities, it is more rational to use the EVI to assess the state of the flora depending on climate changes on the regional scale, which provides a comparable level of accuracy both for the assessment of dynamics based on average annual data and the data of the growing season. The NDVI can only be used to track dynamics based on average annual data, as its response to the climatic factor during the growing season is low. Other scientists agree with this statement (Karkauskaite et al., 2017; Qiu et al., 2018).

Regarding the improvement in vegetation conditions for the flora of the Kherson region based on a positive 10-year trend, there are currently no convincing data to assert the positive impact of changes in climatic factors on the vegetation of the region, especially since there is a negative relationship between vegetation indices and average air temperature during the growing season. Simulations by Jiang et al. (2011) show that vegetation cover will inevitably transform under the influence of climate change, and plant biomass is expected to increase by 21% and 36% for the periods 2051-2060 and 2090-2098, respectively. This especially applies to the mid- and northern latitudes of the planet. However, Woodward et al. (1998) previously emphasized the inequity of the relationship between flora and global warming, indicating that the latter will have a positive effect on the vegetation of higher latitudes, while thinning of the vegetation cover and gradual desertification are expected in the southern regions.

The question of the dependence of vegetation indices on the amount of precipitation is debatable. Even though our results indicate a low (but positive both at the level of the year as a whole and the growing season in particular) impact of the amount of precipitation on the value of EVI and NDVI, a number of scientific works claim the opposite. The statistically significant dependence of vegetation indices on the amount of precipitation was proven in the studies of Zoungrana et al. (2015) and Wang et al. (2003). This contradiction, which at first glance is a rather significant argument against our results, was resolved by Schultz & Halpert (1993), who concluded that the degree of influence of air temperature and amount of precipitation on the value of NDVI varies significantly depending on climatic zones. Thus, in cold regions with a large amount of precipitation, the NDVI depends more strongly on the air temperature, while in hot and arid regions, this index will strongly depend on the amount of precipitation. The work of Ding et al. (2007) also shows the different strength of the correlation between NDVI and precipitation in different years and in different areas of the Tibetan Plateau.

In summary, it is worth paying attention again to the main results obtained by remote sensing data, which would be quite difficult and expensive to obtain by ground-based research methods, namely: at the regional level in the Kherson region in the last decade, there has been an improvement in the vegetation conditions of the flora as a natural, as well as of anthropogenic origin, which is undoubtedly related to climatic factors, the most significant of which, according to the average annual analysis, is the air temperature, and in the growing season – the amount of precipitation, that is, the level of natural humidification, which is an additional indirect indicator of the high need for a sufficient moisture supply for normal growth and development of plants in the region, which is impossible to achieve without irrigation in the conditions of annual increase in air temperature. The models of the dependence of vegetation indices on meteorological factors allow prediction of possible changes in the flora conditions in the Kherson region based on meteorological forecasts, and to take the necessary measures to preserve natural and maintain the homeostasis of artificial phytocenoses in conditions of climate change.

5.2. Yield forecasting of crops using normalized difference vegetation index values

At the current stage of development of information technologies and geoinformation systems, the areas of application of the normalized difference vegetation index in agricultural science are constantly expanding. Thus, the value of NDVI, as a chlorophyll-dependent index, is an indirect marker of the potential photosynthetic activity of plants and therefore can be successfully used to study the processes of formation of the potential productivity of crops. The relationship between the value of NDVI and the amount of absorbed photosynthetically active radiation (PAR) according to Gamon et al. (1995) is sufficiently strong and almost linear. Sellers (1985), Myneni et al. (1995) also provide evidence in favor of the above claim. Thus, the strong relationship between these two indicators suggests the existence of a strong close relationship between the value of NDVI and the yield of cultivated plants, since the latter directly depends on the amount of effectively absorbed PAR, (Zhu et al., 2010; Raines, 2011). Therefore, NDVI is a promising vegetation index for predicting the yield of crops in precision agriculture systems, since the modern technical and technological level and the industrialization of the plant production require new approaches to programming and forecasting the productivity of cultivated plants. The use of remote sensing data allows for prompt and highly accurate yield forecasting and does not require complex multiyear studies to create empirical productivity models, significantly reducing the cost of relevant developments (Kouadio et al., 2014). Furthermore, satellite imagery on the main commercial platforms for precision agriculture is provided with high regularity and allows for almost every individual field and plot, making real-time crop programming possible and attractive even for small farms and in very tight time frames. (Maas, 1988; Atzberger, 2013).

The purpose of the study was to establish the relationship between the value of the NDVI and the yield of certain crops (namely, grain and sweet corn, grain sorghum, soybeans and winter wheat) grown in the South of Ukraine, in order to determine the possibility of early high-precision forecasting of their yield based on remote sensing data.

The analysis of the NDVI value at the main stages of growth and development of grain corn, which are most often used for early forecasting of the yield, namely at the beginning of the panicle ejection and during the appearance of the first stigma on the ear, made it possible to reveal an interesting feature: the value of the vegetation index was very evenly distributed over time, and therefore the value of NDVI actually remained unchanged during the specified phases of crop vegetation over the years of research, which resulted in the same level of accuracy and quality of crop productivity forecasting based on satellite monitoring data (Table 5.2.1).

The regression statistics of the model testify to the high quality and precision of forecasting the yield of grain corn yield, especially on strong crops with a grain yield potential of more than 10 t/ha. The lowest precision is given by the yield forecast on weak crops with a yield of up to 5 t/ha. Regression analysis made it possible to establish the strength of the relationship between the value of NDVI and the yield of grain corn, which, according to the empirical rule, is very high and positive with the correlation coefficient R 0.9906 and the coefficient of determination R^2 0.9813 (Mukaka, 2012; Schober et al., 2018). The mathematical model of the forecast has high precision, since the *MAPE* for all the experimental pairs is less than 10% (Moreno et al., 2013) (Tables 5.2.1-5.2.2).

As for sweet corn, yield prediction can be performed according to the phenological phases of "panicle ejection" and "ripening". The value of the vegetation index varies according to the specified stages of growth and development of the crop, as well as the accuracy of the forecast. The results of the mathematical forecast of the harvest of marketable sweet corn ears with husks and regression statistics of the model are presented in the Tables 5.2.3, 5.2.4. A significantly higher accuracy of predicting crop productivity and a better quality of fit of the yield model were established when using NDVI values in the "panicle ejection" phenological phase as the base values, which is evidenced by lower absolute error values (28.13% vs. 46.73%) and a higher coefficient of determination of the model (0.4218 vs. 0.2808).

Table 5.2.1

Grain corn yields predicted by the polynomial model and actual, t/ha

Pair number	Y_{act}	NDVI	Y_{pred}	*MAPE* (%)
1	2.87	0.40	2.44	15.04
2	3.82	0.43	3.33	12.71
3	3.92	0.43	3.33	14.94
4	4.21	0.44	3.64	13.62
5	4.43	0.45	3.94	11.05
6	7.77	0.55	7.07	8.97
7	9.72	0.61	9.03	7.05
8	10.52	0.63	9.70	7.77
9	10.78	0.64	10.04	6.87
10	11.35	0.66	10.72	5.58
11	11.97	0.68	11.40	4.75
12	13.57	0.73	13.14	3.14
13	13.87	0.74	13.50	2.69
14	14.09	0.75	13.85	1.69
15	14.51	0.76	14.21	2.07
16	3.06	0.45	3.94	28.77
17	3.46	0.46	4.25	22.71
18	3.57	0.46	4.25	18.93
19	3.89	0.47	4.55	17.05
20	4.17	0.48	4.86	16.60
21	8.25	0.60	8.70	5.50
22	10.11	0.66	10.72	6.00
23	10.39	0.67	11.06	6.43
24	10.81	0.68	11.40	5.47
25	10.82	0.68	11.40	5.38
26	11.09	0.69	11.75	5.92
27	13.75	0.75	13.85	0.75
28	14.09	0.76	14.21	0.85
29	14.32	0.77	14.57	1.73
30	14.59	0.78	14.93	2.32
Average	9.13	0.61	9.13	8.75
CV	0.47	0.21	0.45	

Table 5.2.2

Regression statistics for the grain corn yield prediction by the NDVI in the phenological phase «panicle ejection – appearance of stigma»

Regression statistics	Value
Correlation coefficient (*R*)	0.9906
Coefficient of determination (R^2)	0.9813
Adjusted (R_{adj}^2)	0.9799
Standard deviation (*SD*)	0.6027
Model equation	–8.0534 + 22.7549×NDVI + 8.5707×NDVI^2

The mathematical model for predicting the yield of sweet corn depending on the value of NDVI has average accuracy (Moreno et al., 2013). The maximum errors in the estimation occur for pairs with the minimum (up to 10 t/ha) and maximum (over 15 t/ha) yield, while the median yield pairs show the minimum level of inaccuracy in the range of 0.80-41.46%. The values of the coefficients of correlation and determination indicate the average strength of the relationship between the productivity of sweet corn and the vegetation index (Schober et al., 2018). In general, the mathematical model can be used to predict the yield of the crop during the cultivation of medium-yielding hybrids according to conventional agricultural technology, since the forecast of the yield on both low and high intensity crops will give a significant error.

The yield of grain sorghum, modeled by the value of the vegetation index in the flag leaf and flowering phenological phases, varies slightly (Table 5.2.5).

Thus, relatively higher accuracy and quality of curve fitting is provided by the forecast model based on the value of NDVI in the flowering phenological phase of the crop, which is evident from the 4.39% lower average absolute error and 0.0885 higher coefficient of determination (Table 5.2.6). The model for the flowering phenological phase provides a very good quality of curve fitting and a very strong correlation between sorghum grain yield and the vegetation index value, while the model for the flag leaf phenological phase shows a strong level of correlation Schober et al. (2018). According to Moreno et al. (2013) the mathematical model of grain sorghum yield for the "flowering" phenological phase provides a good quality of prediction (*MAPE*<20%), while the model for the "flag leaf" phenological phase already belongs to the lower gradation – medium prediction accuracy.

Table 5.2.3

Sweet corn ears yields (in husks) predicted by the polynomial model and actual, t/ha

Pair number	$Y_{act.}$	NDVI «panicle ejection»	Y_{pred}	*MAPE* (%)	NDVI «ripening»	$Y_{pred.}$	*MAPE* (%)
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	6.72	0.35	9.95	29.98	0.32	11.08	64.93
2	8.06	0.36	10.78	25.24	0.32	11.08	37.51
3	8.49	0.36	10.78	21.25	0.32	11.08	30.55
4	8.78	0.36	10.78	18.55	0.32	11.08	26.24
5	8.86	0.36	10.78	17.81	0.32	11.08	25.10
6	8.90	0.36	10.78	17.44	0.33	11.63	30.73
7	11.45	0.37	11.54	0.80	0.35	12.56	9.72
8	12.24	0.38	12.22	0.15	0.35	12.56	2.64
9	12.36	0.38	12.22	1.27	0.36	12.94	4.70
10	12.50	0.38	12.22	2.57	0.35	12.56	0.51
11	13.61	0.39	12.84	7.15	0.35	12.56	7.69
12	14.04	0.39	12.84	11.15	0.37	13.26	5.55
13	14.79	0.39	12.84	18.11	0.38	13.52	8.57
14	15.40	0.40	13.38	18.71	0.38	13.52	12.19
15	15.92	0.40	13.38	23.54	0.39	13.73	13.77
16	16.32	0.40	13.38	27.26	0.37	13.26	18.74
17	16.76	0.40	13.38	31.34	0.36	12.94	22.79
18	17.04	0.41	13.86	29.54	0.38	13.52	20.64
19	18.23	0.42	14.26	36.85	0.36	12.94	29.01
20	19.20	0.43	14.59	42.78	0.38	13.52	29.57
21	19.87	0.44	14.85	46.58	0.38	13.52	31.94
22	20.09	0.45	15.04	46.87	0.38	13.52	32.69
23	22.23	0.46	15.16	65.64	0.39	13.73	38.25
24	25.34	0.47	15.21	94.08	0.40	13.87	45.25
25	3.83	0.67	1.22	24.22	0.58	6.62	72.96
26	4.04	0.57	11.77	71.80	0.55	9.13	126.07
27	4.30	0.63	6.30	18.53	0.53	10.52	144.58
28	4.25	0.62	7.39	29.12	0.53	10.52	147.46
29	4.33	0.65	3.90	3.98	0.60	4.66	7.69
30	4.81	0.62	7.39	23.92	0.58	6.62	37.72
31	5.11	0.65	3.90	11.23	0.60	4.66	8.75
32	4.84	0.55	13.03	76.04	0.52	11.12	129.79
33	7.34	0.60	9.35	18.70	0.58	6.62	9.75
34	9.36	0.57	11.77	22.39	0.55	9.13	2.42
35	10.68	0.57	11.77	10.14	0.57	7.52	29.60
36	9.38	0.62	7.39	18.52	0.58	6.62	29.38
37	6.97	0.6	9.35	22.13	0.58	6.62	4.96
38	7.69	0.62	7.39	2.82	0.57	7.52	2.23
39	8.78	0.63	6.30	23.07	0.58	6.62	24.55
40	7.78	0.48	15.19	68.78	0.53	10.52	35.18
41	10.24	0.60	9.35	8.23	0.57	7.52	26.58
42	12.33	0.58	11.04	12.01	0.50	12.16	1.39
43	14.95	0.53	14.00	8.82	0.55	9.13	38.91
44	13.09	0.60	9.35	34.70	0.55	9.13	30.23
45	9.37	0.60	9.35	0.15	0.55	9.13	2.53

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
46	10.10	0.62	7.39	25.21	0.58	6.62	34.41
47	11.85	0.62	7.39	41.46	0.55	9.13	22.92
48	10.25	0.55	13.03	25.80	0.52	11.12	8.51
49	8.29	0.60	9.35	9.88	0.44	13.88	67.45
50	8.20	0.55	13.03	44.84	0.44	13.88	69.28
51	8.39	0.65	3.90	41.69	0.46	13.54	61.36
52	2.43	0.31	5.92	32.40	0.36	12.94	432.55
53	3.08	0.44	14.85	109.35	0.41	13.96	353.32
54	8.20	0.55	13.03	44.84	0.55	9.13	11.38
Average	10.77	0.50	10.77	28.13	0.46	10.77	46.73
CV	0.48	0.22	0.31		0.22	0.26	

Table 5.2.4

Regression statistics for the sweet corn yield prediction by the NDVI

Regression statistics	Value
Phenological phase «panicle ejection»	
Correlation coefficient (R)	0.6495
Coefficient of determination (R^2)	0.4218
Adjusted (R_{adj}^2)	0.3991
Standard deviation (SD)	4.0331
Model equation	$-63.8839 + 335.3911 \times NDVI - 355.5484 \times NDVI^2$
Phenological phase «ripening»	
Correlation coefficient (R)	0.5299
Coefficient of determination (R^2)	0.2808
Adjusted (R_{adj}^2)	0.2526
Standard deviation (SD)	4.4981
Model equation	$-37.0737 + 242.9827 \times NDVI - 289.0359 \times NDVI^2$

It is interesting that for grain sorghum there is a pattern of increasing absolute error in pairs of low crop yields, as well as for grain corn and sweet corn. This suggests a better ability of the normalized difference vegetation index to convey the essence of production processes for crops that are not under stressful conditions for providing plants with one or more vital elements of productivity (heat, moisture, light, nutrients).

Table 5.2.5

Grain sorghum yields predicted by the polynomial model and actual, t/ha

Pair number	Y_{act}	NDVI «flag leaf»	Y_{pred}	*MAPE* (%)	NDVI «flowering»	Y_{pred}	*MAPE* (%)
1	1.98	0.55	4.04	103.88	0.60	3.53	78.16
2	2.43	0.56	4.20	72.99	0.61	3.74	53.82
3	2.46	0.56	4.20	70.88	0.61	3.74	51.95
4	2.98	0.57	4.38	46.94	0.62	3.96	32.84
5	3.19	0.58	4.56	43.02	0.63	4.19	31.34
6	4.36	0.61	5.16	18.44	0.66	4.95	13.44
7	4.59	0.62	5.38	17.24	0.67	5.22	13.70
8	6.27	0.67	6.59	5.17	0.72	6.74	7.49
9	6.39	0.67	6.59	3.20	0.72	6.74	5.48
10	6.80	0.68	6.86	0.92	0.73	7.08	4.05
11	7.00	0.69	7.14	1.98	0.74	7.42	6.02
12	7.02	0.69	7.14	1.69	0.74	7.42	5.72
13	7.15	0.69	7.14	0.16	0.74	7.42	3.80
14	8.36	0.73	8.33	0.38	0.78	8.91	6.58
15	8.58	0.75	8.97	4.58	0.80	9.72	13.25
16	2.08	0.30	2.60	25.19	0.50	2.00	3.90
17	2.28	0.31	2.56	12.29	0.51	2.10	7.68
18	2.35	0.31	2.56	8.94	0.51	2.10	10.43
19	2.76	0.34	2.48	10.17	0.53	2.35	14.93
20	3.26	0.37	2.47	24.10	0.55	2.63	19.24
21	4.92	0.48	3.10	36.89	0.61	3.74	24.03
22	5.08	0.49	3.21	36.76	0.62	3.96	22.07
23	6.81	0.61	5.16	24.17	0.69	5.80	14.89
24	6.89	0.61	5.16	25.05	0.69	5.80	15.88
25	7.11	0.63	5.61	21.14	0.70	6.10	14.20
26	7.32	0.65	6.08	16.89	0.71	6.41	12.37
27	7.51	0.67	6.59	12.19	0.72	6.74	10.25
28	7.65	0.68	6.86	10.30	0.72	6.74	11.90
29	8.54	0.74	8.65	1.25	0.75	7.78	8.92
30	8.67	0.75	8.97	3.50	0.75	7.78	10.29
Average	5.43	0.59	5.43	22.01	0.66	5.43	17.62
CV	0.43	0.23	0.38		0.13	0.40	

Table 5.2.6

Regression statistics for the grain sorghum yield prediction by the NDVI

Regression statistics	Value
Phenological phase «flag leaf»	
Correlation coefficient (*R*)	0.8809
Coefficient of determination (R^2)	0.7760
Adjusted (R_{adj}^2)	0.7594
Standard deviation (*SD*)	1.1350
Model equation	7.8331 – 30.0646×NDVI + 42.1131×NDVI^2
Phenological phase «flowering»	
Correlation coefficient (*R*)	0.9298
Coefficient of determination (R^2)	0.8645
Adjusted (R_{adj}^2)	0.8545
Standard deviation (*SD*)	0.8827
Model equation	10.0315 – 42.1255×NDVI + 52.1927×NDVI^2

The accuracy of soybean yield modeling by NDVI value in the "second internode" and "flowering" phenological phases differed significantly, and an interesting fact is the better efficiency of the model specifically for the very early forecast in the first phenological phase (Table 5.2.7). The model for the "second internode" phenological phase belongs to very high-accuracy models ($MAPE$<10%), and in the "flowering" phenological phase to good-accuracy models (10%<$MAPE$<20%) according to the classification proposed by Moreno et al. (2013). As with the corn and grain sorghum yield prediction models, the magnitude of the absolute error tends to increase as the crop yield decreases to less than 3 t/ha.

The quality of the fit of the yield curve also turned out to be better when forecasting soybean productivity by the value of the vegetation index in the "second internode" phenological phase (Table 5.2.8). Thus, the coefficient of determination is higher by 0.1157, and according to the classification of Schober et al. (2018) belongs to a very strong relationship (>0.90). Therefore, the most accurate yield forecast can be obtained at the earliest stages of soybean growth and development, which is especially valuable for planning the production process and the economic and organizational component of agricultural activity in plant production.

In general, it is worth noting that the model of soybeans productivity depending on the value of the vegetation index in the "second internode" phenological phase of the crop provided the highest possible accuracy and quality compared to the forecast models developed for other crops that we studied.

Table 5.2.7

Soybeans yields predicted by the polynomial model and actual, t/ha

Pair number	$Y_{act.}$	NDVI «second internode»	$Y_{pred.}$	*MAPE* (%)	NDVI «flowering»	Y_{pred}	*MAPE* (%)
1	1.58	0.45	1.77	11.79	0.35	1.44	9.08
2	2.17	0.51	2.31	6.30	0.43	1.97	9.01
3	2.51	0.55	2.67	6.22	0.48	2.31	8.11
4	2.54	0.55	2.67	4.97	0.48	2.31	9.20
5	2.62	0.56	2.76	5.19	0.49	2.37	9.45
6	2.76	0.57	2.85	3.10	0.51	2.50	9.28
7	2.82	0.58	2.94	4.09	0.52	2.57	8.88
8	3.39	0.64	3.47	2.43	0.60	3.09	8.87
9	3.56	0.66	3.65	2.55	0.62	3.22	9.61
10	3.62	0.67	3.74	3.32	0.64	3.35	7.57
11	3.81	0.69	3.92	2.85	0.67	3.54	7.17
12	4.06	0.72	4.19	3.10	0.70	3.73	8.21
13	4.28	0.74	4.36	1.96	0.73	3.92	8.52
14	4.31	0.74	4.36	1.25	0.73	3.92	9.16
15	4.49	0.75	4.45	0.83	0.75	4.04	10.02
16	1.37	0.40	1.31	4.04	0.40	1.77	29.47
17	2.11	0.48	2.04	3.47	0.51	2.50	18.67
18	2.21	0.49	2.13	3.77	0.52	2.57	16.27
19	2.32	0.50	2.22	4.45	0.54	2.70	16.39
20	2.48	0.52	2.40	3.36	0.56	2.83	14.13
21	2.57	0.53	2.49	3.25	0.57	2.90	12.66
22	2.68	0.54	2.58	3.87	0.59	3.02	12.86
23	3.25	0.60	3.11	4.17	0.67	3.54	8.83
24	3.38	0.61	3.20	5.21	0.69	3.66	8.39
25	3.71	0.65	3.56	4.00	0.74	3.98	7.22
26	3.79	0.66	3.65	3.67	0.75	4.04	6.60
27	3.86	0.67	3.74	3.10	0.76	4.10	6.29
28	3.96	0.68	3.83	3.30	0.78	4.23	6.74
29	4.30	0.72	4.19	2.66	0.83	4.54	5.47
30	4.47	0.75	4.45	0.39	0.80	4.35	2.67
Average	3.17	0.61	3.17	3.75	0.66	3.17	10.16
CV	0.28	0.16	0.28		0.21	0.26	

Table 5.2.8

Regression statistics for the grain sorghum yield prediction by the NDVI

Regression statistics	Value
Phenological phase «second internode»	
Correlation coefficient (R)	0.9914
Coefficient of determination (R^2)	0.9830
Adjusted (R_{adj}^2)	0.9817
Standard deviation (SD)	0.1197
Model equation	$-2.4740 + 9.6725 \times NDVI - 0.5885 \times NDVI^2$
Phenological phase «flowering»	
Correlation coefficient (R)	0.9378
Coefficient of determination (R^2)	0.8795
Adjusted (R_{adj}^2)	0.8706
Standard deviation (SD)	0.3184
Model equation	$-1.2588 + 8.0774 \times NDVI - 1.3550 \times NDVI^2$

Modeling the yield of winter wheat depending on the value of NDVI in the "stem elongation" and "earing" phenological phases proved that the maximum closeness of the relationship between the vegetation index and crop productivity is observed in the later phenological phase – the value of the average absolute error was 13.42% against 17.53%, respectively (Table 5.2.9). However, the difference can be considered not very significant because, according to the classification of Moreno et al. (2013), both models fall under the same accuracy class.

Regarding the quality of the fit of the approximation curve, it had a significantly higher correspondence to the real trend when using the NDVI value in the "earing" phenological phase in yield modeling (the coefficient of determination is higher by 0.0686), however, the closeness and strength of the relationship between the value of the vegetation index and the yield of winter wheat according to the gradation of Schober et al. (2018) was at the same level for simulations in both investigated phenological phases (Table 5.2.10).

Table 5.2.9

Winter wheat yields predicted by the polynomial model and actual, t/ha

Pair number	$Y_{act.}$	NDVI «stem elongation»	$Y_{pred..}$	*MAPE* (%)	NDVI «earing»	$Y_{pred.}$	*MAPE* (%)
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	2.72	0.35	2.80	3.08	0.5	2.73	0.34
2	2.91	0.37	2.94	1.01	0.51	2.99	2.91
3	3.11	0.39	3.08	0.95	0.52	3.26	4.67
4	3.22	0.40	3.15	2.08	0.52	3.26	1.09
5	3.39	0.42	3.30	2.59	0.53	3.51	3.56
6	5.28	0.60	4.89	7.37	0.56	4.25	19.54
7	5.36	0.61	4.99	6.86	0.56	4.25	20.74
8	5.61	0.63	5.20	7.33	0.57	4.48	20.06
9	6.02	0.67	5.63	6.50	0.59	4.94	17.90
10	6.17	0.68	5.74	6.98	0.60	5.16	16.30
11	6.17	0.68	5.74	6.98	0.60	5.16	16.30
12	6.29	0.69	5.85	6.97	0.61	5.38	14.45
13	6.3	0.69	5.85	7.12	0.61	5.38	14.59
14	6.97	0.74	6.43	7.71	0.64	6.00	13.89
15	7.11	0.75	6.55	7.83	0.70	7.11	0.05
16	2.83	0.35	2.80	0.93	0.50	2.73	3.56
17	2.99	0.36	2.87	3.99	0.51	2.99	0.16
18	3.15	0.37	2.94	6.69	0.52	3.26	3.34
19	3.27	0.38	3.01	7.98	0.52	3.26	0.45
20	3.45	0.40	3.15	8.61	0.53	3.51	1.76
21	5.37	0.57	4.60	14.42	0.61	5.38	0.20
22	5.39	0.57	4.60	14.74	0.61	5.38	0.17
23	5.69	0.60	4.89	14.04	0.62	5.59	1.71
24	6.15	0.64	5.30	13.75	0.64	6.00	2.40
25	6.25	0.65	5.41	13.42	0.65	6.20	0.81
26	6.27	0.65	5.41	13.70	0.65	6.20	1.12
27	6.38	0.66	5.52	13.49	0.66	6.39	0.19
28	6.38	0.66	5.52	13.49	0.66	6.39	0.19
29	7.03	0.72	6.20	11.86	0.69	6.94	1.27
30	7.29	0.75	6.55	10.11	0.70	7.11	2.42
31	3.45	0.58	4.69	36.02	0.58	4.72	36.70
32	3.51	0.59	4.79	36.50	0.58	4.72	34.36
33	3.36	0.53	4.22	25.61	0.58	4.72	40.36
34	3.66	0.75	6.55	79.05	0.63	5.80	58.47
35	3.65	0.73	6.31	72.98	0.63	5.80	58.90

36	3.53	0.61	4.99	41.43	0.55	4.01	13.53
37	3.37	0.54	4.31	27.96	0.50	2.73	19.01
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
38	2.16	0.55	4.41	103.95	0.53	3.51	62.53
Average	4.77	0.58	4.77	17.53	0.59	4.77	13.42
CV	0.33	0.23	0.26		0.10	0.28	

Table 5.2.10

Regression statistics for the winter wheat yield prediction by the NDVI

Regression statistics	Value
Phenological phase «stem elongation»	
Correlation coefficient (R)	0.7793
Coefficient of determination (R^2)	0.6073
Adjusted (R_{adj}^2)	0.5848
Standard deviation (SD)	1.0200
Model equation	1.3148 + 1.8649×NDVI + 6.8262×NDVI^2
Phenological phase «earing»	
Correlation coefficient (R)	0.8479
Coefficient of determination (R^2)	0.7189
Adjusted (R_{adj}^2)	0.7028
Standard deviation (SD)	0.8630
Model equation	–16.7294 + 51.0578×NDVI – 24.2807×NDVI^2

As well as for other studied crops, the winter wheat yield model is characterized by a tendency to increase the forecast error at lower (up to 4 t/ha) yield levels.

Based on the results of mathematical modeling, a productivity scale was created for the studied crops based on the value of NDVI in the phenological phase recommended for forecasting: "panicle ejection - the appearance of the first stigma" for grain corn, "panicle ejection" for sweet corn, "flowering" for grain sorghum, "second internode" for soybeans, "earing" for winter wheat, respectively (Table 5.2.11).

The results of the study indicate that it is quite possible to predict the yield of crops in the early stages with relatively high precision based on the value of NDVI. The minimum forecast accuracy for the largest amplitude of forecast productivity values was recorded for sweet corn and the maximum for soybeans.

Table 5.2.11

Yielding scales (t/ha) of the studied crops depending on the NDVI*

NDVI	Grain corn	Sweet corn	Grain sorghum	Soybeans	Winter wheat
0.3	–	3.40-6.00	–	0.35-0.40	–
0.4	2.20-2.65	9.50-17.00	1.25-1.80	1.25-1.35	–
0.5	5.00-6.00	10.50-19.00	1.65-2.35	2.10-2.30	2.35-3.10
0.6	7.90-9.45	6.70-12.00†	2.90-4.15	3.00-3.25	4.45-5.90
0.7	11.00-13.15	–	5.00-7.15	3.85-4.20	6.15-8.10
0.8	14.00-17.00	–	8.00-11.40	4.70-5.10	7.40-9.75

* *Notes*: «–» values of the NDVI that are out of a typical range for the model; † - decrease in the sweet corn yields under the greater NDVI values relates to the fact that NDVI≥0.6 is the edge variant for the developed model.

A comparison of the given results with those obtained by other researchers reveals a high consistency. Thus, the works of Xu & Katchova (2019), Bolton & Friedl (2013), and the work of Johnson (2014) additionally confirm this fact for grain corn, as well as the sufficiently high strength of the relationship between the value of the vegetation index and the yield of soybeans.

Nagy et al. (2018) testified to the possibility of highly accurate prediction of grain corn productivity by NDVI 6-8 weeks before the planned harvest date. Wang et al. (2016) established a strong statistically significant relationship between the yield of grain corn and the value of the vegetation index in the period before the appearance of the first stigma, which allows to prevent crop losses due to the action of adverse factors of abiotic and biotic nature in this period. The study of Fernandez-Ordoñez & Soria-Ruiz, (2017) proved the extremely high accuracy and quality of predicting the productivity level of grain corn when using the NDVI values in the flowering phase of the crop in a mathematical model, the model error in this case was only 3%. Obviously, the periods of forecasting grain corn yield recommended by foreign researchers actually coincide with the period recommended in this study. Of course, some data show that the maximum accuracy of predicting the yield of this crop is in other phenological phases, for example, in the phase of pre-milk ripeness of kernels (Maresma et al., 2020). However, the differences may lie in the use of different sources of obtaining the NDVI value, since Maresma et al. (2020) did not use remote sensing data, but the results of measuring the index using field surveys by drones.

For grain sorghum and sweet corn, very limited data are currently available in the scientific literature on the effectiveness of predicting the productivity of these crops using satellite data. There is evidence of a high correlation between NDVI value and sorghum biomass growth, which allows predicting the forage productivity of the crop even at the initial stages of its growth and development (Zinke-Wehlmann et al., 2019). A large-scale study on the relationship between satellite vegetation indices and yields of soybean, sorghum, and corn indicated a strong correlation between these indicators, with correlation coefficients of 0.74, 0.65, and 0.86, respectively (Petersen, 2018). It is noticeable that the minimum strength of the relationship was established for sorghum, which is in full agreement with the results of our work.

Given the high, but sometimes still insufficient, accuracy of "NDVI – crop yield" models, the future development of this approach to programming and yield prediction will consist either in the improvement of methods and technical and technological equipment to obtain better quality satellite images with higher resolution and multiplicity of execution in time, or in a combined approach to modeling, which will involve improving the functional efficiency of mathematical models due to the addition of additional input parameters (for example, plant growth parameters, meteorological data) and the involvement of more modern algorithms for working with data (for example, artificial neural networks), which also can significantly improve the practical relevance of satellite monitoring in precision agriculture (Báez-González et al., 2002; Fang & Hoogenboom, 2011; Stas et al., 2016; Tiwari & Shukla, 2020).

5.3. Crops growth monitoring using normalized difference vegetation index

The normalized difference vegetation index at the beginning of the twentieth century. has become the standard for satellite monitoring of crops, their productivity forecasting, and the study of the characteristics of their growth and development because of its wide availability, flexibility, and strong connection with the indicators that determine the formation and development of agrophytocenoses (Shammi & Meng, 2021). Despite certain shortcomings associated with errors in determining the value of the index depending on atmospheric, weather phenomena, soil type, relief, vegetation cover structure (Tian et al., 2016), NDVI is the most widely used in agricultural science and practice satellite vegetation index.

The development of the direction of studying the annual dynamics of the vegetation index in various plant groups is relevant, the possibility of identifying the features of a typical model (pattern) of development for each of the types of phytocenoses, which will be of great practical importance in the mapping of fields and natural lands, will contribute to a better understanding of dynamic processes in various plant groups, can be used as a basis for improving the operational management of crops' cultivation technologies, increasing the accuracy of setting the terms of fertilizing and irrigation. Certain achievements in this direction have already been achieved by both foreign and domestic scientists. The studies of Magney et al. (2016) testified to the high degree of correlation between the seasonal movement of the NDVI value, the duration of phenological phases, and the productivity of spring wheat, and also established the possibility of performing the analysis of crop phenology using satellite monitoring data with high accuracy. Pan et al. (2015) mapped the phenological changes of individual cultivated plants based on the data of the NDVI time series, and the timing of the onset of phenological phases modeled by the vegetation index actually coincided with those recorded at the agrometeorological station during ground surveys. Seo et al. (2019) created a model based on NDVI values to estimate the phenology of corn and soybeans, the error of which averaged to just 2.6 days.

Domestic scientists also did not neglect studying the possibilities of remote monitoring of plant communities of both natural and artificial origin. Thus, Жуков & Гофман (2016) studied the annual dynamics of NDVI in Veliky Chapelsky pod, which made it possible to determine the cyclical transformation of natural vegetation in the area. Диченко & Ласло (2020) performed an analysis of the dynamics of the vegetation index in the Poltava region, reached conclusions about the suitability of remote sensing data for establishing critical phases of growth and development of crops, and also developed typical models of the temporal dynamics of development for the studied plant species. Семенова (2014a, 2014b) proposed models for forecasting the productivity of winter wheat based on the value of the normalized difference vegetation index for the Steppe of Ukraine, and also developed a methodology for drought monitoring based on NDVI.

The information available in the scientific literature is not yet sufficient to fully cover the topic of monitoring the dynamics of growth and development of cultivated plants using remote sensing data and the formation of clear final recommendations and applied scientific and practical intellectual products. The aim of the study was to determine the annual dynamics of the NDVI in the crops, typical for the agrarian formations of the South of Ukraine, and to link the value of the vegetation index to the average dates of the onset of the phenological phases of the studied crops.

Analysis of annual NDVI dynamics on the fallow field proved that the upper limit of the value of the index for a field free from cultivated plants fluctuates from 0.26±0.04 to 0.24±0.07 (Fig. 5.3.1). The value of the vegetation index in the fallow field was 0.17±0.05 in the average annual section. Thus, NDVI ≥ 0.22 should be taken as a marker of the beginning (renovation for winter crops) of active vegetation of the cultivated plants. Values of the vegetation index that are less than 0.22 indicate: bare soil; depressed state or a state of rest in the crops; the impossibility of establishing plant conditions due to weather conditions; the insufficient level of plant development for identification by remote sensing (for example, the period of early germination). This result is confirmed by the work of Семенова (2014b), where the NDVI value at the level of 0.21-0.30 is marked as "suppressed vegetation". Uskov et al. (2020) also cite as a guideline an NDVI value of 0-0.2 as "bare soil", 0.2-0.5 as "weak vegetation".

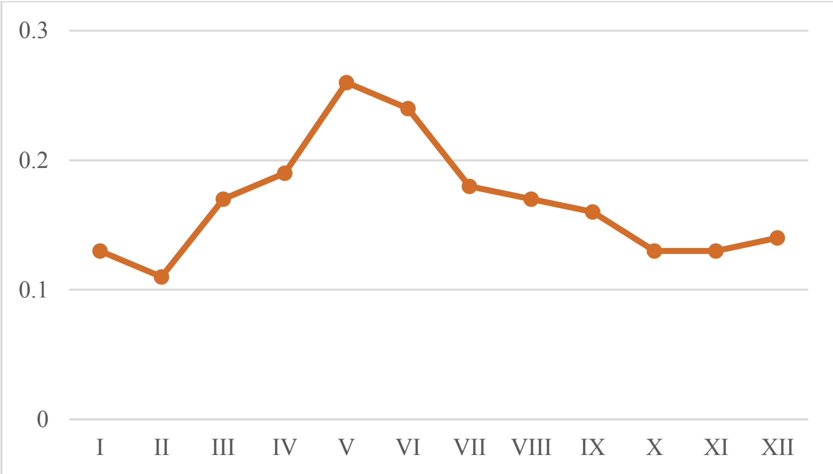


Fig. 5.3.1. NDVI dynamics in the fallow field averaged for 2016-2021

The analysis of the annual dynamics of NDVI for several crops showed that the vegetation index reaches its peak values in the period of May in winter crops (wheat, barley, rapeseed) and early spring crops (chickpeas, peas), while in late spring crops (sunflower, soybeans, grain sorghum, millet, grain corn, sweet corn, tomato of the usual planting period) the maximum value of the index falls on the month of July. In crops such as spring potatoes, peak NDVI values were recorded in June, and in late tomatoes, in August. For convenience of a visual assessment of the dynamics of the vegetation index in fields with the studied crops, the latter were divided into four groups according to biological and economic characteristics: winter wheat, winter barley, winter rapeseed – winter crops (Fig. 5.3.2); chickpeas, peas – early spring crops (Fig. 5.3.3); sunflower, soybeans, grain sorghum, millet, grain corn – late spring crops (Fig. 5.3.4); sweet corn, regular tomato, late tomato, spring potato – vegetable crops (Fig. 5.3.5). Development periods when plants are absent in the field (time before sowing and after harvesting) for all the studied crops were taken as the same as in the fallow field.

Fig. 5.3.2. NDVI dynamics for winter wheat (dark green), winter rapeseed (green), and winter barley (light green) averaged for 2016-2021

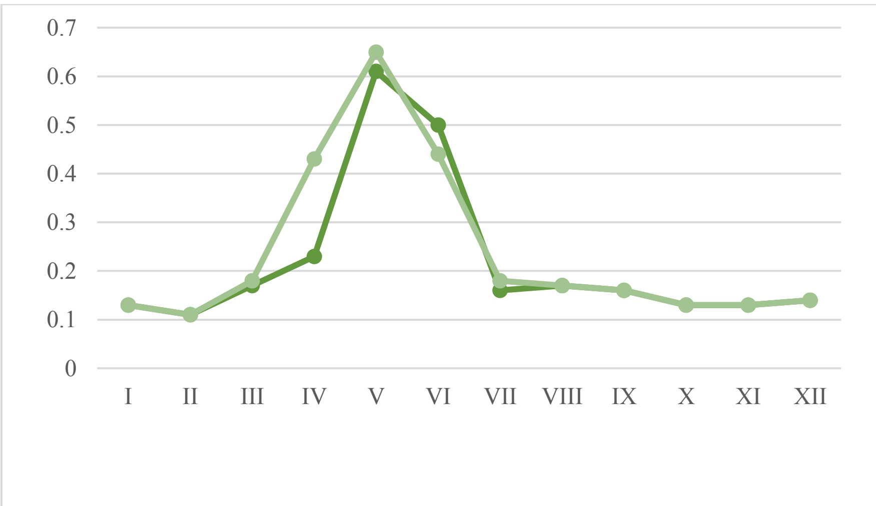


Fig. 5.3.3. NDVI dynamics for chickpea (green) and peas (light green) averaged for 2016-2021

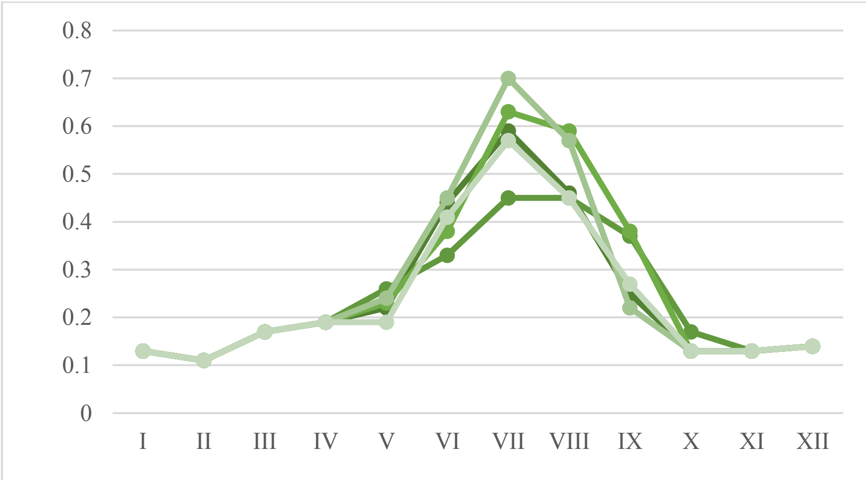


Fig. 5.3.4. NDVI dynamics for sunflower (ultra-green), soybeans (dark green), grain sorghum (green), grain corn (light green), and millet (ultra-light green) averaged for 2016-2021

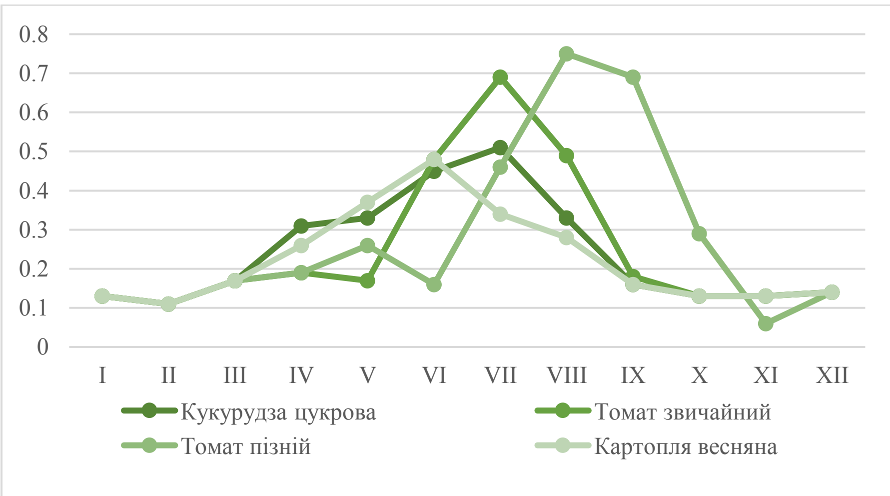


Fig. 5.3.5. NDVI dynamics for sweet corn (dark green), regular tomato (green), late tomato (light green), and potato (ultra-light green) averaged for 2016-2021*
*Notes: * for sweet corn – average for 2016, 2019-2020;*
for potato –2019-2020

Considering that the normalized difference vegetation index indirectly reflects the degree of intensity of growth processes and accumulation of green biomass by plants (Savin & Negre, 2003; Li et al., 2019), it can be concluded that winter and early spring crops will have the highest requirements for moisture supply and nutrition in late spring and early summer, while late spring crops in mid-summer. It has been proven that the dynamics of the annual NDVI trend can be used for better detailed and clarification of the irrigation schedule both for individual crops and in terms of crop rotation and the farm as a whole (Trout & Johnson, 2007; O'Connell et al., 2010), which is especially relevant for regions where irrigated agriculture is dominating, for example, southern Ukraine. It is worth taking into account the established regularity of the seasonal dynamics of growth processes during fertilization planning with mineral macro and micro fertilizers and operational planning of irrigation regimes, especially carefully calculating the load on the hydro module and planning land reclamation measures in advance, since Козленко та ін. (2021) established that in the Ingulets irrigation array the quality of irrigation water varies significantly by months of the year, and irrigation in the period of July (when the moisture supply requirements in most late spring crops reach a maximum) without the use of appropriate restorative and preventive measures has the highest risk of secondary salinization and alkalinization of soils.

A visual assessment of the annual monthly dynamics made it possible to notice that several crops have high similarity in growth patterns, namely such crops as winter wheat and winter barley, chickpeas and peas, millet and sunflower. Therefore, with the help of mathematical algorithms for automatic recognition of the dynamic pattern of NDVI, it will be difficult to distinguish crops in the specified pairs with high accuracy, since it will be almost impossible to set the parameters of the difference in the regularity of the annual course of the vegetation index (and this difference must be significant) for sorting satellite images (Areshkina, 2011; Bartalev & Zakora, 2019; Барталёв и др., 2011). As for other crops, they have their own characteristic features of the seasonal dynamics of the vegetation index; therefore, the patterns of annual NDVI movement established in the study can be successfully integrated into the systems of automated recognition and mapping of agricultural land based on remote sensing.

Comparison of the dynamics of the NDVI value with the average dates of the onset of the phenological phases of the studied crops in the period 2016-2021 made it possible to establish the correspondence between the range of the value of the vegetation index and the main phases of growth and development of the cultivated plants (Tables 5.3.1-5.3.14).

Table 5.3.1

Correspondence between NDVI and phenological phases of winter wheat (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts	0.25±0.11
Winter dormancy	0.19±0.07
Tillering	0.35±0.14
Stem elongation	0.52±0.12
Earing	0.50±0.15
Grain ripening	0.31±0.17
Full ripeness	0.18±0.06

Table 5.3.2

Correspondence between NDVI and phenological phases of winter barley (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts	0.26±0.10
Winter dormancy	0.17±0.09
Tillering	0.40±0.18
Stem elongation	0.57±0.13
Earing	0.47±0.18
Grain ripening	0.33±0.17
Full ripeness	0.16±0.01

Table 5.3.3

Correspondence between NDVI and phenological phases of winter rapeseed (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts	0.32±0.15
Winter dormancy	0.19±0.14
Rosette of leaves	0.34±0.18
Stem growth	0.47±0.19
Budding	0.51±0.17
Flowering	0.56±0.16
Pods formation and seed ripening	0.35±0.18

Table 5.3.4

Correspondence between NDVI and phenological phases of chickpeas (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts	0.23±0.05
Branching	0.61±0.11
Flowering and beans formation	0.57±0.16
Seed ripening	0.30±0.22

Table 5.3.5

Correspondence between NDVI and phenological phases of peas (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts	0.35±0.17
Branching	0.49±0.16
Budding and flowering	0.52±0.19
Seed formation and ripening	0.32±0.19

Table 5.3.6

Correspondence between NDVI and phenological phases of sunflower (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts	0.22±0.04
Rosette of leaves	0.35±0.14
Stem growth	0.54±0.12
Budding and flowering	0.53±0.12
Seeds formation and ripening	0.40±0.16
Full ripeness and senescence	0.25±0.09

Table 5.3.7

Correspondence between NDVI and phenological phases of soybeans (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts	0.26±0.12
Branching	0.30±0.12
Flowering	0.39±0.17
Beans formation	0.45±0.19
Seeds formation and ripening	0.41±0.16
Full ripeness	0.27±0.15

Table 5.3.8

Correspondence between NDVI and phenological phases of grain sorghum (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts	0.23±0.03
Tillering	0.38±0.10
Stem elongation	0.56±0.14
Panicle ejection and flowering	0.61±0.11
Seeds formation and ripening	0.48±0.18
Full ripeness	0.29±0.18

Table 5.3.9

Correspondence between NDVI and phenological phases of grain corn (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts – 3-5 leaves	0.24±0.07
5-10 leaves	0.45±0.13
Panicle ejection and flowering	0.70±0.03
Cobs and kernels formation	0.62±0.12
Seed ripening	0.41±0.20
Full ripeness	0.22±0.06

Table 5.3.10

Correspondence between NDVI and phenological phases of sweet corn (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts – 3-5 leaves	0.32±0.06
5-10 leaves	0.45±0.05
Panicle ejection and flowering	0.48±0.07
Cobs formation	0.46±0.11
Technical ripeness	0.33±0.04

Table 5.3.11

Correspondence between NDVI and phenological phases of millet (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts	0.19±0.02
Tillering	0.41±0.06
Stem growth	0.48±0.10
Panicle ejection and flowering	0.55±0.09
Seeds formation and ripening	0.34±0.13

Table 5.3.12

Correspondence between NDVI and phenological phases of regular spring tomato (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Planting of seedlings	0.17±0.03
Vegetation growth	0.32±0.18
Budding	0.48±0.15
Flowering	0.60±0.15
Fruit formation	0.69±0.07
Fruit ripening	0.45±0.23

Table 5.3.13

Correspondence between NDVI and phenological phases of late tomato (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Planting of seedlings	0.16±0.03
Vegetation growth	0.41±0.22
Budding	0.52±0.15
Flowering	0.68±0.14
Fruit formation	0.69±0.07
Fruit ripening	0.21±0.19

Table 5.3.14

Correspondence between NDVI and phenological phases of spring potato (averaged for 2016-2021)

Phenological phase	Average NDVI ± standard deviation
Sprouts	0.30±0.11
Budding	0.43±0.14
Flowering	0.41±0.15
Senescence	0.31±0.12

It was established that the vegetation index reaches its peak values in the following phenological phases of the studied crops: winter wheat, winter barley – stem elongation; winter rapeseed – flowering; chickpeas – branching; peas – budding and flowering; sunflower – stem growth; soybeans – formation of beans; grain sorghum – panicles ejection and flowering; grain corn – panicle ejection and flowering; millet – panicle ejection and flowering; sweet corn – panicle ejection and flowering; spring potatoes – budding; tomato (regardless of the time of planting) – fruit formation. Therefore, the results of the study show that the value of NDVI can be used as an indirect indicator to determine the moisture needs of cultivated plants, since the maximum value of the vegetation index for most of the studied crops was observed precisely in those phenological phases, which are empirically established critical phases for them in terms of water consumption (Зінченко та ін., 2001). This statement was confirmed in several scientific works, in which NDVI was successfully used as an independent or additional parameter to determine irrigation timing and rates, which differed from the traditional FAO method with improved precision and resulted in significant savings in irrigation water (Hunsaker et al., 2006, 2007; Fontanet et al., 2020). Haghverdi et al. (2020) used the normalized differential vegetation index as an indicator of the response of irrigated crops to irrigation.

The research by Patel & Oza (2014) also proved the possibility of a sufficiently accurate tracking of the timing of the phenological phases of crops by the value of NDVI. However, one cannot avoid problems in recognizing the phenological phases of the same crop, if it was sown in completely different terms (for example, millet can be sown both in the main and in intermediate crops), as well as because of the use in the production of varieties and hybrids of different maturity groups, which was reflected in the work of Терехин (2014). Additionally, the difference may be related to the use of different sources to calculate the value of the vegetation index. In our study, the Sentinel-1/2 satellite images were the basis, while when using images, for example, from the Landsat-8 satellite, the difference in the value of NDVI according to the phases of crop development may be slightly different. Although, despite the difference in the varietal composition, different environmental conditions, and parameters of grain corn cultivation technology in the Kherson and Belgorod regions (Russian Federation), the annual dynamics of NDVI for this crop in these regions is very similar, the peak values of the vegetation index are noted in the period " the end of June – July" (Терехин, 2014). Similarly, the dates of the maximum value of the vegetation index for soybeans coincided in July, while, for example, a certain difference can be observed for sunflowers: in our work, the maximum occurred in July, in the work of Терехин (2015) – at the end of June. In general, the study of the annual dynamics of NDVI and the development of reference models for various crops is useful for clarifying and simplifying phenological observations and fixing the onset of the phases of growth and development of cultivated plants based on satellite data over large areas. Mao et al. (2003) studied the dynamics of NDVI on wheat crops, established significant fluctuations in the value of the vegetation index depending on the phenological phase of the crop.

The established patterns of annual NDVI dynamics can be applied in systems of automated recognition, typology and mapping of agricultural land based on remote sensing data, as it has been proven that each crop has its own unique pattern of seasonal changes in the vegetation index. For example, Khvostikov & Bartalev (2018) proposed mathematical models for recognizing vegetation types based on patterns of seasonal NDVI dynamics, with a model error of 8%. Hanbing et al. (2011) confirm the existence of a significant difference in the patterns of seasonal dynamics of NDVI of different plant groups. Note that some researchers pay additional attention to the great importance of choosing the right algorithms for mathematical processing of seasonal NDVI values, which will improve the accuracy of automatic recognition of agricultural crops (Wei et al., 2015).

5.4. Relationship between normalized difference vegetation index and fraction of green canopy cover in crops

In the current stage of agricultural production development, the transition from conventional agriculture to precision agriculture is inevitable. Such a transfer cannot be imagined without the implementation and integration of the models of automated management and decision-making with simulation of agroecological processes in phytocenoses (for example, DSSAT, APSIM, AquaCrop), as well as technical and technological means for receiving, reading, analyzing, and interpreting the remote sensing data, which already are successfully and actively used by science and practice for programming and forecasting the productivity of agroecosystems and agroecological monitoring (Jones et al., 2003; Liaghat & Balasundram, 2010). So far, compared to Western European and American farmers, the Ukrainian agrarian is very little aware of the possibilities of improving the process of management, planning, and increasing the productivity of plant production using remote sensing data. There is not only a lack of knowledge about the technologies themselves and how they are applied in practice. The domestic market for high-tech products does not actively offer a highly regarded and financially attractive arsenal of technical means and systems to implement the principles of precision agriculture. Information support also has practically no alternative to the high-cost foreign one, and the national software product has a not much lower cost for incomparable quality, so most private owners and farmers cannot afford to purchase it, which greatly inhibits the development of precision agriculture at the national level. Thus, forecasting the productivity of agricultural crops and monitoring the condition of crops around the world is carried out using data on the normalized difference vegetation index (Shafi et al., 2019; Shanmugapriya et al., 2019; Tenreiro et al., 2021). Foreign information platforms (for example, AgroAPI, Earth Observation Systems, CERES Imaging, VEGA-PRO), which provide high-quality and ready-to-use information on vegetation indices without additional knowledge and processing, require large capital investments, which increase in proportion to the increase of the cultivated areas involved in monitoring and needs for additional (for example, meteorological) information. At the same time, free services and services for academic institutions (for example, offered by Copernicus and NASA) provide the user with "raw" satellite images that require additional professional camera processing. Trial versions of software products provide low quality and provide limited access to remote sensing data (both temporally and spatially). Therefore, the problem arises of the possibility of obtaining data on the normalized differential vegetation index at minimum costs and with the highest possible accuracy from alternative sources or by an alternative method. The solution to this problem can be the fractional green canopy cover (FGCC) conversion of the value into the value of NDVI.

The fractional green canopy cover is an indicator that can be automatically calculated in a few steps for any part of the field with a modern smartphone running Android or iOS with a camera. All you must do is download the free Canopeo mobile application, take a photo of the field, holding the smartphone camera parallel to the soil surface at a height of 1.5-2.5 m (depending on the height of the cultivated plants and the features of the micro-relief), and get the results about percentage of green cover in this area (Patrignani & Ochsner, 2015). The method is very convenient, intuitively simple, does not require high capital investments, and most importantly, the calculation results can be used directly in models to assess the productivity of fodder lands and the growth of plant biomass (Jáuregui et al., 2019), as well as for conversion to those used in precision agriculture systems, and most models of growth and development of agricultural crops have a normalized differential vegetation index (Reed et al., 2021).

At the moment, there are few studies on the mutual conversion between NDVI and FGCC, but the reports available in the scientific literature are sufficient to prove a close correlation between the values of these indices in a number of crops. Thus, a strong direct proportional relationship has been established for vegetable and garden crops, grain corn, soybeans, winter wheat and barley. The maximum closeness of the connection between the NDVI and FGCC values, according to preliminary data, belongs to the crops of the narrow-row sowing method. The data available in domestic and foreign scientific literature are insufficient for a complete understanding of the relationship between these two indicators, since the range of studied crops, the geography of research, and the volume of input data sets are insufficient. In addition, most models are limited to establishing a linear relationship without taking into account the nonlinear component of the course of processes in agroecosystems (Lukina et al., 1999; Trout et al., 2008; De la Casa et al., 2018; McGlinch et al., 2021). A detailed study of the strength, direction and regularities of the relationship between the values of NDVI and FGCC for each individual crop is essential, as previous studies have shown that it can vary widely even in related species and may also depend to some extent on agroclimatic conditions and agricultural cultivation techniques (Lyon, 2016; Tenreiro et al., 2021).

The aim of this study is to assess the relationship between the values of NDVI, obtained from the remote sensing data, and FGCC, calculated from ground photographs in the Canopeo mobile application (Fig. 5.4.1). It is important to emphasize that although the main task is to find models for converting FGCC to NDVI, a reverse conversion model will also be of high practical value in some cases, when for certain reasons (impossibility to reach the field due to weather conditions, too high plant height on the site, extremely large territorial shooting scale, etc.) it becomes impossible to obtain data on green cover from ground photographs, but data on the normalized difference vegetation index for a given area are available, as it was shown in the studies of numerousforeign authors (McPherson, 1993; Calera et al., 2001; Rahman et al., 2004; Schmitz & Kandel, 2021; Tsakmakis et al., 2021).

The results of mathematical-statistical processing of data pairs "FGCC – NDVI" (100 pairs for each studied crop) made it possible to assert the presence of a strong direct proportional relationship between these indices for each crop, which is confirmed by the correlation coefficient values within 0.8475-0.9758 (Table 5.4.1).

The highest tie closeness was recorded for safflower, chickpeas, beans, winter rapeseed and peas (the determination coefficient exceeded 0.90), and the minimum was for tomato, millet, and sunflower (the coefficient of determination was less than 0.80). Average quality of fitting is in the models of winter wheat and grain corn. In general, it is noticeable that crops that traditionally have higher plant density and are sown in a narrow-row manner demonstrate a higher correspondence between the indices of green cover and the normalized difference vegetation index. Regarding tomatoes, the decrease in the strength of the connection between the investigated parameters may be due to the peculiarities of the architecture of plants, the stems of which are to a certain extent twisted and during the period of formation and ripening of fruits, they spread over the surface of the soil, which causes distortions during the assessment of both the fraction of green leaf cover and vegetation index.

Regarding the accuracy of the developed models, it is worth noting the extremely high correspondence between simulated and real NDVI values for such crops as chickpeas, safflower, peas, winter wheat, and grain corn, where the value of *MAPE* did not exceed 10%, which indicates the highest quality and reliability of these models. High conversion accuracy is provided by the models for industrial tomato, sunflower and millet, the *MAPE* of which is in the range of 10-20%. For winter rapeseed and beans, the conversion of FGCC to NDVI for these crops is possible, but its precision is at an average level (Moreno et al., 2013). The mathematical polynomial models for the conversion of the FGCC value to NDVI for each crop are given in Table 5.4.2.

Table 5.4.2

Polynomial models for conversion of FGCC (%) into NDVI (pts.) for the studied crops

Crop	Model
Grain corn	$0.1384 + 0.0062 \times FGCC + 3.0000 \times 10^{-6} \times FGCC^2$
Sunflower	$0.0448 + 0.0091 \times FGCC – 2.3000 \times 10^{-5} \times FGCC^2$
Tomato	$0.1718 + 0.0098 \times FGCC – 2.0460 \times 10^{-5} \times FGCC^2$
Millet	$0.0168 + 0.0098 \times FGCC – 4.8510 \times 10^{-5} \times FGCC^2$
Winter wheat	$0.2080 + 0.0045 \times FGCC + 1.357 \times 10^{-5} \times FGCC^2$
Winter rapeseed	$–0.1305 + 0.0127 \times FGCC – 4.7241 \times 10^{-5} \times FGCC^2$
Safflower	$0.1034 + 0.0036 \times FGCC + 2.6415 \times 10^{-6} \times FGCC^2$
Beans	$–0.1166 + 0.0121 \times FGCC – 3.2024 \times 10^{-5} \times FGCC^2$
Chickpeas	$0.0132 + 0.0066 \times FGCC + 2.0827 \times 10^{-6} \times FGCC^2$
Peas	$0.0051 + 0.0105 \times FGCC – 2.4200 \times 10^{-5} \times FGCC^2$

The results of mathematical and statistical processing of data pairs "NDVI – FGCC" (100 pairs for each studied crop, reverse direction of conversion) confirmed the existence of a strong direct proportional correlation between these indices for each crop, which confirms the regularity established by the previous analysis (Table 5.4.3).

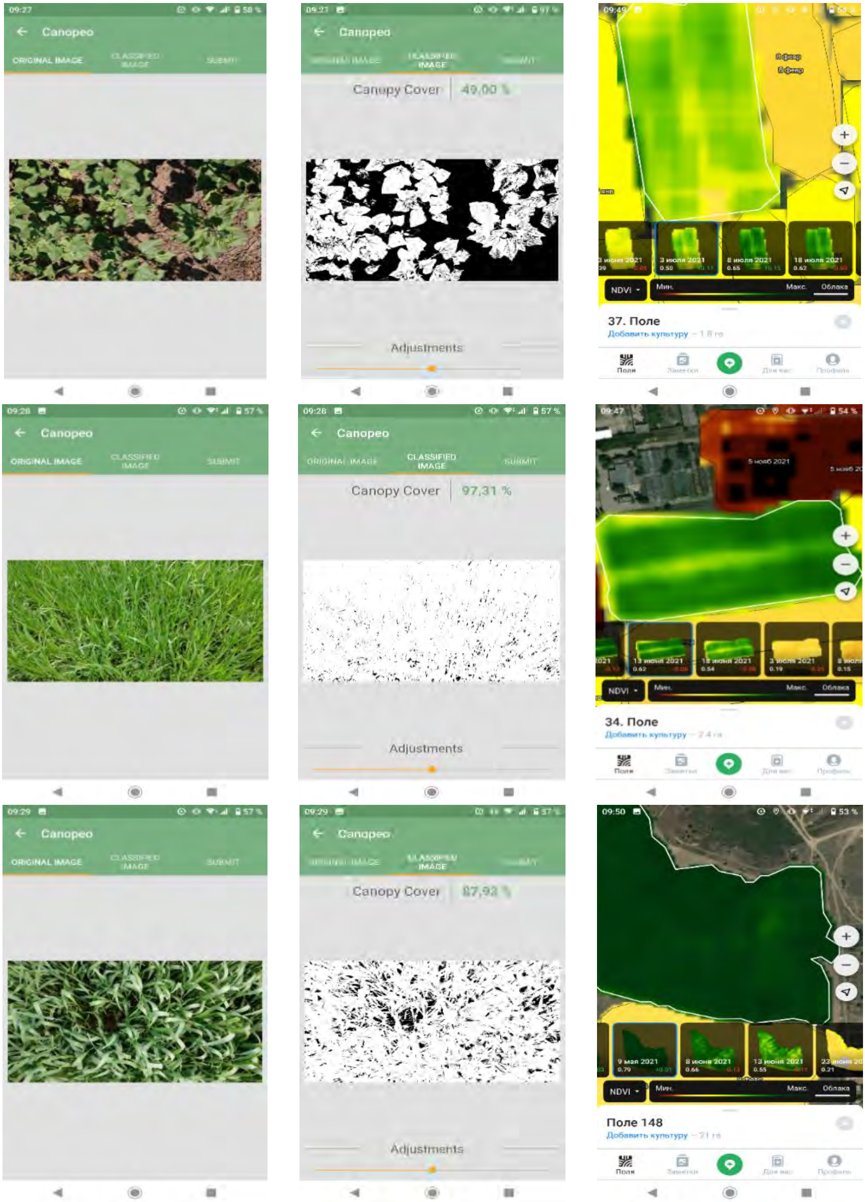


Fig. 5.4.1. Example of FGCC calculation in Canopeo and corresponding NDVI at the OneSoil AI platform for remote sensing crops monitoring

Table 5.4.1

Regression statistics of the polynomial models for FGCC (%) into NDVI (pts.) conversion for the studied crops

Statistical indices	Grain corn	Sunflower	Tomato	Millet	Winter wheat	Winter rapeseed	Safflower	Beans	Chickpeas	Peas
Correlation coefficient (*R*)	0.8985	0.8795	0.8475	0.8887	0.9487	0.9625	0.9890	0.9733	0.9758	0.9494
Coefficient of determination(R^2)	0.8073	0.7735	0.7182	0.7899	0.9000	0.9265	0.9782	0.9473	0.9522	0.9014
Adjusted (R_{adj}^2)	0.8033	0.7689	0.7124	0.7855	0.8979	0.9250	0.9777	0.9462	09512	0.8994
Mean absolute percentage error (*MAPE*)	9.94%	15.97%	14.30%	16.75%	9.37%	37.88%	2.15%	30.02%	1.28%	9.37%

During the evaluation of the quality of the reverse conversion models, it was established that the highest fitting quality was provided by the latter for such crops as safflower, chickpeas, beans, winter rapeseed and peas (the coefficient of determination is higher than 0.90), the minimum (the coefficient of determination below 0.80) was provided by the models for millet and tomato. The average quality of fitting is observed for the models of such crops as grain corn, sunflower, and winter wheat. In general, it is noticeable that the reverse conversion for certain crops (sunflower, millet, winter rapeseed, beans, chickpeas, and peas) ensured a higher quality of fitting compared to the direct one. At the same time, the reduction of the coefficients of determination during the conversion of NDVI to FGCC is established for grain corn, winter wheat, tomato and safflower.

Regarding the precision of the NDVI to FGCC conversion models, the models provide extremely high reliability for winter wheat, winter rapeseed, safflower, chickpeas and pea (*MAPE*<10%), high – for grain corn, sunflower, tomato, millet, and beans. It should be noted that, unlike the models for direct conversion, all reverse conversion models provided higher accuracy, since none of the MAPE models exceeded the value *MAPE* of 20% (Moreno et al., 2013). Mathematical polynomial models for the conversion of FGCC into NDVI for each crop are presented in Table 5.4.4.

The results of the study supplement the previously acquired knowledge about the closeness and peculiarities of the relationship between the studied indicators. In particular, the data available in the scientific literature refer to a limited range of crops, limited to certain garden and vegetable crops (Trout et al., 2008), wheat (Lukina et al., 1999; Goodwin et al., 2018), sorghum (Chung et al.., 2017), fodder crops (Jáuregui et al., 2019), barley (McGlinch et al., 2021) and soybeans (De la Casa et al., 2018). In addition, the linear relationships proposed by the authors, in our opinion, do not fully correspond to natural non-linear processes, and the very laws of the relationship between NDVI and FGCC will also vary greatly depending on geography, natural-climatic, soil and agro-technological conditions of research.

Table 5.4.3

Regression statistics of the polynomial models for NDVI (pts.) into FGCC (%) conversion for the studied crops

Statistical indices	Grain corn	Sunflower	Tomato	Millet	Winter wheat	Winter rapeseed	Safflower	Beans	Chickpeas	Peas
Correlation coefficient (*R*)	0.8969	0.9000	0.8234	0.8927	0.9428	0.9639	0.9856	0.9748	0.9759	0.9522
Coefficient of determination(R^2)	0.8044	0.8099	0.6779	0.7969	0.8889	0.9292	0.9714	0.9502	0.9524	0.9066
Adjusted (R_{adj}^2)	0.8004	0.8060	0.6713	0.7927	0.8866	0.9277	0.9709	0.9492	0.9514	0.9047
Mean absolute percentage error (*MAPE*)	10.15%	16.63%	18.21%	15.73%	3.90%	2.87%	4.95%	16.27%	1.75%	5.43%

Table 5.4.4

Polynomial models for conversion of NDVI (pts.) into FGCC (%) for the studied crops

Crop	Model
Grain corn	$3.5721 + 79.6233 \times NDVI + 44.5291 \times NDVI^2$
Sunflower	$-0.7472 + 127.2628 \times NDVI - 19.1083 \times NDVI^2$
Tomato	$0.0754 + 70.0017 \times NDVI + 19.0338 \times NDVI^2$
Millet	$-1.4352 + 127.4283 \times NDVI - 13.9308 \times NDVI^2$
Winter wheat	$-4.0062 + 116.3299 \times NDVI - 1.5687 \times NDVI^2$
Winter rapeseed	$-25.0306 + 249.1919 \times NDVI - 133.5281 \times NDVI^2$
Safflower	$-3.5951 + 152.4170 \times NDVI - 4.1673 \times NDVI^2$
Beans	$-26.9276 + 238.6282 \times NDVI - 120.2829 \times NDVI^2$
Chickpeas	$-3.2480 + 163.8229 \times NDVI - 26.4700 \times NDVI^2$
Peas	$21.8760 + 18.8732 \times NDVI + 90.3971 \times NDVI^2$

An interesting fact is that different crops have a different tendency to increase the intensity of the NDVI value with an increase in FGCC. Therefore, when the green cover is only 20%, almost all crops studied are likely to have an NDVI value that, according to the gradation given in Section 5.3, belongs to suppressed vegetation (<0.2). Only when FGCC reaches 40% is the transition of all studied cultivated plants to the phase of growth of vegetative mass noticeable. At the same time, safflower is distinguished by the slowest increase in the value of the normalized difference vegetation index, while tomato has the most rapid increase in its value. Most of the crops studied are limited by the peak value of NDVI in the range of 0.70-0.75, while tomato is able to reach the maximum possible values of the index 0.85 in FGCC 85% (Table 5.4.5).

As for the inverse pattern, the maximum growth rates of FGCC are observed for such crops as chickpeas and safflower, which reach peak FGCC values at submaximal NDVI 0.65. They are followed by grain corn, sunflower, millet, and beans. Crops such as tomato, winter wheat, winter rapeseed, and peas reach submaximal values of the FGCC at the submaximal value of the NDVI 0.80 (Table 5.4.6). The established regularities are an important source of knowledge regarding the features of the real display of the growth processes of cultivated plants by remote and ground-based vegetation indices. The mathematical models for mutual conversion between fractional green canopy cover and normalized difference vegetation index are presented in an intuitive form in the mobile application NDVI Converter, available for smartphones based on the Android OS (Fig. 5.4.2). For convenience, the application is published in three languages: Ukrainian, English, and Russian. This will allow a domestic farmer who has a smartphone with installed applications Canopeo and NDVI Converter to quickly calculate not only the FGCC for each field or its separate plot, but also recalculate it to NDVI to receive fresh data on the vegetation index without additional costs.

Table 5.4.5

Correspondence between FGCC and NDVI in the studied crops

FGCC (%)	NDVI (pts.) ± standard deviation									
	Grain corn	Sunflower	Tomato	Millet	Winter wheat	Winter rapeseed	Safflower	Beans	Chickpeas	Peas
20	0.26±0.02	0.22±0.03	0.36±0.05	0.19±0.03	0.30±0.03	0.10±0.04	0.18±0.01	0.11±0.03	0.15±0.01	0.21±0.02
30	0.33±0.03	0.30±0.05	0.45±0.06	0.27±0.04	0.36±0.03	0.21±0.08	0.21±0.01	0.22±0.07	0.21±0.01	0.30±0.03
40	0.39±0.04	0.37±0.06	0.53±0.08	0.33±0.06	0.41±0.04	0.30±0.11	0.25±0.01	0.32±0.09	0.28±0.01	0.39±0.04
50	0.46±0.04	0.44±0.07	0.61±0.09	0.39±0.06	0.47±0.04	0.39±0.15	0.29±0.01	0.41±0.12	0.35±0.01	0.47±0.04
60	0.52±0.05	0.51±0.08	0.69±0.10	0.43±0.07	0.53±0.05	0.46±0.17	0.33±0.01	0.49±0.15	0.42±0.01	0.55±0.05
70	0.59±0.06	0.57±0.09	0.76±0.11	0.47±0.08	0.59±0.06	0.57±0.20	0.37±0.01	0.57±0.17	0.49±0.01	0.62±0.06
80	0.65±0.06	0.63±0.10	0.82±0.12	0.49±0.08	0.65±0.06	0.58±0.22	0.41±0.01	0.65±0.19	0.55±0.01	0.69±0.06
90	0.72±0.07	0.68±0.11	0.86±0.12*	0.51±0.08	0.72±0.07	0.63±0.24	0.45±0.01	0.71±0.21	0.62±0.01	0.75±0.07

Notes: * crops, for which the peak NDVI is reached at FGCC 85%.

Table 5.4.6

Correspondence between NDVI and FGCC in the studied crops

NDVI (pts.)	FGCC (%) ± standard deviation									
	Grain corn	Sunflower	Tomato	Millet	Winter wheat	Winter rapeseed	Safflower	Beans	Chickpeas	Peas
0.3	31.47±3.19	35.71±5.94	22.79±4.15	35.54±5.59	30.75±1.20	37.71±1.08	41.75±2.07	33.84±5.51	50.01±0.88	35.67±1.94
0.4	42.55±4.32	47.10±7.83	31.12±5.67	47.31±7.44	42.27±1.65	53.28±1.53	56.70±2.81	49.28±8.02	64.54±1.13	43.89±2.38
0.5	54.22±5.53	58.11±9.66	39.83±7.25	58.80±9.25	53.77±2.10	66.18±1.90	71.57±3.54	62.32±10.14	78.54±1.37	53.91±2.93
0.6	67.38±6.84	68.73±11.43	48.93±8.91	70.01±11.01	65.23±2.54	76.41±2.19	86.35±4.27	72.95±11.87	92.01±1.61	65.74±3.57
0.7	81.13±8.23	78.97±13.13	58.40±10.64	80.94±12.73	76.66±2.99	83.97±2.41	93.72±4.64*	81.17±13.21	98.55±1.72*	79.38±4.31
0.8	88.34±8.97†	83.95±13.96†	68.26±12.43	86.30±13.57†	88.05±3.43	88.86±2.55	98.55±1.72*	84.38±13.73†	98.55±1.72*	94.83±5.15

Notes: * crops, for which the peak FGCC is reached at NDVI 0.65; † - crops, for which the peak FGCC is reached at NDVI 0.75

Fig. 5.4.2. Interface of the mobile app NDVI Converter

For those who use devices running other OS, an online application with similar functionality is available at the link https://tinyurl.com/y8vma89u.

It is worth noting that the models were developed and tested in the conditions of the South of Ukraine, and therefore the maximum accuracy of conversion is guaranteed precisely for this area of farming.

Conclusions to Chapter 5

1. It has been established that vegetation indices in the Kherson region reach their peak values in the period May–July: NDVI – 0.53-0.54, EVI - 0.32-0.33. Starting from August, there is a process of gradual senescence of annual flora and transition to a state of dormancy in perennial flora, which renovates the next life cycle since March.

The study of the long-term dynamics of the state of the region's flora based on satellite data indicates a sustainable trend toward the improvement in the general condition of vegetation, which is confirmed by a gradual increase in the value of the vegetation indices. The EVI vegetation index is more sensitive and shows a steeper linear dynamic to increase compared to NDVI. According to the results of the mathematical evaluation of the average annual indicators, a significantly higher sensitivity to meteorological factors was established for the NDVI. The evaluation of the relationship between meteorological indicators and vegetation indices during the growing season showed a higher sensitivity to changes in the multiyear section of the NDVI value, while it is better to use the EVI value to evaluate the dynamics within the annual period. It was established that NDVI did not respond to the climatic factor when evaluated within the growing season. The direction of the influence of the increase in air temperature on the flora of the Kherson region when evaluated in terms of different time series changes to the opposite: when evaluating the average annual dynamics, it has a positive effect on vegetation, while during the growing season it is negative. Regarding precipitation, the direction of its influence is the same for both evaluation periods, and the strength of influence decreased within the growing season. It was established that the value of NDVI is less variable both for monthly periods and for years than the value of EVI. The variation of both vegetation indices increases in the cold period of the year (October – March). Thus, according to established regularities, it is more rational to use the EVI vegetation index to assess the state of the flora depending on climate changes at the regional scale, which provides a comparable level of accuracy both for dynamic assessments based on average annual data in multi-year dynamics and for short time series within a year or growing season. The normalized difference vegetation index can be used to monitor the dynamics of the average annual data in a multi-year section, since its response to the climatic factor in the growing season is too low. Models of the dependence of vegetation indices on meteorological factors make it possible to predict possible changes in the flora of the Kherson region based on meteorological forecasts, and to take the necessary measures to preserve natural and maintain the homeostasis of artificial phytocenoses under conditions of climate change.

2. Regression analysis made it possible to establish the strength of the relationship between the value of NDVI in the phase of " panicle ejection – appearance of stigma" and the yield of grain corn, which turned out to be very high and positive with a coefficient of determination of 0.9813, with *MAPE* 8.75 %. For sweet corn, higher prediction accuracy and fit quality of the crop yield model were observed when using the phenological phase of NDVI value in the "panicle ejection», while *MAPE* was 28.13%, and the model determination coefficient of determination of the model was 0.4218. For grain sorghum, the highest accuracy and quality of modeling is provided by the value of NDVI in the "flowering" phenological phase: *The MAPE* of the model is 17.62%, and the coefficient of determination is 0.8645. For soybeans, the yield prediction model in the phenological phase of the "second

internode» turned out to be the determination best – *MAPE* was 3.17%, the coefficient was 0.9830. In winter wheat, the closest relationship between vegetation index and crop yield was recorded in the 'earing' phase: the value of *MAPE* was 13.42%, the determination coefficient 0.7189. In general, the minimum accuracy of yield prediction based on satellite data was recorded for sweet corn and the maximum – for soybeans. The accuracy of prediction decreases for weak crops and is highest for medium-yielding ones. Based on the results of mathematical modeling, a productivity scale was created for the studied crops based on the value of NDVI in the phenological phase recommended for prediction: "panicle ejection – appearance of stigma" for grain corn, "panicle ejection" for sweet corn, "flowering" for grain sorghum, "second internode" for soybeans, "earing" for winter wheat.

3. The analysis of the annual dynamics of the normalized difference vegetation index on the fallow field led to the conclusion that the marker of the beginning (recovery for winter crops) of active vegetation of crops should be taken as the value of NDVI is ≥ 0.22. The vegetation index reaches its maximum values in May for winter crops (wheat, barley, rapeseed) and early spring crops (chickpeas, peas), in July for late spring crops (sunflower, soybean, grain sorghum, millet, grain corn, sweet corn, spring planted tomato). In spring potatoes, the maximum value of NDVI was recorded in June, in late tomatoes – in August. The vegetation index reaches its peak values in the following phenological phases: winter wheat, winter barley, stem elongation; winter rapeseed – flowering; chickpeas, branching; peas – budding and flowering; sunflower, stem growth; soybeans – beans formation; grain sorghum, panicle ejection and flowering; grain corn, panicle ejection and flowering; millet, panicle ejection and flowering; sweet corn – panicle ejection and flowering; spring potatoes, budding; tomato (regardless of the time of planting) – fruit formation. A high similarity of growing patterns was established in crops such as winter wheat and winter barley, chickpeas and peas, millet, and sunflower. In general, each crop has characteristic features of the seasonal dynamics of the vegetation index; therefore, the templates established as a result of the research can be integrated into the systems of automated recognition of cultivated plants and field mapping based on satellite data.

4. The results of mathematical and statistical processing of the FGCC and NDVI data pairs for each of the crops studied confirmed the existence of a strong direct proportional relationship between these indices: the values of the correlation coefficient values ranged from 0.8475 to 0.9758. The maximum tightness of the connection was established for safflower, chickpeas, beans, winter rapeseed, and peas (determination coefficient is > 0.90), the minimum for tomato, millet and sunflower (determination coefficient is < 0.80). The maximum accuracy of FGCC into NDVI conversion is provided by mathematical models for chickpeas, safflower, peas, winter wheat and grain corn, where the value of *MAPE* is <10%. High conversion accuracy is provided by the models for tomato, sunflower, and millet, *MAPE* of which is within the range of 10-20%. For winter rapeseed and beans, the

conversion of FGCC into NDVI is possible, but the accuracy of the model is average. Evaluation of the quality of the reverse conversion models showed that the highest quality was ensured for safflower, chickpeas, beans, winter rapeseed and peas (determination coefficient is > 0.90), minimum (determination coefficient is < 0.80) – the models for millet and tomato. The models for winter wheat, winter rapeseed, safflower, chickpeas and peas (*MAPE*<10%) provide maximum conversion reliability, high – for grain corn, sunflower, tomato, millet, beans. Most of the crops studied are limited by the peak value of NDVI in the range of 0.70-0.75, while tomato is able to reach the maximum possible values of the index ≥0.85 at the FGCC approximately 85%. The mathematical models for mutual conversion between fractional green canopy cover and normalized difference vegetation index are presented in an intuitive form in the mobile application for smartphones based on the Android OS – NDVI Converter.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The presented scientific work offers a new perspective on agroclimatic zoning and irrigation requirements on the territory of Ukraine, taking into account the climatic situation; the role of crop production as a climate-forming factor is established and promising directions for the transformation of modern practices of farming, land use and forestry are considered; approaches to flora monitoring in large areas were proposed, productivity prediction models and phenology tracking approaches were developed for several chosen crops grown in the Kherson region. The results of the research work can be summarized and generalized in the following points:

1. Climate change is an urgent agro-ecological problem that significantly affects agro-industrial production and food security, requires an integrative approach a review of agro-climatic zoning, the structure of sown areas, species and varietal composition of crops, cultivation technologies based on the climate-oriented adaptive approach. The industrialization and informatization of crop production on the basis of precision digital agriculture, which involves the complex use of modern satellite monitoring technologies, geo-information systems, IoT and a modern machine-tractor park, is one of the important prerequisites for the successful implementation of the strategy of adapting the agro-industrial sector to current challenges, requires comprehensive approach to the transformation of the agricultural sector of the state at all levels, including economic, political-legal, social, technical-technological and scientific-educational.
2. Analysis of the meteorological situation in the Kherson region over a multi-year period indicates the risks of increasing aridity in the region. By 2050, the territory of the region is likely to become extremely arid – the forecasted aridity index is 0.22. Irrigation will acquire the status of a decisive factor in the sustainable development of crop production, which is confirmed by the results of the regression analysis for the pair "total productivity of arable land – volumes of water used for irrigation" in the region (R^2 is 0.7378).
3. A statistically reliable trend towards an increase in the average annual air temperature, which for the period 2021-2050 is likely to reach the forecast mark of +11.1-11.2ºC, has been observed throughout the territory of Ukraine in recent years. The most rapid climatic changes in the last 30 years were recorded in Chernihiv, Kharkov, Sumy and Vinnitsa regions. The minimum climatic changes are observed in the Kherson, Volyn, Mykolaiv, Odesa, Poltava and Zaporizhzhia regions. An intense increase in aridity was recorded in Chernivtsi, Khmelnitsky, L'viv, Sumy, Ternopol, Vinnitsa, and Zhytomyr regions. The minimum statistically significant dynamics is observed in the southern regions of Ukraine – Kherson, Mykolaiv, Odesa, Zaporizhzhia, and Dnipropetrovsk regions. A trend of increasing irrigation needs has been established in all regions of Ukraine. As of 2021, irrigation is not needed to ensure sustainable crop production only in the western and north-western

regions. The current level of meeting irrigation needs in Ukraine is catastrophically low and is, according to various estimates, 2.5-10.0%.

4. Based on the results of a mathematical analysis of retrospective agrometeorological data on the territory of Ukraine for the period 1971-2020, reference evapotranspiration assessment models were developed based on the value of the average air temperature based on the standardized FAO Penman-Monteith method. Checking the quality and accuracy of the proposed models confirmed their high quality (R^2 in the range of 0.84-0.95) and accuracy (*MAPE* at the level of 8.96-26.24%), which significantly depended on the region: the maximum – for the Mykolaiv region, Kharkov region, Kirovograd and Dnipropetrovsk regions, the minimal – for the Odesa, Rivne region, Zakarpattia and Zhytomyr regions. For ease of implementation of mathematical models, the online application "ETo Calculator Ukraine" was created based on the Zoho spreadsheet processor and the Android application for smartphones Evapotranspiration Calculator (Ukraine).

5. Reliable trends have been established to increase the average annual global air temperature, the concentration of the main greenhouse gases in the atmosphere, and the area of the ozone hole. It has been proven that CO_2 has a secondary role in global warming (R^2 is 0.70), the leading role belongs to N_2O (R^2 is 0.74). The hypothesis of the influence of greenhouse gases on the temperature regime of the planet has been confirmed ($R > 0.69$).

6. An increase in N_2O and CH_4 emissions associated with anthropogenic activity in the field of crop production was established. Agriculture is the main source of N_2O emissions with a share of >75%, while carbon dioxide emissions are minimized to <8% thanks to modern tillage systems. The presence of a strong inverse correlation between emissions and the concentration of greenhouse gases and the area of forests was proved (R^2 is 0.88). The use of pesticides, nitrogen fertilizers, the increase in the forests area contribute to the reduction of greenhouse gas emissions, while the application of phosphorus-potassium fertilizers, the expansion of arable land and increasing the intensity of the use of tractors leads to its growth according to the mathematical model of the formation of emissions under the influence of farming practices. Forecast calculations have established that without the use of appropriate regulatory measures, the level of greenhouse gas emissions from the crop industry will reach 9.35 million tons by 2050, while optimization of farming practices and forestry will allow emissions to be kept at the level of 7.14 million tons. Forest restoration and afforestation is a powerful lever of influence on the intensity of climate change processes, which is confirmed by a strong inverse relationship between global air temperature and the forest area (R^2 is 0.7225). In addition, forests indirectly affect the productivity of agrophytocenoses. The mathematical model of the total productivity of 1 ha of Ukrainian arable land, depending on the level of its forest cover, has high reliability and good predictive accuracy (R^2_{pred} is 0.4046 at *MAPE* 18.50%). In the period 1990-2019, the ratio of arable land coverage with forest plantations in Ukraine is within 0.3-0.4 without a tendency to increase.

7. According to remote sensing data for the period 2012-2021, it was established that the peak values of the vegetation indices in the Kherson region fall on the period May – July: NDVI is 0.53-0.54; EVI is 0.32-0.33. In August, the process of annual vegetation senescence and transition to a dormant state of perennial vegetation begins, the next life cycle starts in March. EVI is found to be more sensitive than NDVI to dynamic changes in the flora of a region, while NDVI is a better predictor of vegetation response to weather conditions. However, NDVI was completely unresponsive to the climate factor when evaluated within the growing season, rather than multi-yearly. NDVI is less variable than EVI. The variation of both vegetation indices increases in the period from October to March. The developed models of the dependence of vegetation indices on meteorological factors make it possible to predict changes in the flora conditions of the Kherson region based on the data of meteorological forecasts.

8. Mathematical modeling of the productivity of cultivated plants based on the NDVI made it possible to obtain reliable prognostic models and establish the degree of reliability of the forecast for different phenological phases of plant development. A high connection strength and accuracy of the forecast of grain corn yield in the phenological phase ‘panicle ejection – stigma appearance" was established (R^2 is 0.9813, *MAPE* is 8.75%). As for sweet corn, the maximum accuracy of its yield forecast is ensured in the phenological phase of "panicle ejection» (R^2 is 0.42181, *MAPE* 28.13%). For grain sorghum, the highest accuracy of the productivity forecast is provided by the NDVI in the "flowering" phenological phase (R^2 is 0.8654, *MAPE* 17.62%). For soybeans, the yield forecast model in the "second internode" phenological phase is the best (R^2 is 0.9830, *MAPE* 3.17%). In winter wheat, the maximum closeness of the relationship between NDVI and yield is recorded in the "earing" phenological phase (R^2 is 0.7189, *MAPE* 13.42%). The accuracy of predictions according to the developed models decreases for weak crops and is the highest for medium-productive ones. Performance scales, created based on the mathematical models, simplify their practical use.

9. The analysis of the annual dynamics of the normalized difference vegetation index on the fallow field led to the conclusion that the marker of the beginning (recovery for winter crops) of active vegetation of crops should be taken as the value of NDVI is ≥ 0.22. The vegetation index reaches its maximum values in May for winter crops (wheat, barley, rapeseed) and early spring crops (chickpeas, peas), in July for late spring crops (sunflower, soybean, grain sorghum, millet, grain corn, sweet corn, spring planted tomato). In spring potatoes, the maximum value of NDVI was recorded in June, in late tomatoes – in August. The vegetation index reaches its peak values in the following phenological phases: winter wheat, winter barley, stem elongation; winter rapeseed – flowering; chickpeas, branching; peas – budding and flowering; sunflower, stem growth; soybeans – beans formation; grain sorghum, panicle ejection and flowering; grain corn, panicle ejection and flowering; millet, panicle ejection and flowering; sweet corn – panicle ejection and flowering;

spring potatoes, budding; tomato (regardless of the time of planting) – fruit formation. A high similarity of growing patterns was established in crops such as winter wheat and winter barley, chickpeas and peas, millet, and sunflower. In general, each crop has characteristic features of the seasonal dynamics of the vegetation index; therefore, the templates established as a result of the research can be integrated into the systems of automated recognition of cultivated plants and field mapping based on satellite data.

10. The results of mathematical and statistical processing of the FGCC and NDVI data pairs for each of the crops studied confirmed the existence of a strong direct proportional relationship between these indices: the values of the correlation coefficient values ranged from 0.8475 to 0.9758. The maximum tightness of the connection was established for safflower, chickpeas, beans, winter rapeseed, and peas (determination coefficient is > 0.90), the minimum for tomato, millet and sunflower (determination coefficient is < 0.80). The maximum accuracy of FGCC into NDVI conversion is provided by mathematical models for chickpeas, safflower, peas, winter wheat and grain corn, where the value of *MAPE* is <10%. High conversion accuracy is provided by the models for tomato, sunflower, and millet, *MAPE* of which is within the range of 10-20%. For winter rapeseed and beans, the conversion of FGCC into NDVI is possible, but the accuracy of the model is average. Evaluation of the quality of the reverse conversion models showed that the highest quality was ensured for safflower, chickpeas, beans, winter rapeseed and peas (determination coefficient is > 0.90), minimum (determination coefficient is < 0.80) – the models for millet and tomato. The models for winter wheat, winter rapeseed, safflower, chickpeas and peas (*MAPE*<10%) provide maximum conversion reliability, high – for grain corn, sunflower, tomato, millet, beans. Most of the crops studied are limited by the peak value of NDVI in the range of 0.70-0.75, while tomato is able to reach the maximum possible values of the index ≥0.85 at the FGCC approximately 85%. The mathematical models for mutual conversion between fractional green canopy cover and normalized difference vegetation index are presented in an intuitive form in the mobile application for smartphones based on the Android OS – NDVI Converter.

Based on the theoretical and practical outcomes of the study, following recommendations aimed at optimizing and improving the agroecological situation, the efficiency of plant production and the training of highly qualified specialists in the field of knowledge "Agronomy" were formed. The recommendations are grouped by three levels of potential implementation: national, regional, and industrial.

National recommendations are:

- To maintain the functional state and promote the reconstruction of existing irrigation systems in the Kherson, Odesa, Mykolaiv and Zaporizhzhia regions.
- To ensure the expansion of the irrigation systems in the regions, which are most vulnerable to increasing aridity, namely in the Kirovograd, Dnipropetrovsk and Kharkov regions.

- Use the developed methodology and updated maps of agroclimatic zoning of Ukraine in the scientific and educational process in specialized institutions of higher education.
- Ensure the proper implementation of measures for the protection of forests, afforestation and reforestation, carry out repairs and planting of field forest shelter belts to achieve a total area of natural and artificial forest plantations in Ukraine of 135-160 thousand km^2.

Regional recommendations are:

- Use the developed models for determining the flora conditions of the Kherson region based on the data of the vegetation indices EVI and NDVI depending on meteorological factors for effective dynamic monitoring and forecasting of the state of vegetation in the region in conditions of global warming.

Production recommendations are:

- To optimize the use of irrigation water and irrigation regimes in the regions of Ukraine using the developed application "ETo Calculator Ukraine" for operational determination of reference evapotranspiration.
- Reduce the amount of outdated plant protection products, volatile forms of mineral fertilizers, urea, calcium cyanamide, solutions of urea-ammonium nitrate usage to prevent excessive emission of nitrogen oxide into the atmosphere, prevent alkalization and over-compaction of soils of heavy granulometric composition in no-till cultivation systems.
- In the farms of Southern Ukraine, apply the developed crop productivity scale depending on the value of NDVI in certain phases of their growth and development for operational planning of production, management, and adjustment of cultivation technology.
- Carry out remote monitoring of the phenology of crops according to NDVI data in accordance with the established reference values of the index for each phenological phase.
- Use a combination of Canopeo and NDVI Converter mobile applications to interconvert between FGCC and NDVI values in precision agriculture systems to predict crop yields.

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APPENDICES

Appendix A.1

Precipitation by the regions of Ukraine for 1961-2020

Year	Volyn	Rivne	Cherkasy	Chernihiv	Chernivtsi	Dnipro	I.-Frankivsk	Kharkov	Kherson	Khmelnitsky	Kirovograd	Kyiv	L’viv	Mykolaiv	Odesa	Poltava	Sumy	Ternopol	Zakarpattia	Vinnitsa	Zaporizhzhia	Zhytpmyr	Crimea
1961-1990	600	613	532	683	589	518	673	533	399	642	513	664	749	464	422	536	588	636	796	596	486	608	532
1991	574	486	638	892	464	441	679	488	354	530	487	533	738	264	346	423	600	448	680	679	479	442	458
1992	641	507	740	493	503	421	527	447	416	644	275	605	837	243	350	458	512	527	619	468	392	532	603
1993	674	566	412	649	602	488	613	568	334	735	449	686	692	397	349	429	775	713	625	600	480	719	313
1994	680	582	537	574	491	473	504	397	276	547	428	579	647	267	347	517	893	471	744	446	372	609	297
1995	546	419	537	573	687	588	554	647	504	725	574	640	585	374	473	670	745	475	673	548	558	515	581
1996	539	622	710	746	637	526	583	529	404	549	410	664	740	321	412	628	587	495	671	690	357	792	532
1997	744	668	735	622	698	787	585	652	594	747	660	628	798	583	674	751	625	590	784	679	719	707	831
1998	624	732	664	760	642	479	636	443	386	755	526	658	1045	411	499	563	584	731	1110	570	434	785	517
1999	576	605	551	627	544	638	697	394	453	616	515	626	685	404	398	484	499	642	804	500	571	768	766
2000	705	680	615	469	639	718	562	382	542	567	592	580	633	352	482	452	640	545	669	621	413	658	358
2001	587	784	722	749	661	693	945	538	554	737	669	632	997	430	474	781	826	805	826	592	643	814	488
2002	549	598	549	637	637	611	726	488	397	705	569	698	639	361	505	532	572	457	673	686	479	607	541
2003	534	561	557	476	557	567	527	684	483	578	488	553	631	372	495	666	560	539	596	543	542	570	502
2004	742	526	319	547	526	930	666	596	667	576	694	614	837	561	596	737	566	594	733	643	798	588	780
2005	480	663	448	829	605	571	583	588	467	777	535	669	722	494	467	546	512	585	857	535	416	596	542
2006	637	617	533	748	608	514	728	450	321	692	488	621	828	349	511	491	624	603	716	629	408	525	442
2007	741	669	333	624	602	443	662	537	381	736	470	633	804	337	427	650	514	638	733	547	342	655	463
2008	762	761	642	733	640	443	903	442	471	902	574	741	874	441	398	497	536	720	784	623	479	553	412
2009	684	525	513	497	570	628	639	552	466	557	511	454	908	394	402	665	610	509	749	451	537	566	362
2010	664	807	583	853	673	610	958	599	685	769	626	596	931	705	734	645	584	764	1066	715	581	673	572
2011	411	412	477	445	610	421	438	494	284	413	400	578	633	297	394	551	425	400	577	440	403	484	393
2012	807	698	590	636	751	597	732	492	374	745	505	752	677	359	558	705	606	737	657	507	535	751	321
2013	675	631	525	592	604	451	602	561	334	768	451	800	811	362	357	590	614	729	648	620	517	799	533
2014	638	645	424	564	454	680	698	490	365	565	399	547	774	397	487	515	508	583	669	551	599	564	407
2015	521	442	547	375	515	525	482	527	524	453	513	451	650	393	463	542	590	454	523	369	511	481	622
2016	540	527	728	691	692	658	724	746	530	620	702	654	857	574	754	760	770	496	764	468	518	577	575
2017	642	720	411	520	605	495	721	421	310	552	372	590	748	266	444	445	482	543	878	542	436	624	529
2018	552	426	664	694	542	678	638	464	410	574	539	596	820	396	491	623	436	560	591	563	469	655	518
2019	534	513	290	594	445	545	629	429	650	831	415	527	699	392	439	699	422	416	660	537	941	502	408
2020	559	640	380	695	602	453	881	557	319	590	378	605	776	350	357	474	460	575	820	561	507	650	368

Appendix A.2

Evapotranspiration by the regions of Ukraine for 1961-2020

Year	Volyn	Rivne	Cherkasy	Chernihiv	Chernivtsi	Dnipro	I.-Frankivsk	Kharkov	Kherson	Khmelnitsky	Kirovograd	Kyiv	L'viv	Mykolaiv	Odesa	Poltava	Sumy	Ternopol	Zakarpattia	Vinnitsa	Zaporizhzhia	Zhytpmyr	Crimea
1961-1990	750	757	794	804	727	925	724	935	998	747	916	755	694	987	938	893	795	707	884	745	992	733	985
1991	617	486	536	510	494	580	482	542	908	469	547	523	439	251	618	542	500	467	602	485	591	4911	619
1992	668	492	548	548	508	547	507	514	924	488	550	531	495	374	625	526	427	488	625	498	560	488	597
1993	1774	1380	479	499	446	508	464	462	903	443	478	476	461	294	563	477	374	446	584	451	527	447	580
1994	654	520	542	580	459	577	542	522	986	511	556	536	522	524	667	539	516	506	658	513	590	503	675
1995	709	505	1310	541	498	594	504	553	951	490	552	547	492	831	639	554	517	389	590	494	607	505	646
1996	465	498	664	522	531	584	486	545	985	490	562	527	484	1070	624	551	510	467	583	507	595	511	626
1997	555	464	693	506	478	521	468	494	825	450	493	502	451	757	586	587	453	444	560	456	537	462	577
1998	552	491	621	535	510	591	497	561	941	481	548	522	486	1957	648	552	499	487	594	491	603	488	646
1999	538	526	592	560	504	608	524	588	985	518	579	574	523	808	698	583	537	494	618	526	627	522	690
2000	1356	907	1079	977	789	1177	892	888	934	493	1003	921	917	1173	679	558	500	426	1097	875	607	526	675
2001	962	922	1203	913	881	1216	900	928	955	983	1097	929	804	1075	668	566	516	433	1020	871	624	525	678
2002	1036	980	1036	980	1044	1131	1008	976	993	1085	1211	983	926	1094	701	598	545	571	1085	915	656	557	694
2003	861	825	1114	898	819	1050	994	844	966	876	976	878	830	1005	627	533	487	424	1028	823	577	500	605
2004	1349	751	818	897	877	949	888	876	866	613	890	890	813	1275	655	534	510	508	991	835	587	498	634
2005	923	839	830	873	852	984	821	933	953	818	907	904	811	1123	677	563	617	585	963	836	621	518	678
2006	897	812	796	901	921	970	847	918	917	854	921	913	863	1058	664	564	612	511	1053	862	618	541	660
2007	1347	880	833	975	912	1108	946	976	1089	898	1068	989	874	1162	736	607	668	632	1078	927	671	580	712
2008	1172	855	917	964	877	904	903	961	924	835	973	962	874	1103	686	518	541	529	1059	890	639	570	687
2009	1140	875	950	975	877	1030	888	968	971	870	983	966	857	1094	705	588	530	525	1070	902	647	560	710
2010	738	1242	940	1122	1181	1488	1114	1461	1269	1148	1391	1268	1058	1037	918	1316	1327	1124	1122	1192	1236	1085	1192
2011	856	1212	954	1309	1173	1403	1288	1335	1420	1377	1481	1314	1172	1061	895	1281	1181	1250	1282	1294	1259	968	1156
2012	877	1454	1135	1445	1365	1809	1331	1538	1626	1433	1683	1367	1327	1330	1073	1439	1317	1391	1314	1408	1408	1121	1338
2013	951	1262	1094	1260	1140	1555	1254	1305	1392	1182	1455	1250	1126	1207	1116	1229	1181	1176	1271	1319	1293	888	1211
2014	1251	1500	1368	1282	1261	1744	1269	1531	1587	1256	1596	1403	1173	1726	1133	1515	1411	1296	1216	1252	1051	1128	1197
2015	1336	1426	1368	1389	1355	1694	1377	1550	1497	1562	1603	1326	1226	1156	1077	1506	1341	1419	1341	1419	1460	687	1220
2016	1385	1054	1456	1382	1214	1567	1270	1381	1395	1378	1463	1308	1143	1063	931	1333	1242	1459	1252	1337	1328	1049	1307
2017	1259	1385	1370	1405	1260	1456	1311	1358	1550	1453	1617	1405	1151	1157	1110	1483	1303	1551	1171	1390	1321	1177	1323
2018	1227	1331	1328	1262	1129	1577	1204	1497	1519	1435	1540	1268	1139	1200	1169	1384	1321	1302	1285	1251	1421	1056	1400
2019	1090	1315	1208	1414	1271	1603	1310	1430	1512	1433	1537	1464	1205	1153	1098	1294	1319	1387	1119	1377	1191	1116	1360
2020	1096	1422	1267	1287	1229	1678	1207	1547	1387	1405	1575	1315	1141	1400	1373	1436	1353	1307	1224	1305	1536	1083	1415

Appendix A.3
Aridity index by the regions of Ukraine for 1961-2020

Year	Volyn	Rivne	Cherkasy	Chernihiv	Chernivtsi	Dnipro	I.-Frankivsk	Kharkov	Kherson	Khmelnitsky	Kirovograd	Kyiv	L'viv	Mykolaiv	Odesa	Poltava	Sumy	Ternopol	Zakarpattia	Vinnitsa	Zaporizhzhia	Zhytomyr	Crimea
1961-1990	0.80	0.81	0.67	0.85	0.81	0.56	0.93	0.57	0.40	0.86	0.56	0.88	1.08	0.47	0.45	0.60	0.74	0.90	0.90	0.80	0.49	0.83	0.54
1991	0.93	1.00	1.19	1.75	0.94	0.76	1.41	0.9	0.39	1.13	0.89	1.02	1.68	1.05	0.56	0.78	1.20	0.96	1.13	1.40	0.81	0.09	0.74
1992	0.96	1.03	1.35	0.9	0.99	0.77	1.04	0.87	0.45	1.32	0.50	1.14	1.69	0.65	0.56	0.87	1.20	1.08	0.99	0.94	0.70	1.09	1.01
1993	0.38	0.41	0.86	1.30	1.35	0.96	1.32	1.23	0.37	1.66	0.94	1.44	1.5	1.35	0.62	0.9	2.07	1.6	1.07	1.33	0.91	1.61	0.54
1994	1.04	1.12	0.99	0.99	1.07	0.82	0.93	0.76	0.28	1.07	0.77	1.08	1.24	0.51	0.52	0.96	1.73	0.93	1.13	0.87	0.63	1.21	0.44
1995	0.77	0.83	0.41	1.06	1.38	0.99	1.10	1.17	0.53	1.48	1.04	1.17	1.19	0.45	0.74	1.21	1.44	1.22	1.14	1.11	0.92	1.02	0.90
1996	1.16	1.25	1.07	1.43	1.20	0.9	1.20	0.97	0.41	1.12	0.73	1.26	1.53	0.30	0.66	1.14	1.15	1.06	1.15	1.36	0.60	1.55	0.85
1997	1.34	1.44	1.06	1.23	1.46	1.51	1.25	1.32	0.72	1.66	1.34	1.25	1.77	0.77	1.15	1.28	1.38	1.33	1.40	1.49	1.34	1.53	1.44
1998	1.13	1.49	1.07	1.42	1.26	0.81	1.28	0.79	0.41	1.57	0.96	1.26	2.15	0.21	0.77	1.02	1.17	1.50	1.87	1.16	0.72	1.61	0.80
1999	1.07	1.15	0.93	1.12	1.08	1.05	1.33	0.67	0.46	1.19	0.89	1.09	1.31	0.50	0.57	0.83	0.93	1.30	1.30	0.95	0.91	1.47	1.11
2000	0.52	0.75	0.57	0.48	0.81	0.61	0.63	0.43	0.58	1.15	0.59	0.63	0.69	0.30	0.71	0.81	1.28	1.28	0.61	0.71	0.68	1.25	0.53
2001	0.61	0.85	0.60	0.82	0.75	0.57	1.05	0.58	0.58	0.75	0.61	0.68	1.24	0.40	0.71	1.38	1.60	1.86	0.81	0.68	1.03	1.55	0.72
2002	0.53	0.61	0.53	0.65	0.61	0.54	0.72	0.50	0.40	0.65	0.47	0.71	0.69	0.33	0.72	0.89	1.05	0.80	0.62	0.75	0.73	1.09	0.78
2003	0.62	0.68	0.50	0.53	0.68	0.54	0.53	0.81	0.50	0.66	0.50	0.63	0.76	0.37	0.79	1.25	1.15	1.27	0.58	0.66	0.94	1.14	0.83
2004	0.55	0.70	0.39	0.61	0.60	0.98	0.75	0.68	0.77	0.94	0.78	0.69	1.03	0.44	0.91	1.38	1.11	1.17	0.74	0.77	1.36	1.18	1.23
2005	0.52	0.79	0.54	0.95	0.71	0.58	0.71	0.63	0.49	0.95	0.59	0.74	0.89	0.44	0.69	0.97	0.83	1.00	0.89	0.64	0.67	1.15	0.80
2006	0.71	0.76	0.67	0.83	0.66	0.53	0.86	0.49	0.35	0.81	0.53	0.68	0.96	0.33	0.77	0.87	1.02	1.18	0.68	0.73	0.66	0.97	0.67
2007	0.55	0.76	0.40	0.64	0.66	0.40	0.70	0.55	0.35	0.82	0.44	0.64	0.92	0.29	0.58	1.07	0.77	1.01	0.68	0.59	0.51	1.13	0.65
2008	0.65	0.89	0.70	0.76	0.73	0.49	1.00	0.46	0.51	1.08	0.59	0.77	1.00	0.40	0.58	0.96	0.99	1.36	0.74	0.70	0.75	0.97	0.60
2009	0.60	0.60	0.54	0.51	0.65	0.61	0.72	0.57	0.48	0.64	0.52	0.47	1.06	0.36	0.57	1.13	1.15	0.97	0.70	0.50	0.83	1.01	0.51
2010	0.90	0.65	0.62	0.76	0.57	0.41	0.86	0.41	0.54	0.67	0.45	0.47	0.88	0.68	0.80	0.49	0.44	0.68	0.95	0.60	0.47	0.62	0.48
2011	0.48	0.34	0.50	0.34	0.52	0.30	0.34	0.37	0.20	0.30	0.27	0.44	0.54	0.28	0.44	0.43	0.36	0.32	0.45	0.34	0.32	0.50	0.34
2012	0.92	0.48	0.52	0.44	0.55	0.33	0.55	0.32	0.23	0.52	0.30	0.55	0.51	0.27	0.52	0.49	0.46	0.53	0.50	0.36	0.38	0.67	0.24
2013	0.71	0.50	0.48	0.47	0.53	0.29	0.48	0.43	0.24	0.65	0.31	0.64	0.72	0.30	0.32	0.48	0.52	0.62	0.51	0.47	0.40	0.90	0.44
2014	0.51	0.43	0.31	0.44	0.36	0.39	0.55	0.32	0.23	0.45	0.25	0.39	0.66	0.23	0.43	0.34	0.36	0.45	0.55	0.44	0.57	0.50	0.34
2015	0.39	0.31	0.40	0.27	0.38	0.31	0.35	0.34	0.35	0.29	0.32	0.34	0.53	0.34	0.43	0.36	0.44	0.32	0.39	0.26	0.35	0.70	0.51
2016	0.39	0.50	0.50	0.50	0.57	0.42	0.57	0.54	0.38	0.45	0.48	0.50	0.75	0.54	0.81	0.57	0.62	0.34	0.61	0.35	0.39	0.55	0.44
2017	0.51	0.52	0.30	0.37	0.48	0.34	0.55	0.31	0.20	0.38	0.23	0.42	0.65	0.23	0.40	0.30	0.37	0.35	0.75	0.39	0.33	0.53	0.40
2018	0.45	0.32	0.50	0.55	0.48	0.43	0.53	0.31	0.27	0.40	0.35	0.47	0.72	0.33	0.42	0.45	0.33	0.43	0.46	0.45	0.33	0.62	0.37
2019	0.49	0.39	0.24	0.42	0.35	0.34	0.48	0.30	0.43	0.58	0.27	0.36	0.58	0.34	0.40	0.54	0.32	0.30	0.59	0.39	0.79	0.45	0.30
2020	0.51	0.45	0.30	0.54	0.49	0.27	0.73	0.36	0.23	0.42	0.24	0.46	0.68	0.25	0.26	0.33	0.34	0.44	0.67	0.43	0.33	0.60	0.26

Appendix A.4

Evapotranspiration variation within the regions of Ukraine by the data of regional hydrometeorological stations for 1961-1990

Region (Oblast)	Hydrometeorological station				Amplitude, %
	Regional center	I	II	III	
Cherkasy	794	808	867		9.19
Chernivtsi	804				–
Chernihiv	727	742			2.06
Dnipropetrovsk	925	969	894		4.76
Ivano-Frankivsk	724	798			10.22
Kharkov	935	855	874		8.56
Kherson	998	977	1020		2.20
Khmelnitsky	747	770	814		8.97
Kirovograd	916	848	876		7.42
Kyiv	755	757	773	794	5.17
L’viv	694	802	769		15.56
Volyn	750	797	783		6.27
Mykolaiv	987	940	1000		4.76
Odesa	938	874	1015	1056	12.58
Poltava	893	892	910		1.90
Rivne	757	773	788		4.10
Sumy	774	777	784		1.29
Ternopol	707	790			11.74
Zakarpattia	884	990			11.99
Vinnitsa	745	781	799		7.25
Zaporizhzhia	992	973	993		1.92
Zhytomyr	733	756	760		3.68
Crimea (except for coastal and mountainous regions)	985	1130	1067	1254	27.31

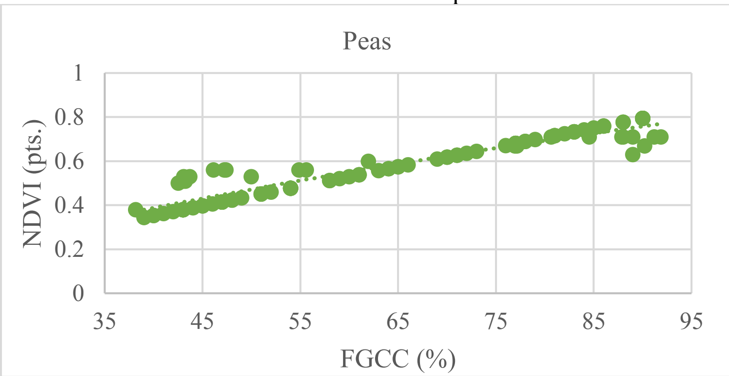
Appendix A.5

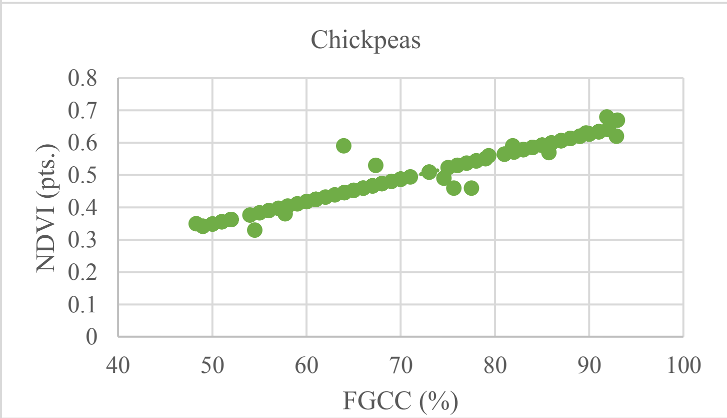
Precipitation variation within the regions of Ukraine by the data of regional hydrometeorological stations for 1961-1990

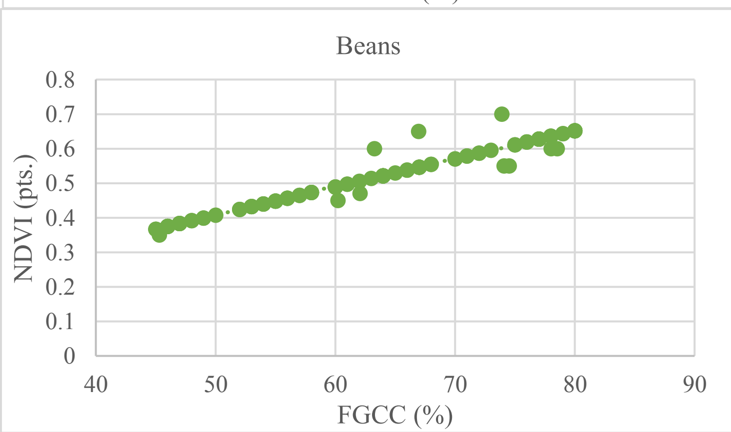
Region (Oblast)	Hydrometeorological station				Amplitude, %
	Regional center	I	II	III	
Cherkasy	532	578	564		8.65
Chernivtsi	683				–
Chernihiv	589	650			10.36
Dnipropetrovsk	518	493	488		5.79
Ivano-Frankivsk	673	686			1.93
Kharkov	533	544	543		2.06
Kherson	399	404	383		4.01
Khmelnitsky	642	649	639		1.09
Kirovograd	513	534	519		4.09
Kyiv	664	661	637	600	9.64
L'viv	749	751	719		4.00
Volyn	600	597	685		14.17
Mykolaiv	464	493	423		8.84
Odesa	422	446	452	490	16.11
Poltava	536	563	618		15.30
Rivne	613	633	606		3.26
Sumy	588	651	596		10.71
Ternopol	636	694			9.12
Zakarpattia	796	722			9.30
Vinnitsa	596	615	689		15.60
Zaporizhzhia	486	467	497		3.91
Zhytomyr	608	653	683		12.34
Crimea (except for coastal and mountainous regions)	532	407	443	659	23.87

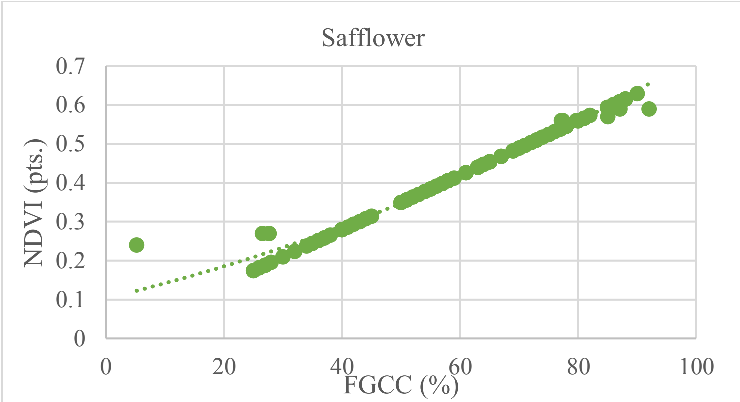
Appendix B.1

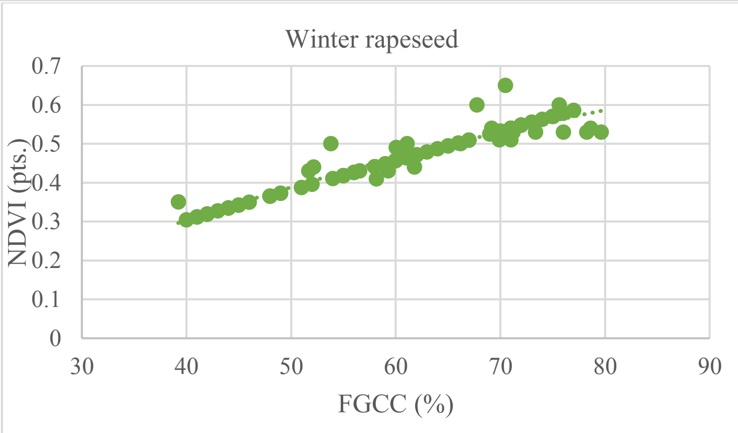
Approximation curves for the models of FGCC (%) into NDVI (pts.) conversion for the studied crops

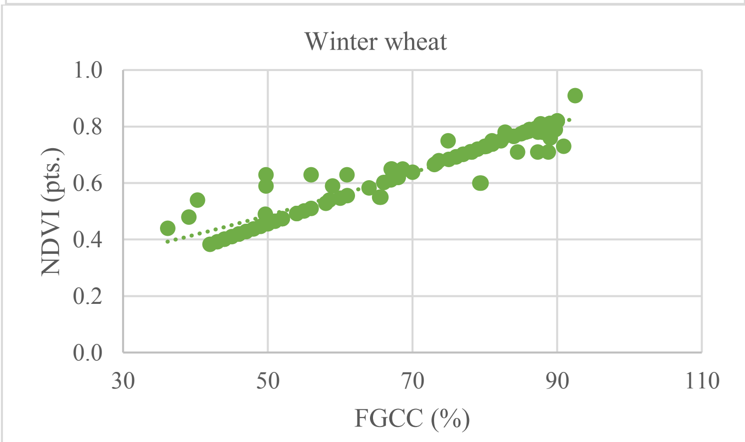


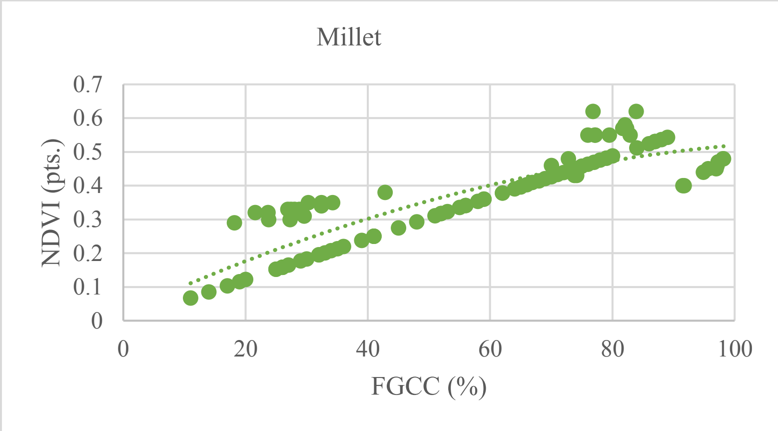


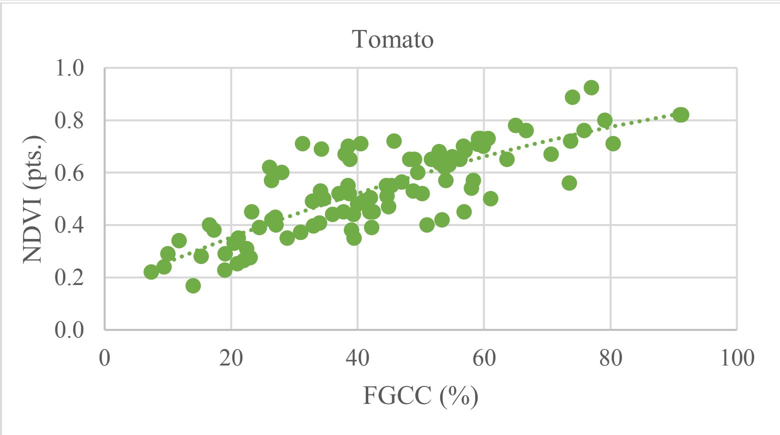


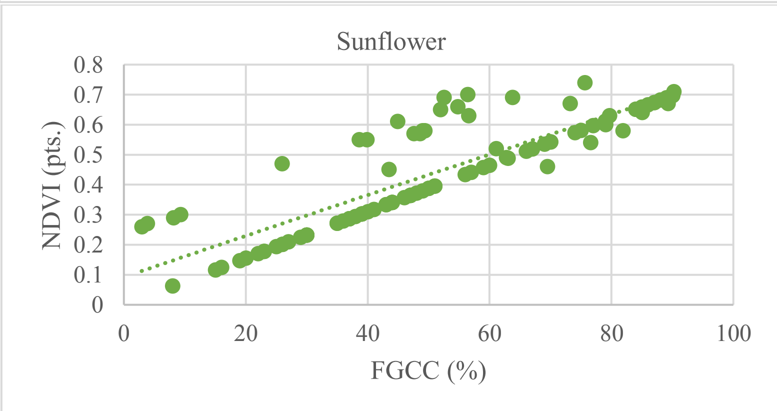

Safflower
NDVI (pts.)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
FGCC (%)

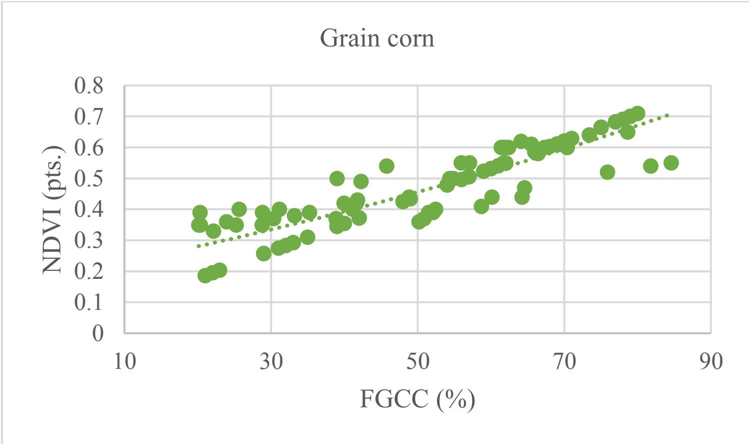

Winter rapeseed
NDVI (pts.)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
30
40
50
60
70
80
90
FGCC (%)


Winter wheat
NDVI (pts.)
1.0
0.8
0.6
0.4
0.2
0.0
30
50
70
90
110
FGCC (%)


Millet
NDVI (pts.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
20
40
60
80
100
FGCC (%)

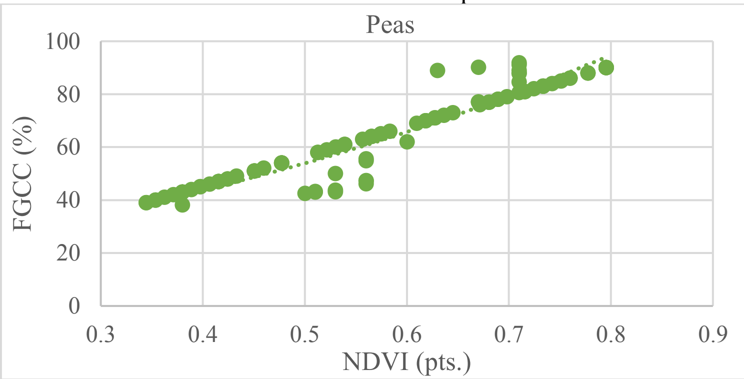

Tomato
NDVI (pts.)
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80
100
FGCC (%)

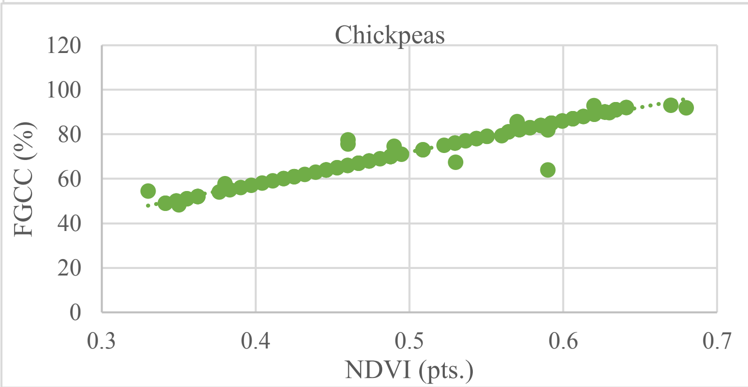

Sunflower
NDVI (pts.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
20
40
60
80
100
FGCC (%)

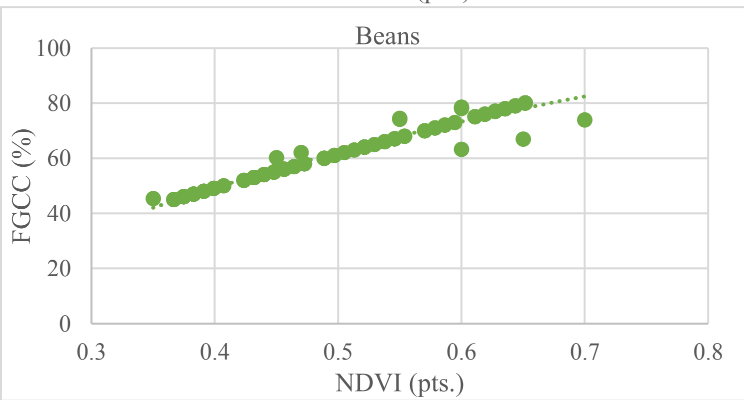

Grain corn
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
NDVI (pts.)
10
30
50
70
90
FGCC (%)

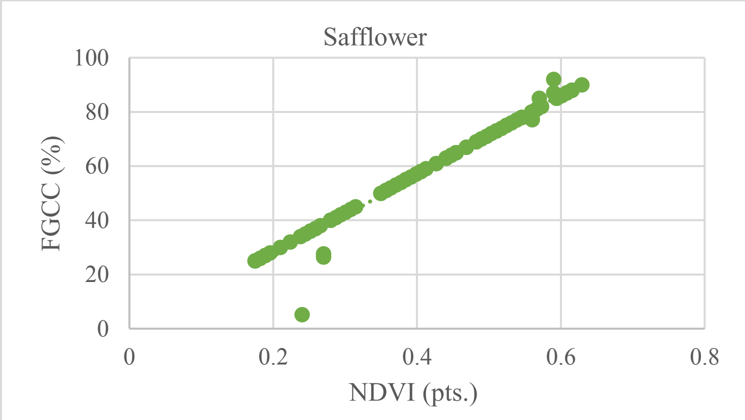
Appendix B.2

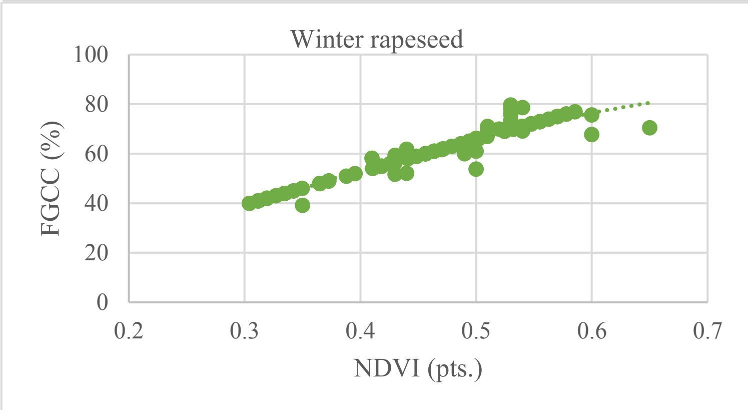
Approximation curves for the models of NDVI (pts.) into FGCC (%) conversion for the studied crops

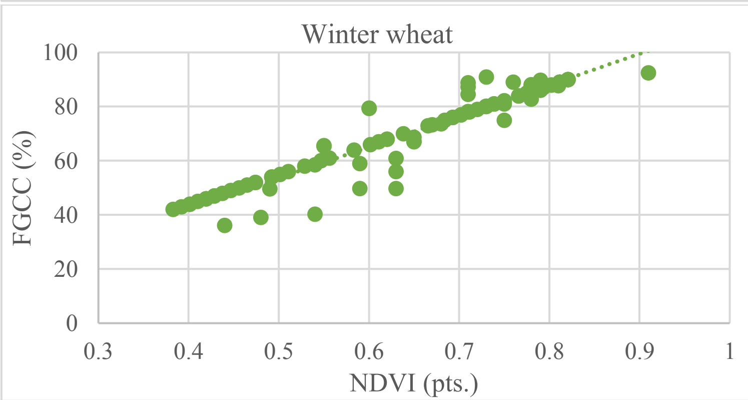


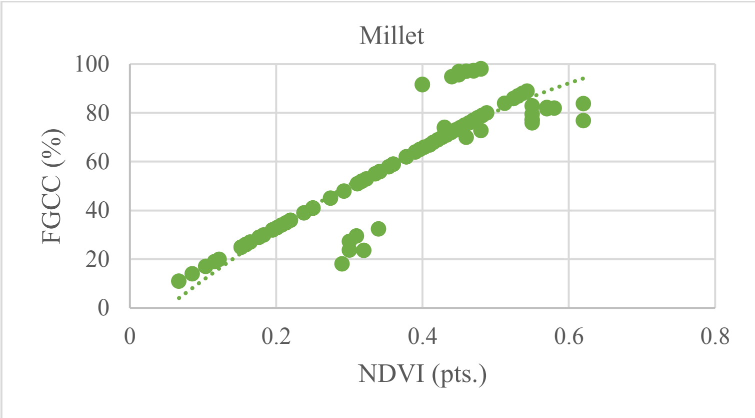


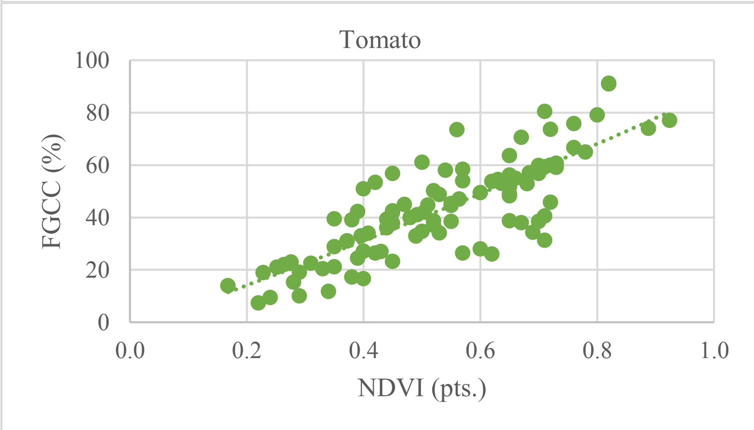


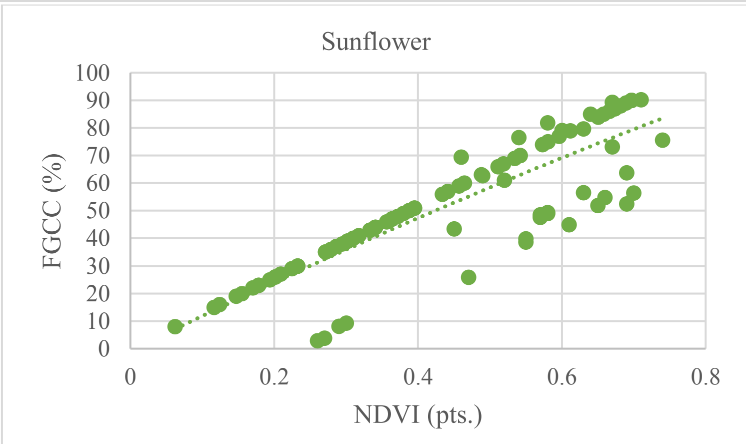

Safflower
100
80
60
40
20
0
FGCC (%)
0
0.2
0.4
0.6
0.8
NDVI (pts.)

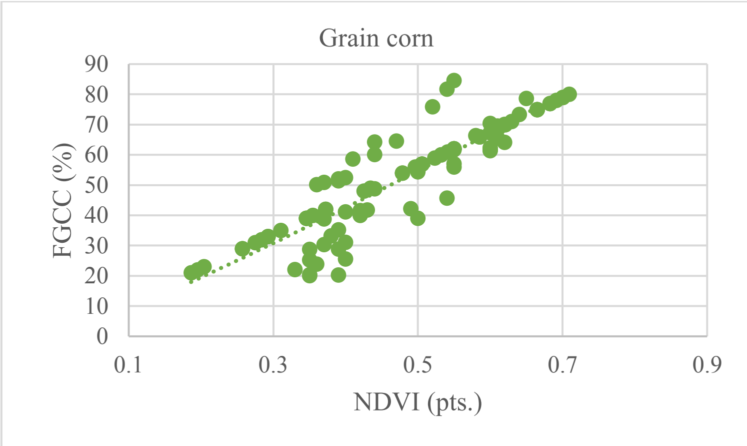

Winter rapeseed
100
80
60
40
20
0
FGCC (%)
0.2
0.3
0.4
0.5
0.6
0.7
NDVI (pts.)


Winter wheat
100
80
60
40
20
0
FGCC (%)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
NDVI (pts.)


Millet
100
80
60
40
20
0
FGCC (%)
0
0.2
0.4
0.6
0.8
NDVI (pts.)

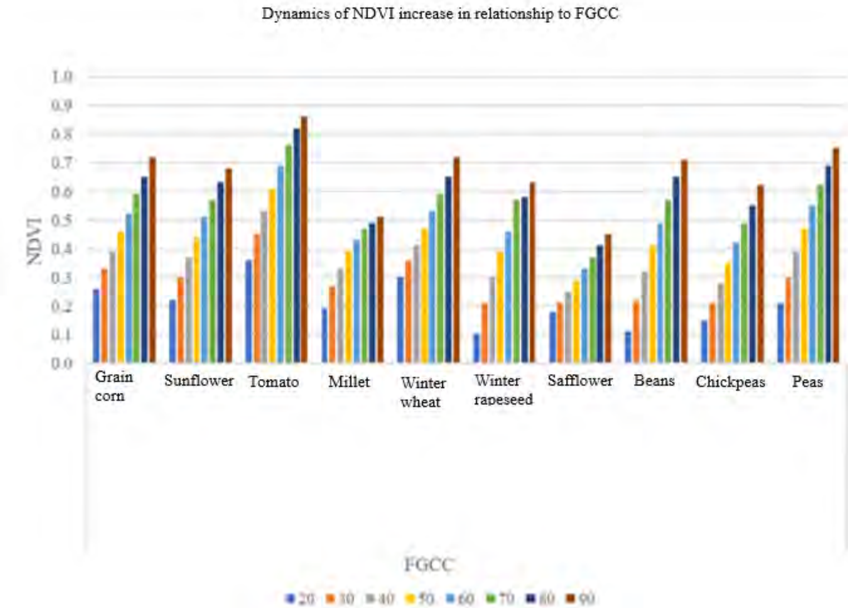

Tomato
100
80
60
40
20
0
FGCC (%)
0.0
0.2
0.4
0.6
0.8
1.0
NDVI (pts.)

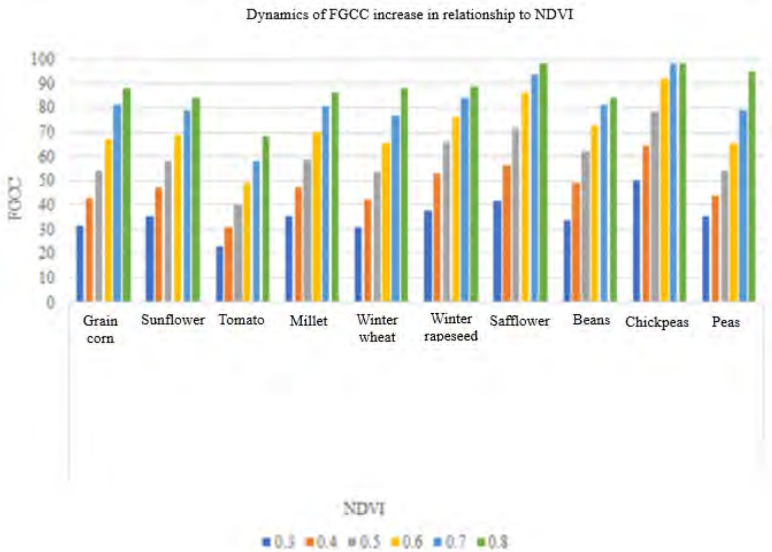

Sunflower
100
90
80
70
60
50
40
30
20
10
0
FGCC (%)
0
0.2
0.4
0.6
0.8
NDVI (pts.)


Grain corn
FGCC (%)
NDVI (pts.)
90
80
70
60
50
40
30
20
10
0
0.1
0.3
0.5
0.7
0.9

Appendix B.3

Correspondence between FGCC and NDVI at direct and reverse conversion





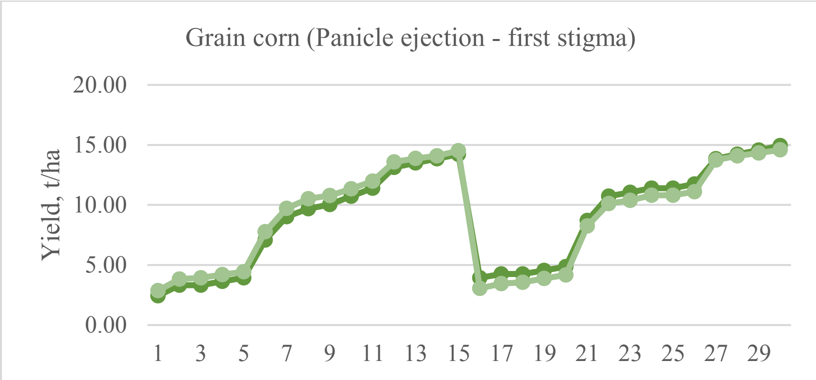
Appendix B.4

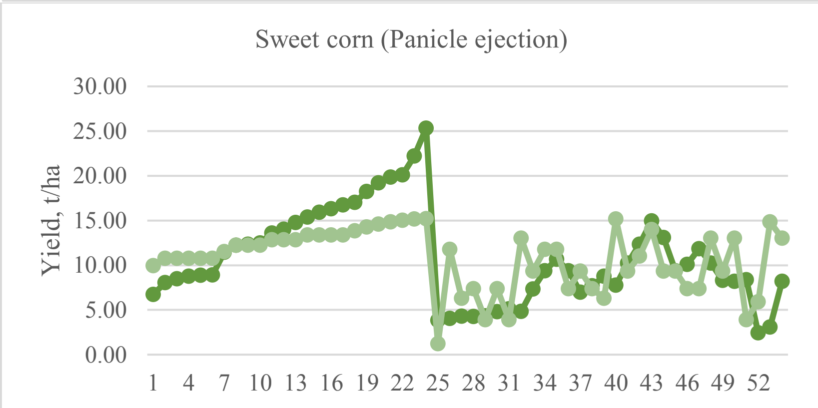
Climate, meteorological, and vegetation indices in Kherson oblast for 2012-2021

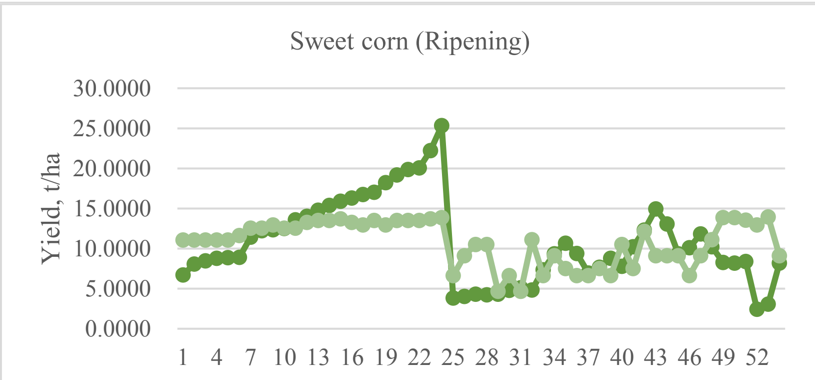
Year	Month	T, ºC	Rainfall, mm	NDVI	EVI	Year	T, ºC	Rainfall, mm	NDVI	EVI
2012	I	-1.3	56.2	0.34	0.14	2016	-3.1	61.1	0.39	0.15
	II	-7.2	15.1	0.31	0.14		3.9	28.5	0.40	0.18
	III	2.4	26.7	0.33	0.16		6.2	24.2	0.45	0.23
	IV	12.8	18.7	0.39	0.20		12.7	55.0	0.51	0.28
	V	20.5	65.4	0.46	0.25		16.3	82.6	0.56	0.33
	VI	23.3	25.6	0.50	0.29		22.1	72.6	0.57	0.35
	VII	26.4	19.0	0.51	0.29		24.3	19.4	0.56	0.33
	VIII	23.9	49.1	0.50	0.29		24.9	34.2	0.53	0.30
	IX	19.2	3.5	0.49	0.26		18.0	33.2	0.49	0.26
	X	14.9	22.4	0.47	0.25		8.4	74.4	0.46	0.23
	XI	7.0	7.3	0.46	0.23		4.0	34.2	0.42	0.20
	XII	-0.4	31.2	0.42	0.21		-1.2	26.3	0.38	0.17
2013	I	0.1	39.8	0.39	0.19	2017	-4.7	27.5	0.36	0.16
	II	2.5	22.2	0.40	0.20		-0.8	20.3	0.37	0.17
	III	3.3	41.3	0.43	0.22		7.0	5.1	0.42	0.21
	IV	11.6	8.0	0.47	0.26		9.3	87.9	0.49	0.27
	V	20.5	12.0	0.50	0.29		16.3	25.6	0.53	0.31
	VI	23.0	70.1	0.51	0.31		22.0	10.3	0.54	0.32
	VII	23.6	48.1	0.50	0.30		23.4	39.8	0.52	0.31
	VIII	24.2	12.4	0.49	0.27		25.4	4.8	0.49	0.28
	IX	15.1	43.7	0.48	0.25		19.9	0.7	0.47	0.25
	X	9.3	53.9	0.47	0.24		11.3	12.0	0.47	0.23
	XI	7.5	4.0	0.47	0.22		5.4	40.6	0.47	0.21
	XII	0.5	3.7	0.45	0.21		5.9	35.4	0.31	0.19
2014	I	1.1	39.5	0.42	0.20	2018	-0.3	24.1	0.44	0.18
	II	0	7.8	0.42	0.20		-0.2	33.3	0.43	0.19
	III	6.8	17.7	0.45	0.24		1.5	61.0	0.46	0.23
	IV	11.0	23.6	0.49	0.28		14.1	1.6	0.50	0.28
	V	18.1	42.6	0.52	0.31		19.5	35.7	0.53	0.31
	VI	20.8	85.9	0.52	0.31		22.9	23.1	0.53	0.32
	VII	25.0	18.6	0.49	0.29		24.2	90.8	0.53	0.31
	VIII	24.5	24.8	0.46	0.26		25.5	0	0.51	0.28
	IX	18.4	65.1	0.43	0.23		18.7	42.8	0.48	0.25
	X	9.3	31.1	0.42	0.20		13.5	9.6	0.45	0.22
	XI	3.3	19.0	0.40	0.18		2.7	31.1	0.42	0.19
	XII	0.4	45.5	0.36	0.15		0.1	56.3	0.39	0.18
2015	I	-0.4	32.2	0.35	0.16	2019	-0.6	23.0	0.39	0.17
	II	0.9	39.9	0.38	0.18		1.4	9.8	0.41	0.19
	III	5.2	57.7	0.44	0.23		5.9	7.3	0.46	0.24
	IV	9.4	57.8	0.50	0.29		10.5	56.0	0.52	0.30
	V	17.0	44.8	0.55	0.34		18.0	72.8	0.56	0.34
	VI	21.3	60.6	0.57	0.35		23.8	92.6	0.56	0.35
	VII	23.5	64.2	0.55	0.33		23.2	48.7	0.54	0.33
	VIII	24.1	25.7	0.51	0.29		23.4	22.1	0.51	0.30
	IX	20.9	3.8	0.46	0.24		18.1	12.1	0.50	0.27
	X	9.6	19.1	0.42	0.20		11.6	10.4	0.51	0.25
	XI	7.4	50.7	0.40	0.17		7.1	37.9	0.53	0.25
	XII	2.6	5.2	0.39	0.15		4.3	26.3	0.55	0.24

Year	Month	T, ºC	Rainfall, mm	NDVI	EVI	Year	T, ºC	Rainfall, mm	NDVI	EVI
2020	I	0.9	16.8	0.47	0.22	2021	0.1	71.6	0.42	0.20
	II	2.7	56.6	0.46	0.22		-0.6	18.9	0.40	0.20
	III	7.7	5.9	0.48	0.26		3.4	40.3	0.45	0.25
	IV	9.8	2.4	0.51	0.30		8.9	43.4	0.54	0.34
	V	14.7	29.7	0.53	0.32		15.9	97.7	0.61	0.42
	VI	22.7	44.4	0.51	0.31		20.7	91.1	0.61	0.43
	VII	24.7	58.7	0.45	0.28		25.3	77.3	0.55	0.38
	VIII	23.8	25.3	0.39	0.24		24.4	7.1	0.47	0.31
	IX	20.8	25.0	0.38	0.21		16.1	12.6	0.39	0.23
	X	15.4	21.5	0.43	0.24		10.1	5.1	0.35	0.18
	XI	4.9	10.2	0.48	0.26		6.5	33.3	0.34	0.15
	XII	1.7	18.0	0.48	0.25		1.9	64.4	0.34	0.14

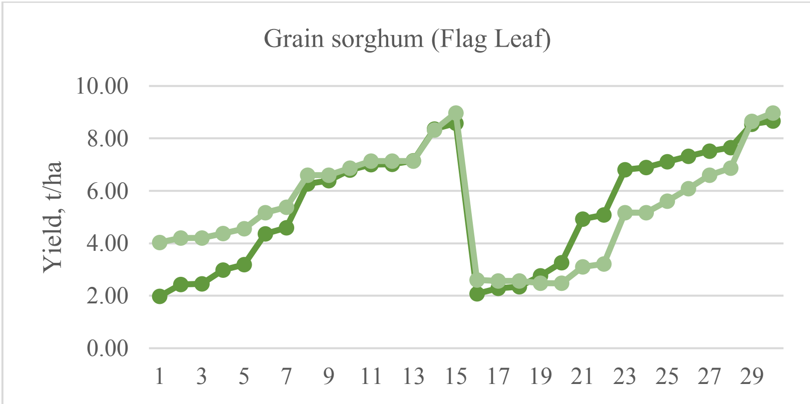
Appendix B.5
Approximation of the models for yield prediction of the studied crops by NDVI values

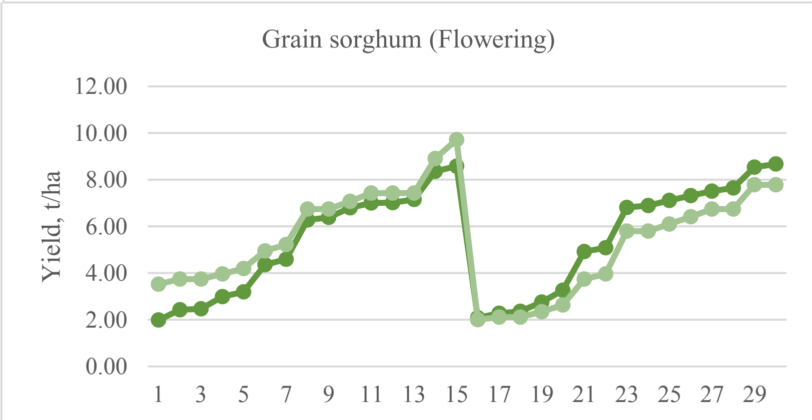


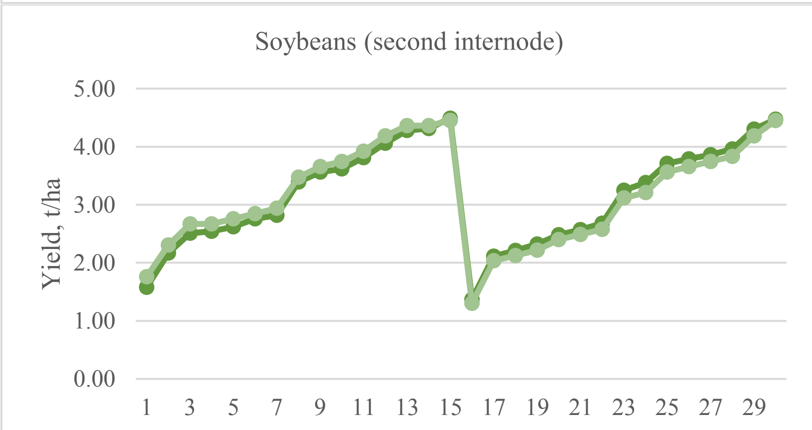




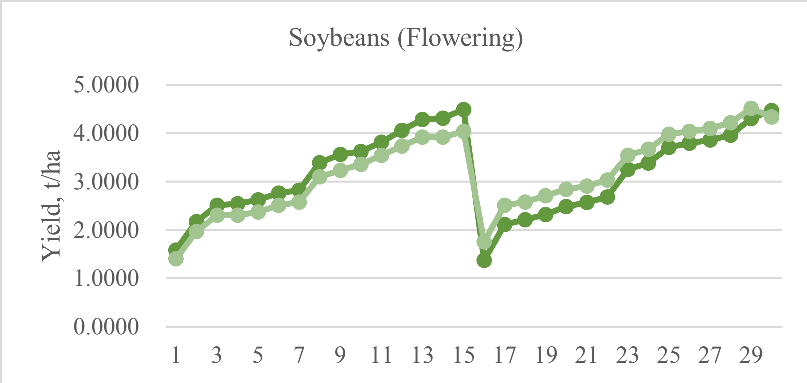
(Green line – actual yield, light-green line – predicted yield)

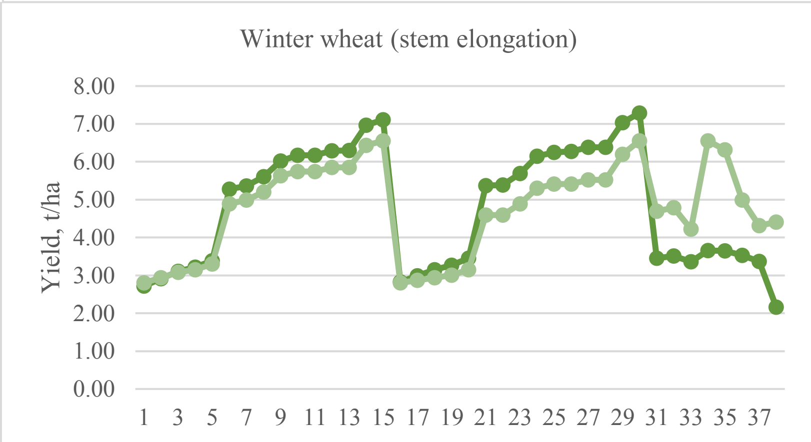


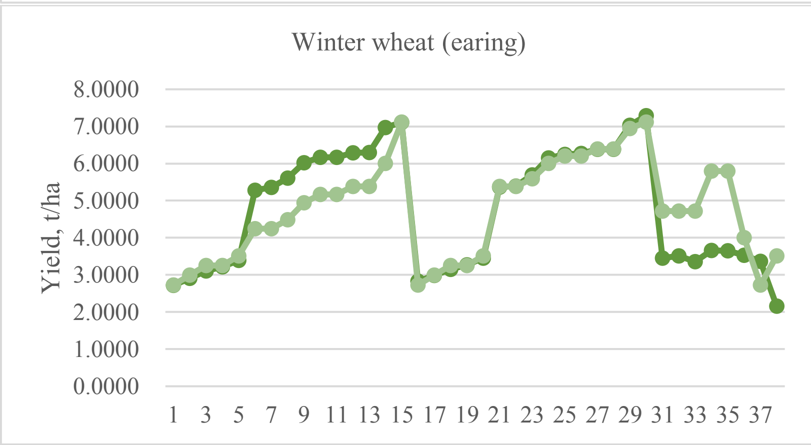




(Green line – actual yield, light-green line – predicted yield)


Soybeans (Flowering)
Yield, t/ha
5.0000
4.0000
3.0000
2.0000
1.0000
0.0000
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29


Winter wheat (stem elongation)
Yield, t/ha
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37


Winter wheat (earing)
Yield, t/ha
8.0000
7.0000
6.0000
5.0000
4.0000
3.0000
2.0000
1.0000
0.0000
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37

Appendix B.6
Average monthly NDVI for the studied crops*

Month	Crop														
	Winter wheat	Winter rapeseed	Winter barley	Chickpeas	Peas	Sunflower	Soybeans	Grain sorghum	Grain corn	Sweet corn	Millet	Tomato	Late tomato	Spring potato	Fallow field
I	0,19 ±0,04	0,10 ±0,10	0,17 ±0,03	–	–	–	–	–	–	–	–	–	–	–	0,13 ±0,08
II	0,26 ±0,06	0,27 ±0,15	0,23 ±0,11	–	–	–	–	–	–	–	–	–	–	–	0,11 ±0,03
III	0,25 ±0,09	0,37 ±0,19	0,38 ±0,15	–	0,18 ±0,09	–	–	–	–	–	–	–	–	–	0,17 ±0,06
IV	0,47 ±0,11	0,51 ±0,17	0,56 ±0,16	0,23 ±0,05	0,43 ±0,14	–	–	–	–	0,31 ±0,01	–	–	–	0,26 ±0,10	0,19 ±0,02
V	**0,57 ±0,12**	**0,56 ±0,16**	**0,58 ±0,10**	**0,61 ±0,11**	**0,65 ±0,08**	0,22 ±0,04	0,26 ±0,12	0,23 ±0,03	0,24 ±0,07	0,33 ±0,08	0,19 ±0,02	0,17 ±0,03	–	0,37 ±0,11	**0,26 ±0,04**
VI	0,44 ±0,14	0,49 ±0,15	0,33 ±0,17	0,50 ±0,25	0,44 ±0,19	0,44 ±0,12	0,33 ±0,12	0,38 ±0,10	0,45 ±0,13	0,45 ±0,05	0,41 ±0,06	0,48 ±0,15	0,16 ±0,03	**0,48 ±0,14**	0,24 ±0,07
VII	0,18 ±0,06	0,20 ±0,04	0,16 ±0,01	0,16 ±0,02	0,18 ±0,06	**0,59 ±0,08**	**0,45 ±0,19**	**0,63 ±0,08**	**0,70 ±0,03**	**0,51 ±0,07**	**0,57 ±0,06**	**0,69 ±0,07**	0,46 ±0,09	0,34 ±0,14	0,18 ±0,05
VIII	–	–	–	–	–	0,46 ±0,12	0,45 ±0,19	0,59 ±0,13	0,57 ±0,13	0,33 ±0,04	0,45 ±0,03	0,49 ±0,21	**0,75 ±0,05**	0,28 ±0,10	0,17 ±0,03
IX	–	–	–	–	–	0,25 ±0,09	0,37 ±0,12	0,38 ±0,16	0,22 ±0,06	–	0,27 ±0,07	0,18 ±0,09	0,69 ±0,07	–	0,16 ±0,03
X	*0,20 ±0,09*	*0,44 ±0,12*	*0,25 ±0,05*	–	–	–	0,17±011	0,13 ±0,11	–	–	–	–	0,29 ±0,20	–	0,13 ±0,04
XI	*0,30 ±0,16*	*0,34 ±0,25*	*0,28 ±0,16*	–	–	–	–	–	–	–	–	–	0,06 ±0,02	–	0,13 ±0,08
XII	*0,13 ±0,04*	*0,20 ±0,10*	*0,13 ±0,04*	–	–	–	–	–	–	–	–	–	–	–	0,14 ±0,08

**Notes*: maximum NDVI values are in bold; the months that were presented by the data of the previous year are in italics; the symbol «–» points that this period is not associated with the crop's growing season and the NDVI value could be referred to that in the fallow field for the corresponding period.

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