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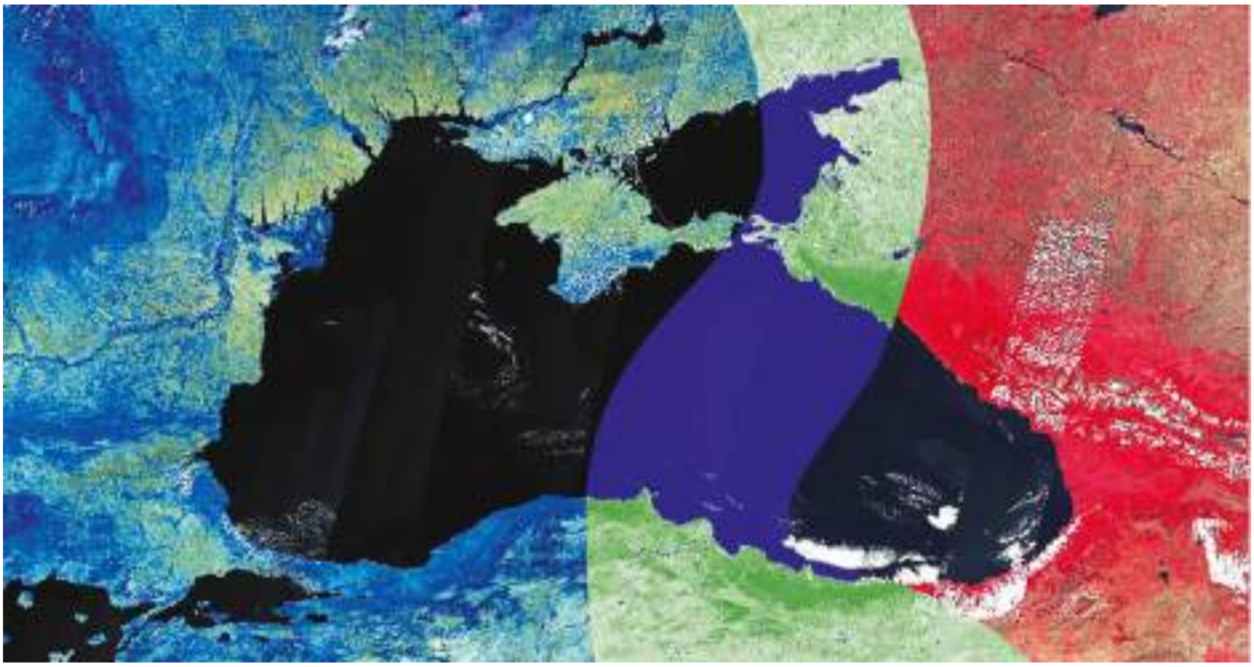

AGRICULTURAL WATER BALANCE, WATER PRODUCTIVITY, AND WATER STRESS INDICES

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INTRODUCTION

It is well known that water scarcity stands as one of the most important limiting factors of agricultural sector optimum production (Zamani et al., 2019; Linker et al., 2016). According to the latest reports, irrigation is accountable for the 51.4% and 59% of the total fresh water consumption in USA and EU respectively (EEA, 2019; Maupin et al., 2014), whilst a further increase up to 30% is expected in the water demand on the agriculture sector by 2030 (Beddington, 2009). Additionally, the impact of the ongoing climate change on the rainfall events severity is expected to result in a substantial loss of water through runoff, deteriorating the status of the groundwater resources, with a parallel increase in the irrigation water requirements by up to 70-90% until 2050 (Resende et al., 2019; Li et al., 2018).

Coastal river deltas and the areas in the broader area around them, serve usually as major places of intensive agriculture exploitation, industry, and commerce (Loucks, 2019). Consequently, the pressure that is imposed to these complex and sensitive areas by the daily human socioeconomic activities, resulted in their degradation by e.g., salinity intrusion in coastal areas (Nguyen et al., 2019; Rahman et al. 2019), leaching of nutrients (nitrogen, phosphorus) (Mai et al., 2010), and pesticides and herbicides substances from the agricultural land into the river delta (Papadopoulou-Mourkidou et al., 2003; Vryzas et al., 2009; Vryzas et al., 2011). Moreover, the climate change extremes and the expected sea-level rise, in combination with coastline erosion impose a further threat to these systems (Loucks, 2019).

Recent studies have showed the potential of crop models to be used as irrigation scheduling tools, contributing to the rational use of the available water resources, securing the agricultural sector sustainability and increase its resilience in the ongoing changes (Tsakmakis et al., 2017; Pereira et al., 2020). However, crop models have an innate certain level of uncertainty, due to the differences among crop cultivars and potential divergence in plants response to different soils and climate conditions. New generations of low-cost and reliable meteorological stations and soil moisture sensors (that can be monitoring the climate conditions and soil moisture almost in real time), in combination with the advances in satellite remote sensing images in terms of temporal and spatial resolution, promise to ameliorate the crop models uncertainty via an operational in season correction and re-adjustment (Tsakmakis et al., 2021).

However, one of the main drawbacks of the crop models is that most of them perform point-based simulations (Tenreiro et al., 2020). This fact renders their value for region level estimations limited. To bridge this gap some researchers proposed and studied the coupling of crop models with hydrological models (e.g., Hydrus) (Siad et al., 2019). Nevertheless, this approach requires a lot of input data to feed into the hydrological model, making its wide implementation difficult. On the other hand, the contemporary developments in remote sensing imagery, allowed the upscaling from single point modeling into regional scale calculations, by exploiting the spatial distribution of vegetation indices (e.g., Normalized Difference Vegetation Index, NDVI) within the region (Bellón et al., 2017; Han et al., 2020). The acquired remote sensing images in combination with in-situ observations and advanced programming technics (e.g., deep learning) allow the production of reliable regional crop maps (Frolking et al., 2002; Kussul et al., 2017; Wardlow and Egbert, 2008).

This deliverable of PONTOS project aims to (a) calculate the water use by the agricultural sector in the study area; (b) calculate and propose water productivity benchmark values for most popular and water demanding crops; and (c) estimate the potential annual water stress level that is induced by the farmers to the crops. The ultimate objective of the proposed methodology is to provide a dynamic, functional tool that could contribute to the rational use of the available water resources from field to watershed level.

In this report, the Ukrainian study area is presented and characterized from agricultural and water balance perspective, as well as the methodology of the study and the results of its application discussed.

1. AGRICULTURAL WATER BALANCE, WATER PRODUCTIVITY, AND WATER STRESS INDICES: KEY DEFINITIONS

Under the European Union's ENI CBC Black Sea Basin Programme "PONTOS", the following work aims to be an introduction of one the most contemporary relevant topics researched in climate change studies: the relationship between water, climate change and crop production. Moreover, this research wants to present to the reader possible methods, models and technologies against climate change, especially related to agriculture and crop production like the *AquaCrop* model developed by FAO. To review all the topics mentioned, this work is characterized by a methodological structure that includes a brief study on water-related terminology (Chapter 1.1) in order to offer to the reader a more accurate understanding of water-related vocabulary and acquire the ability to distinguish the most used terms of water phenomena and climatic situations characterized by limited water availability. In Chapter 1.2 of this research we present a first acquaintance on the relationship between water-issues and their use in the agriculture sector and the impact of climate change on cultivation and productivity. Moreover, modern technological solutions would be analyzed as the *Aquacrop* model from FAO, able to simulate the yield response of herbaceous crops to different weather conditions and is particularly well suited in settings where water is a key limiting factor in crop production. Also, examples of this model application will be provided by analyzing its application in PONTOS Ukrainian pilot area. In conclusion, Chapter 1.3 introduces to the reader the notions of *"mitigation"* and *"adaptation"* related to climate change, actions with the aim to manage climate risks and taking advantage of any positive opportunities that may arise.

1.1 Assessment-related Terminology

In our daily language there are many expressions that want to indicate those phenomena in which there is a negative disproportion between the availability of water for use and the fulfilment of the needs that require a certain amount of it. We read and heard indifferently about drought, water scarcity, water emergency, desertification etc. However, these expressions in technical language are not all synonyms but refer to phenomena that are different in character and etiology. Distinguishing and defining precisely, as far as possible, these terms is not just a mere linguistic exercise, but represents an important prerequisite in order to identify the necessary measures and actions to be implemented to deal with water-related information in a more accurate manner.

In the past decades, the technical-scientific field has developed many indices, studies and methodologies to effectively evaluate water resources vulnerability but there was not created a univocal, universally accepted definition of water-phenomena. For different experts and organisations (Wang et al., 2021; CEO, 2014; Mariani et al., 2018) in order to be able to create a more cooperative and productive research environment, the scientific community should define an essential terminology in order to monitor and assess water-related challenges. This paragraph will present the main definitions for water availability phenomena by analysing and selecting the main technical vocabularies from academic and scientific related literature of high cited publications.

One of the main conceptual debates that a great number of experts (White, 2014; Distefano, 2017; Wang 2021) have noted is that there is no widely accepted definition for "water scarcity", "water stress", and "water risk" terms that are regularly used by the media, government reports, NGOs, international organisations as well as in the academic literature, to highlight areas where water resources are under pressure. Comparing different studies and authors like the CEO Water Mandate (2014), Zingaretti (2013) and Mariani (2018) that were specifically analysing the differences between different water terminology and methodology with the aim of reaching a broad conceptual agreement, this research find that their main definitions of water "scarcity", "stress" and "risk" seem to converge and offer to the reader a reliable understanding of the phenomena. Moreover, to achieve a broader understanding of the main terminology of water-vulnerability terms the concepts of "water consumption", "water withdrawal", "drought", "desertification" and "water footprint" will be explained.

- *Water scarcity*

"Water scarcity" is a condition determined by anthropogenic (Mariani, 2018) or human-driven (CEO, 2014) factors and it refers to the volumetric quantity of freshwater resources and to the function of the volume of human water consumption relative to the volume of water resources in a given area. The "scarcity" term wants to indicate the imbalance that arises from an overuse of water resources, caused by consumption being significantly higher than the natural renewable availability (Schmidt and Benítez, 2013). Also, it indicates the physical abundance of fresh water rather than whether that water is suitable for human use (CEO, 2014). As a matter of fact, a territory that may have abundant water resources and thus not be considered water scarce but, at the same time, have such severe pollution that those supplies are unfit for human or ecological uses.

- *Water stress*

By *"Water stress"* refers to a condition of excessive water withdrawal compared to the natural availability of the renewable water resource therefore, it represents the lack of freshwater for the human and ecological demand. Compared to scarcity, "water stress" is a more inclusive and broader concept because it considers several physical aspects related to water resources, like water availability, water quality, and the accessibility of water (i.e., whether people are able to make use of physically-available water supplies), which is often a function of the sufficiency of infrastructure and the affordability of water, among other things. The particular feature of the water stress concept is that it is assessed differently depending on societal values. For example, societies may have different thresholds for what constitutes sufficiently clean drinking water or the appropriate level of environmental water requirements to be afforded to freshwater ecosystems, and thus assess stress differently (CEO, 2014).

In short, water scarcity is considered as a lack of physical abundance of freshwater resources but without considering whether water is suitable for use, and water stress as a lack of ability to meet human and ecological demand for freshwater, in terms of water quantity and quality and accessibility to water.

- *Water risk*

"Water risk" refers to the possibility for a specific entity (e.g. business, local community, manufacturing chain, government) to experience water-related threats (e.g. flooding, water scarcity, infrastructure decay, drought). The extent of danger is a function of the likelihood of a specific challenge occurring and the severity of the challenge's impact. The main characteristic of water risk is that it is defined and interpreted differently by each sector of society and the organisations within them. Thus is measured at a micro level because its values and characteristics are interpreted differently in every new context it is analysed. Many water-related conditions, such as water shortage, pollution, bad governance, inadequate infrastructure, climate change and others create risks for many sectors and different organisations simultaneously. This condition is also referred to as "shared water risk" (Baleta & Winter, 2017) that suggests that different sectors of society have a common interest in understanding and addressing shared water-related challenges. However, some contest the appropriateness of this term on the basis that risk is felt uniquely and separately by individual entities and is typically not shared, per se (CEO, 2014).

- *How "water scarcity", "water stress", and "water risk" are related one to another:*

"Water scarcity" is an indicator of a problem with water availability where there is a high ratio of water consumption to water resources in a given area, thus is one aspect of many that contribute to and inform *"water stress."* Water availability, water quality, and water accessibility are the three components that are compromised by water stress. Scarcity and stress both directly inform one's understanding of risks due to basin conditions (Schulte, 2014). Companies and organisations cannot gain robust insight into water risk unless they have a firm understanding of the various components of water stress (i.e., availability, quality, accessibility), as well as governance and other non-water-related-stress factors.

- *Different definitions of water scarcity and water stress*

As this work previously mentioned, different studies and researches used the terms "scarcity" and "stress" interchangeably, and one of the objectives of this work is to distinguish their meaning and use. Also, we stressed that there is not a universally agreed definition of "water stress" and "scarcity". Taking into consideration that, the following paragraph has the objective of showing the most highly cited definition of the notion of water stress and scarcity that are summarised in the *Table 1.1* and *1.2* of this section. The criteria of selection is based on the most cited definitions in the academic literature of water-vulnerability topics, which reflects how different authors understand the severity of the water challenges[1], the nature of the challenges[2] and their causal relationship[3].

Table 1.1: Highly quoted definitions and conceptions of "water scarcity"

Who?	Term	Definition	Reference
European Environmental Agency	Water Scarcity	Water scarcity occurs where there are insufficient water resources to satisfy long-term average requirements.	European Environmental Agency
FAO	Water Scarcity	A shortage of water supply of an acceptable quality; low levels of water supply, at a given place and a given time, relative to design supply levels.	FAO AQUASTAT
Water Footprint Network	Blue Water Scarcity	The ratio of blue water footprint to blue water availability where blue water Link availability is equal to natural flows minus environmental water	Water footprint Network

[1] Some existing definitions think of "scarcity" and "stress" as different degrees of the same challenge. For example, under the Falkenmark Indicator, an area is thought to reach water stress when per capita water availability is below 1,700 cubic metres per person per year (based on an estimation of human water requirements), and to have reached scarcity when per capita water availability is below 1,000 cubic metres per person per year (CEO, 2014).

[2] Others think of scarcity and stress as challenges that are distinct in nature (even if slightly) and consider different factors. For example, according to the European Environment Agency, scarcity refers to "long-term water imbalances, combining low water availability with a level of water demand exceeding the supply capacity of the natural system", whereas stress occurs when "the demand for water exceeds the available amount during a certain period or when poor quality restricts its use" (CEO, 2014).

[3] Others conceptualise water stress as the effects of water scarcity. For example, FAO AQUASTAT considers water stress to be "the symptoms of water scarcity or shortage, e.g. widespread, frequent and serious restrictions on use, growing conflict between users and competition for water, declining standards of reliability and service, harvest failures and food insecurity." (CEO, 2014).

		requirements.	
Water Footprint Network	Green Water Scarcity	The ratio of green water footprint to green water availability.	Water footprint Network
Falkenmark indicator	Water scarcity	The fraction of the total annual run-off available for human use.	Global Water Forum
CEO Water Mandate	Water scarcity	The volumetric abundance, or lack thereof, of freshwater resources.	CEO Water Mandate
International Organisation for Standardisation (ISO)	Water scarcity	Extent to which demand for water compares to the replenishment of water in Link an area, e.g. a drainage basin, without taking into account the quality of water.	ISO 14046
International Water Management Institute (IWMI)	Water Scarcity	Approach that includes a critical ratio of countries that are predicted to be unable to meet their water demand without investment in water infrastructure and efficiency as economically water scarce; and countries predicted to be unable to meet their future demand, even with such investment, as physically water scarce.	International Water Management Institute (IWMI)
International Water Management Institute (IWMI)	Water Poverty Index	This approach attempts to take into account the role of income and wealth in determining water scarcity by measuring: the level of access to water; water quantity, quality, and variability; water used for domestic, food, and productive purposes; capacity for water management; and environmental aspects.	Natural Resources Forum (UN)

Table 1.2: Highly quoted definitions and conceptions of “water stress”

Who?	Term	Definition	Reference
European Environmental Agency	Water Stress	Water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use.	European Environmental Agency
FAO	Water Stress	The symptoms of water scarcity or shortage, e.g. widespread, frequent and serious restrictions on use, growing conflict between users and competition for water, declining standards of reliability and service, harvest failures and food insecurity.	FAO AQUASTAT
Vanham, D., et al. (2018)	Blue water stress	The ratio of total fresh water withdrawn by all sectors to the water availability (total renewable freshwater resources minus environmental flow requirements) in a particular country or regíón.	Science of the total environment
Pfister's definition	Water Stress	A logistic function of the ratio of total annual freshwater withdrawals to hydrological availability, and water stress ranges from 0 to 1.	Assessing the Environmental Impacts of Freshwater Consumption in LCA
WRI AQUEDUCT	Baseline water stress	The annual water withdrawals divided by the mean of available blue water. Baseline water stress measures the level of competition for available water, and estimates the degree to which freshwater availability is an ongoing concern.	World Resource Institute

- *Water consumption and withdrawal*

Another component that is essential to provide meaningful information on the relative extent of water "stress" is the difference between water consumption and water withdrawal. With the term *"water withdrawals"* we refer to the volume of freshwater extracted from a surface or groundwater source, without accounting for how much is returned to the freshwater source after use (Kohli et al., 2010). Furthermore, it is important to stress that the water withdrawn rarely returns the source in perfect condition after being used by industry, agriculture, as well as by other users, and the change in quality contributes to raising water impact levels.

With *"water consumption"* we refer to the volume of water that is extracted from a freshwater source and not returned to that source after use (CEO, 2014). Water is consumed due to evaporation or being incorporated into a product. Also, water consumption estimates help measure the impact of water use on downstream water availability and are essential for assessing water shortages and shortages at the river basin level, including impacts and on aquatic ecosystems.

Finally, understanding whether the volume of “withdrawals” exceeds available water resources in a given area, sheds light on whether this is enough water to meet human and ecological demand, thus the usefulness of both “consumption” and “withdrawals” is in understanding the total water “stress”.

- *Drought and Desertification*

Drought and desertification are global environmental problems affecting developed and developing countries. They are accompanied by the reduction in the natural potential of the land, the depletion of surface and groundwater have negative repercussions on the living conditions and the economic development of the people are impacted by it (Abahussain et al., 2002). Drought and desertification processes integrate climatic elements with human activities in transforming productive land, into an ecological impoverished area generally referred to as desert (Olagunju, 2015).

According to the United Nation Convention to Combat Desertification (UNCCD), *“desertification”* is land degradation in arid, semi-arid and humid areas resulting from various factors, including climatic variations and human activities (UNCCD, 2008). The climate affects the chemical and biological deterioration of the soil and conditions water and wind erosion. The state of the soil (texture, structure and chemical and biological properties) is the major vulnerability factor, particularly in the dry sub-humid zones where the influence of climatic factors is less predominant.

With the term “*droughts”* we refer to the natural and temporary meteorological condition in which, for a sufficiently long time and over a large geographical area, a significant reduction in the amount of precipitation happened. This condition determined significant negative effects on the environment and on the economic activities. It is a natural phenomenon linked to the variability of climatic conditions, in particular of precipitation, and can be considered a magnet (Mariani, 2018).

The relations between desertification and drought on the one hand, and human influence on the other, are unknown and complex. Occasional droughts (due to seasonal or inter-year variations in rainfall) and long-term severe droughts can both be caused or aggravated by the influence of man on the environment (the reduction in vegetation cover, the changes in the local climate, the greenhouse effect, etc.). Human activities can, therefore, accelerate desertification and aggravate its negative consequences on people (FAO).

- *Water Footprint: blue, green and grey water*

Other main terms in the quantitative assessment of water security are the concepts of blue, green and grey green water. As noted by different researchers (Wang et al., 2021; Munoz Castillo et al., 2017) still nowadays many studies around water availability don't make any difference if during their analysis they are focusing only on the stress induced by one source of water or they are also considering different forms of water available in that area.

With the term *“blue water”* we refer to water that has been sourced, withdrawn and/or consumed from surface and groundwater resources. Furthermore, blue water is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time (Hoekstra, 2011). Meanwhile, the term *“green water*” refers to water that is stored in the root zone of the soil by precipitation and then evaporated, transpired or incorporated by plants. It is particularly relevant for agricultural, horticultural and forestry products (Hoekstra, 2011), is very important for crop production, the ecosystem and grazing lands. Last, we refer as *"grey water"* to the volume of freshwater that is required to assimilate the load of pollutants in order to meet existing ambient water quality standards.

Moreover, blue, green and grey water are of main importance when we use the *"water footprint"* indicator, which can be considered as a comprehensive indicator of freshwater resources appropriation, next to the traditional and restricted measure of water withdrawal. Its main purpose is the calculation of the volumetric use of freshwater used for the creation of a product over the full supply chain. It's a multidimensional measurement showing water consumption volumes by source and polluted volumes by type of pollution. All components of a total water footprint are specified geographically and temporally. The water footprint indicator offers a better and wider perspective on how a consumer or producer relates to the use of freshwater systems.

The local environmental impact of a certain amount of water consumption and pollution depends on the vulnerability of the local water system and the number of water consumers and polluters that make use of the same system. Water footprint accounts give spatiotemporally explicit information regarding how water is appropriated for various human purposes. They can feed the discussion about sustainable and equitable water use and allocation and also form a good basis for a local assessment of environmental, social and economic impacts.

In general, blue water resources are generally scarcer and have higher opportunity costs than green water, so that may be a reason to focus on accounting the blue water footprint only. However, green water resources are also limited and thus scarce, which gives an argument to account for the green water footprint as well. Besides, green water can be substituted by blue water – and in agriculture the other way around as well – so that a complete picture can be obtained only by accounting for both. The argument for including green water use is that the historical engineering focus on blue water has led to the undervaluation of green water as an important factor of production (Falkenmark, 2003; Rockström, 2001). The idea of the grey water footprint was introduced in order to express water pollution in terms of a volume polluted, so that it can be compared with water consumption, which is also expressed as a volume (Chapagain et al, 2006b; Hoekstra and Chapagain, 2008). If one is interested in water pollution and in comparing the relative claims of water pollution and water consumption on the available water resources, it is relevant to account the grey in addition to the blue water footprint.

- *The Life Cycle Assessment* (LCA) & *The Water Footprint Assessment* (WFA)

The Life Cycle Assessment is an analytical and systematic methodology that evaluates the environmental footprint of a product or service, along its entire life cycle. The calculation ranges in fact from the phases of extraction of the raw materials constituting the product, to its production, its distribution, use and its final disposal, returning the environmental impact values associated with its life cycle. Similarly, through LCA techniques, the environmental footprint of a service can be calculated, accounting for the footprint of everything needed for the provision of that same service. At the end of the calculations, the environmental footprint value of a product/ service is thus returned according to different "impact categories", which represent all the different impacts that this generates in the various environmental sectors (Iyyanki et. al, 2017).

The relevance of LCA techniques lies mainly in their innovative approach, which consists in being able to evaluate all the phases of a production process as related and dependent: among the tools created for the analysis of industrial systems, LCA has therefore taken on an important role in recent years and is growing strongly in terms of national and international technical uses. The water footprint Assessment (WFA) is the fraction of the impacts analysed in the LCA system which are related to water. They include impacts associated with water use, and the subsequent effect on water availability for humans and ecosystems, as well as direct impacts on the water resource and its users from emissions to air, soil and water. These later are quantified using the traditional LCA impact categories (Hoekstra, 2011).

The Water Footprint is a geographically explicit indicator, which indicates not only the volumes of used or polluted water, but also the place where this occurs. The water footprint is an innovative concept that allows you to analyse the water consumption and the pollution phenomena that develop along the production chains, to evaluate the sustainability of water uses and identify where and how can best be done to reduce the use of water.
On the concept of water footprint and on the calculation methodologies introduced by Professor Arjen Hoekstra builds the Water Footprint Network (WFN) a non-profit foundation, established in 2008. This is basically an international dynamic learning network. The WFN proposes itself as a connecting platform for different actors (private sector, non-governmental sector, governments, the United Nations and dissemination centres of the knowledge) interested in sustainability, equity and efficiency in use of water. The application of the concept of virtual water allows us to discover that the water we consume is actually much more than what we see flow before our eyes for domestic uses; most of us
it ignores, in fact, that immense volumes of water are involved in our activities daily, primarily in food production.

- *Conclusion*

The terminology used to refer to different aspects of water challenges has evolved over the past decades like the social and economic demands of our world where water started to be a precious resource, and its quantity and quality is disputed between different users. Water challenges like scarcity and stress are relative and dynamic concepts, and can occur at any level of market supply or civil demand, but they are also social constructs: its causes are all related to human interference with the water cycle. For example, nowadays the focus of water-vulnerability studies link the social demand created by the population growth as a way to measure gaps in water availability (Brown, 2011). Actually, the continuous increase of domestic water withdrawals and demands led to the recognition of the importance of water for ecological sustainability.

Water-related challenges can be expected to intensify with most forms of economic development, but, if correctly identified, many of its causes can be predicted, avoided or mitigated. For example, the next paragraph of this work is going to explore how agriculture and the primary sector can impact the water phenomena, especially water stress and scarcity and the scientific developments to control and manage the impact of agriculture on water vulnerability.

1.2 Agricultural Water Stress

Nowadays, agriculture is the sector where water vulnerability has the greatest relevance, since it accounts for 70% of global freshwater withdrawals and more than 90% of its consumptive use (FAO, 2017). One cause linked to the increasing demand of agricultural products is the fact that in the last decades, world's population has grown very fast, in particular in developing countries where people also started to have new demands on their diet including more variability, more meat and dairy products. This situation is putting additional pressure on water resources (Steduto, 2012) and by different studies of FAO (2009, 2017) it is expected that 60% more food will be needed between now and 2050 to satisfy the demand of an eventual population of more than 9 billion people.

In general terms, agricultural water use is increasing the severity of water scarcity in many areas of the globe, and causing water scarcity even in geographic spaces that are relatively well endowed with water resources. Agriculture, and in particular irrigated agriculture, is undergoing rapid changes and facing both old and new challenges. Farmers across the world have to adapt to a world where trade and globalisation have rapidly increased interconnection and interdependence between people's production and consumption patterns, and where technological progress has boosted agricultural productivity. The green revolution and subsequent progresses in agronomy have helped agricultural production outpace population growth and feed an ever-increasing number of people with ever more diversified food of increasing quality. But it has also come with a large environmental cost (Steduto, 2012).

The current global environmental situation, the diminution of natural water resources, the recent and sudden climate changes are causing an atypical impact on the territory and consequently on the productivity of cultivated plants. The consequence of water vulnerability in agriculture lies in the biological productivity in climatically arid areas that have important consequences like: erosion, soil degradation, salinization, deforestation and loss of biodiversity. Global climate change is a significant factor in the reduction of agricultural productivity causing a decrease in the growth period, extreme meteorological events during the phases of the reproductive cycle, heavy rainfall during planting, heat stress during flowering and long dry periods.

Furthermore, the lack of water can lead to further stress due to the increase in soil salinity which limits the productivity and growth of cultivated plants (Shrivasta, 2015). At a physiological level, plants suffer three main types of damage: osmotic, nutritional and toxic. The first one is linked to the water potential of the soil that causes a reduction in cellular turgor which leads to alteration of metabolic processes and inhibition of growth; The nutritional stress on the other hand, is determined by competition ionic in the processes of absorption at the root level and finally the toxic damage that affects both the functionality of the membrane by altering its permeability and transport; Finally, the enzymatic activities damaging metabolic processes such as photosynthesis and respiration. Therefore, it can be noted that the growth and productivity of crop plants largely depend on their vulnerability to environmental stresses. High salinity, absence of water and high temperatures are the major stressful conditions that limit agricultural production.

Plants respond to these stresses through a set of biochemical and physiological adaptations, involving the functions of many stress-related genes. Any attempt to improve stress tolerance requires a better understanding of fundamental physiological, biochemical and molecular events (Lisar, 2012). In the last decades, various approaches have been tested, for the production of tolerant plants, through the use of classical genetic methods but also by improving cultivation techniques like the Aquacrop Water Productivity Model developed by the Land and Water Division of FAO.

- *Using the AquaCrop for Evaluation of Water Productivity and Stress*

Given the importance of water for agriculture and food production, and the dominant role of agriculture in global water withdrawal, FAO has undertaken a review of its water programme in order to propose a more effective and more strategic response to the growing issue of water scarcity. AquaCrop model simulates yield response to water of herbaceous crops, and is particularly suited to address conditions where water is a key limiting factor in crop production (FAO) and provide advanced methodology for calculation the crop water requirements and the irrigation scheduling. The development of the AquaCrop model has gone through several phases: its conceptual design, its implementation in a software product, the various functional checks, the calibrations and validations in different environments and for different crops, the improvements of the initial algorithms, and the development of a simple and intuitive user interface. The model consists of four modules: climate, soil, crop and management that through an analysis of the AquaCrop software can provide an optimization of the management of the crops, develop an effective irrigation strategy and make comparison and prediction of current and potential yields.

The first module, *climate*, has five input variables: maximum and minimum atmospheric temperature, rainfall, evaporative demand from the atmosphere (ETo), and the average annual concentration of carbon dioxide (CO_2) in the atmosphere. The *soil* module, with its water balance, is configured by the user by indicating up to a maximum of five horizons of variable depth, each with its own texture. Also, the soil profile is explored by the roots, the model calculates the soil water and salt balance. The *crop* module*,* with its development, growth and yield, is represented through its phenology, the growth of the canopy cover (expressed by the percentage of vegetation that cover the soil), the rooting depth, the accumulation of biomass, the harvest index and the final production. Finally, the *management* is expressed through its major agronomic practices such as the control of the field-surface practices (mulching; soil bunds), fertility level, irrigation method and level and fertilisation.

AquaCrop separates soil evaporation from transpiration and simulates the accumulation of biomass over time as a function of transpiration water, using the 'water productivity' (WP) parameter. The model is able to show the main components of the soil–plant–atmosphere and the parameters driving phenology, canopy cover, transpiration, biomass production and final yield. The main features that distinguish AquaCrop from other crop models are:

- the emphasis of the crop response to water with crop-specific parameters;
- the relatively small number of parameters and variables;
- is aimed at practical end-users, it gives particular attention to the fundamental processes involved in crop productivity and in the responses to water, from a physiological and agronomic background perspective.
- the use of the 'water productivity' (WP) values, normalised for atmospheric evaporative demand and of carbon dioxide concentration, that gives to the model a great versatility in being used in different environments and seasons;
- the model is intuitive and maintains an optimal balance between accuracy, simplicity and robustness, and can be used as a planning or management tool;

An important application of AquaCrop is represented by the comparative analysis between obtainable and actual productivity which allows to identify the causes of any difference between the two productivity. Furthermore, the model lends itself very well to prospective studies such as the impact of climate change on crop productivity.

- *AcquaCrop and the impact of climate change*

The impact of climate change on crop production consists of different elements. Some of these can be assessed with the AquaCrop model, while other components require other scientific approaches. Regardless, the impact of climate change on crop production that are assessed using the AquaCrop model are:

- Changes in precipitation;
- Changes in crop water demand due to changes in reference evapotranspiration;
- Changes in crop base & upper temperature;
- Changes in irrigation applications.

Other impacts of climate change on crops that require a more details and expert-view approach are:

- Impact on pest and diseases;

- Impact on weeds.

With the objective to provide a more empirical understanding on how Aquacrop model works against water stress issue in crop productivity in the following section this research will provide some examples on how this model was used in different pilot areas of PONTOS partnership countries (Armenia, Georgia, Greece and Ukraine). The objective of showing the Aquacrop model, being able to adapt its functions and data management under distinct weather and soil conditions and for different crop productions.

- *Aquacrop in Ukraine*

Ukraine is a country in Eastern Europe and it occupies the southwestern portion of the East European Plain. The country consists almost entirely of level plains at an average elevation of 175 m above sea level. Also, it has a coastline along the Black Sea and in the far southeast, Ukraine is separated from Russia by the Kerch Strait, which connects the Sea of Azov to the Black Sea. Mountainous areas such as the Ukrainian Carpathians and Crimean Mountains account for barely 5% of its area. The Ukrainian landscape nevertheless has some diversity: its plains are broken by highlands running in a continuous belt from northwest to southeast as well as by lowlands.

It covers a land area of 603,550 km^2 and a coastline of 2,782 km long with a population of 43.7 mln which make it one of the most populated countries in Europe. The climate in Ukraine is mostly continental, characterised by a moderate warm and humid air coming from the Atlantic Ocean that gives warm, dry summers and fairly severe winters. Precipitation is disproportionately distributed as it is highest in the west and north and lowest close to the Carpathian Mountains, where precipitation reaches 1,200 mm (47 in) per year, while in the east and southeast precipitations are between 500-600 mm. In contrast to the rest of the country, the southern Crimean coast is characterised by a climate similar to the Mediterranean countries with long warm summers and mild rainy winters. Also, Ukraine has an extensive network of rivers, most of which are transboundary.

The landscape of Ukraine consists mostly of fertile steppes and plateaus, crossed by rivers. Agriculture land represents approximately 70% of the total land, of which more than 56% is arable. Flat steppe, rich soil formed by Chernozem made Ukraine an ideal area for agriculture, with agribusiness representing 9.3% of the national GDP and the employment of 14.11% of the population. Traditional crop production includes: field crop cultivation, grass farming, vegetables, fruits and nuts. Grain production is of prime importance in field crop cultivation and is combined with industrial, fodder, vegetable, melon and gourd cultures and potato crops. Within the structure of crop areas, grain crops account for 46.6%; industrial - 11.7%; potato, vegetables, melon and gourd - 6.6%; and fodder crops - 35.1%. Grain production can reach 35-45 million t/year, the major grain crop being winter wheat, followed by barley, maize, rye and oats. Leguminous plants of high protein content include peas, beans, fodder lupine, soy and forage crops. Industrial crops include sugar beet (50% of the total area sown to industrial crops) and sunflower (40%).

In the last decade, the repetition and the duration of hot weather periods caused by climate change in Ukraine increased significantly. The consequences for agriculture will be related to changes in temperature and humidity conditions, but also to the reduction of soil fertility and desertification. As a matter of fact, the drought caused by adverse climatic conditions lead to crop losses in Ukraine that can range from 10 to 70 percent. This phenomenon is especially visible in the Steppe zone in the southern part of Ukraine with coastal borders. This zone is the warmest region of the country with a drought probability of 40–70% and an average annual level of precipitation about 350-540 mm (Krukivska et al., 2021). According to estimations of the scientists, the region undergoes the most significant transformation due to climate change with a rapid growth of thermal resources and the almost unchanging precipitation, annual level and amount in the summer period, which will affect the humidification of the territory and promote an increase in areas and the repeatability of droughts (Fig. 1.1). Future climate risks are: critical decline in yields by the period of 2050; reduction in productivity due to the lack of adequate technical equipment in rapid climate change; the increasing erosion and loss of soil productivity due to the increasing droughts; loss of production capacity as a result of migration processes due to adverse climatic phenomena; increased risk for plants suffering from diseases and pests due to favourable conditions for the active development of many of their pathogens (Krukivska et al., 2021).

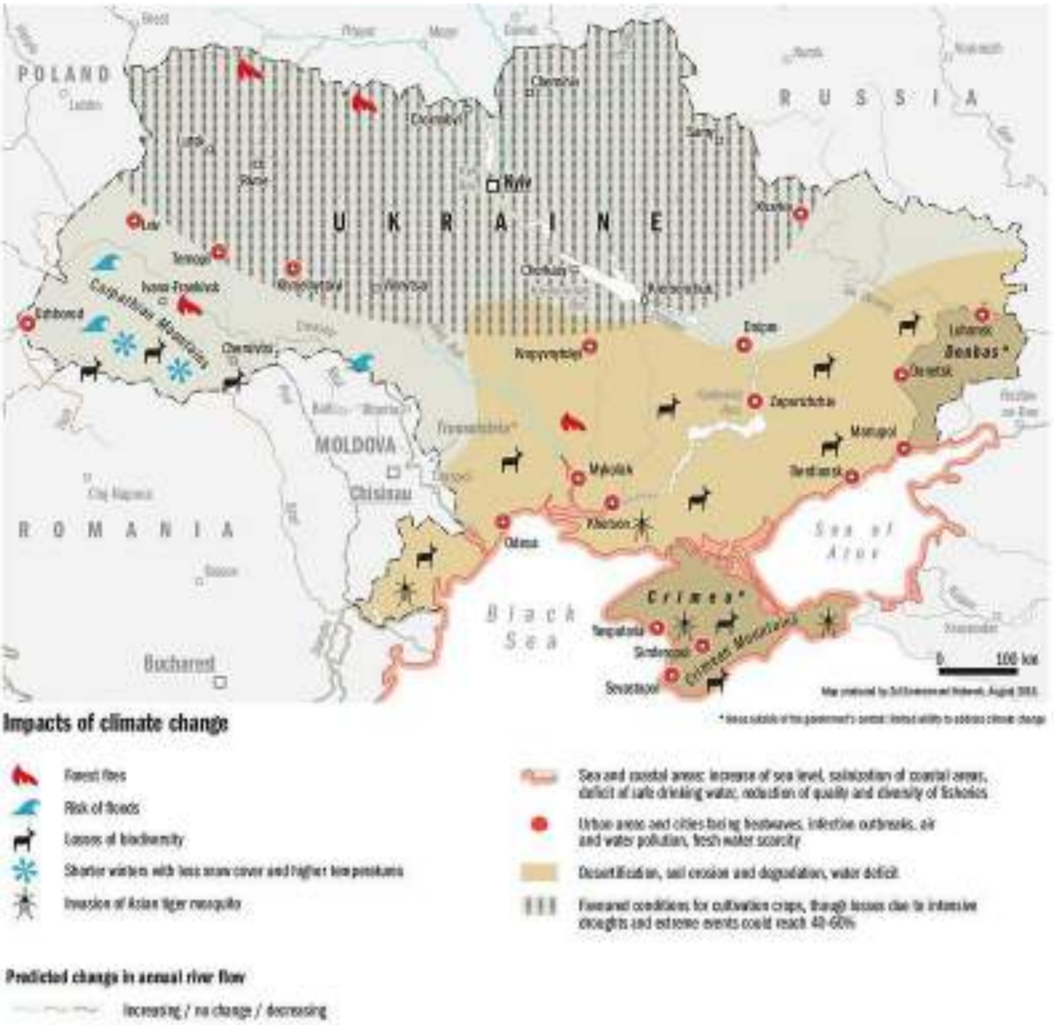


Figure 1.1: Impacts of climate change in Ukraine from Zoï Environment Network

In the Southern Steppe of Ukraine, where vast agriculture production of rice, wheat and sunflower seed is located, according to scientists (Vozhegova, 2014), water scarcity will affect more than 20% of the total area, which is also impacted by reduction in fresh water supplies. For this reason, it was experimented how the use of the Aquacrop model would benefit to precisely control the dynamics of water consumption at the level of the irrigation system in rice fields of that area. In 2017 AquaCrop was able to settle a functional irrigation regime for three rice varieties (Vicont, Premium and Ukraine-96), the adaptation of characteristics of each of the studied rice varieties was performed to enhance seeding and harvesting properties.

The model as usually is formed by four different data modules: the climatic (the include precipitation dynamics, evapotranspiration, temperatures and CO_2 concentration levels), the soil, crop and management data input (that includes information on seeding rates, germination level, distance between rows and plants as well as the number of days of the vegetation season) that automatically calculated the standing density of plants and the initial size of the crop cover (Megrelidze et al., 2021). Other parameters such as the number of days from seeding to germination, the date of formation of the maximum crop cover, the date of "ageing" of the crop cover and the date of full maturity of the crop were created reflecting rice varieties characteristics and duration of flowering. The data of all these modules produce an irrigation strategy and the mode of "automatic generation of irrigation regimes". The main advantage of this model is that the water content in the soils with lowest field moisture and water easily accessible to plants is preserved, while water losses caused by deep infiltration are limited, in this way water stress and crop losses are excluded, which is relevant for rice cultivation. Also, the Aquacrop model thanks to its "Climate-Culture-Soil Moisture" feature that includes the calculation of the optimal amount of biomass and grain yields is able to analyse the highest yields of rice of the different varieties analysed in the fields of Southern Steppe of Ukraine.

The experiment with the Aquacrop model showed that despite using the same irrigation rate for all studied varieties, each had a different yield, amount of biomass and water. The processing of this data had the advantage of controlling water and salt balances of the soil and all the types of stress of the different rice varieties. Stress can be adjusted by increasing or reducing irrigation rates, or by changing the timing and plant density. Finally, the results of the simulation modelling in rice field in Ukraine showed that Aquacrop can offer accuracy and reliability of the developed model for management, modelling and decision-making from the perspective of yield formation of Vicont, Premium, Ukraine-96 rice varieties as well as development of irrigation regimes for effective agricultural production were demonstrated.

Considering the climate change consequences in countries like Ukraine, water is a key limiting factor in crop production and it is necessary to use modern methodologies of agrometeorological research, like Aquacrop, based on numerical multiparameter models while using a wide range of geographic information technologies. At the same time, experts (Vozhegova, 2019; Markovska, 2021) claims that beyond crop modelling, in order to optimise the agriculture sustainability and productivity Ukraine government should encourage the farmers to use new scientific approaches regarding the application of innovative technologies in order to minimise the waste of water, energy, labour and money expenditures, pesticides and consider the location of the root system of crops to determine the optimal irrigation norms, use of solar energy as an alternative energy source, etc.

1.3 Adaptation and Mitigation to Climate Change

We can consider the use of the AquaCrop in the examples analysed in the previous section as actions to fight against climate change and prevent the impacts it causes on the different systems of the planet. *Adaptation* and *Mitigation* measures are popular terms related to climate crisis academic literature and can be considered as actions with the aim to manage climate risks and taking advantage of any positive opportunities that may arise. However, even if these terms are related, their connotation is very different.

With the term "mitigation" we are referring to those actions and measures that are aimed at reducing the extent of climate change, while with "adaptation" we refer to those actions or measures that are based on reducing vulnerability to the effects and impacts of climate change. Therefore, we can consider mitigation as actions that address the causes of climate change, while adaptation´s actions address their impacts. Among the mitigation measures that can be put in place to avoid the increase in polluting emissions are the following:

- Practice energy efficiency;
- Greater use of renewable energies;
- Electrification of industrial processes;
- Implementation of efficient means of transport: electric public transport, bicycle, shared cars, etc;
- Carbon tax and emissions markets.

Regarding adaptation measures, there are several actions that can help reduce the vulnerability to the consequences of climate change:

- Landscape and forest reforestation;
- Creation of more varied crop fields to be prepared against natural disasters that threaten crops;
- Research and development on possible catastrophes, temperature behaviour, etc.;
- Prevention and precautionary measures (evacuation plans, health issues, etc.).

Adaptation and mitigation measures depend greatly on the structural capacity of an affected system, region, or community to cope with the impacts and risks of climate change. For example, the adaptive capacity of communities is determined by their socioeconomic characteristics (Smit and Pilifosova, 2003). It's also important to mention that the impacts of climate change do not affect the entire world population in a homogeneous way. It is considered that those developing countries and those with a low Human Development Index will suffer greater effects, which will affect their Gross Domestic Product. Also, in the same region, country or community, the effects of natural disasters will not have the same repercussions on certain social groups. The territory, socio-economic situation, occupation, age, gender, disability status, health status, educational level, among others; are some variables that could be conditioning inequalities in risk perception, coping actions and responses to extreme events. Research worldwide has revealed the relationship between climate change and poverty, where it has been shown that the poorest populations are the most vulnerable to the effects of natural disasters (Guethón et al., 2019).

Adaptation

Taking actions against climate change requires a long-term inter-sectoral process. When we are analysing the actors in the processes of adaptation and mitigation we should identify which institutions are involved in the process and which is their level of commitment. To get an overview of all the relevant stakeholders in the field of adaptation we should consider not only state institutions but also non-state sectors (as cooperatives and businesses), civil society actors (as non-governmental organisations) and the involvement of the general population. The decisions regarding adaptations can be undertaken at any of several scales, by private individuals, local communities, national governments or international organisations. Where these adaptations are consciously planned activities, whether by public agencies or individuals, there is an interest in assessing the performance or relative merits of alternative measures and strategies. This evaluation can be based on criteria such as costs, benefits, equity, efficiency, and implementability (Smit and Pilifosova, 2003).

A wide variety of adaptation measures can be implemented in response to both observed and anticipated scenarios. The table below shows examples applied for different environmental challenges:

Examples of adaptation measures for agriculture	**Examples of adaptation measures to raise the sea level**
● Efficient management of irrigation water; ● Efficient monitoring and forecast of the weather; ● Change from single-crop to multi-crop farming; ● Use and development of crops that are proved to be resistant to climate	● Effective management and planning of coastlines; ● Protection of coastal wetlands; ● Following building codes and provide well-built building with a strong foundation against floods; ● Effective land-use management;

vulnerabilities and hillnesses; ● Change agriculture production and practice: use multi-cropping and intercropping, adapting new sowing times and use off agroforestry; ● Expansion of arable lands, changes in the geographical distribution of agriculture and management of agriculture´s lands; ● Adoption of new technologies (e.g. GIS).	● Sediment management; ● Creation of barriers that control the seawater intrusion; ● A more sustainable use of water; ● Use of early-warning flood alert systems; ● Encourage fisheries conservation and marine biodiversity protection; ● Disaster risk reduction practices that can help communities adapt to new CC conditions.
Examples of adaptation measures in the water sector	**Examples of adaptation measures in the urban sector**
● Water conservation and demand management (permits, prices and taxes on water); ● Improve water reutilization and recycling; ● Improving the irrigation efficiency; ● Improvement of sustainable and effective water infrastructure; ● Increase the use of rainfed agriculture; ● More cooperation between the institutions and the government in the implementation of the adaptation policies; ● Create more sustainable water extraction techniques; ● Removal of invasive species from water storage; ● Improve the harvesting of rainwater; ● Create effective desalination facilities/techniques.	● Developing heat adaptation strategies: green walls, sidewalk greenways, reduced-albedo sidewalks and street trees; ● Land use planning against pluvial and river flooding; ● Create new sustainable water drainage; ● Heat mapping and thermal imaging; ● Urban biodiversity monitoring; ● Air quality initiatives; ● Implement soil retention strategies; ● Awareness campaigns/education to reduce water use; ● Use of cool pavements; ● Promoting low flow technologies; ● Diversifying power/ energy supplies; ● Incorporating climate change into long-term planning documents.

Furthermore, adaptation measures can be classified into general categories that represent the impact that they can have on a specific context and/or issue:

- ***Modify the threat:*** for some risks, it is possible to exercise a degree of control over the environmental threat itself. When it comes to a "natural" event such as a flood or drought, possible measures include flood control works. For example, one of the main threats of climate change is to find a solution to reduce greenhouse gas emissions and stabilise their concentration in the atmosphere;

- ***Prevent Effects:*** a frequently used group of adaptation measures with the aim to prevent the effects of climate change and variability. In agriculture, e.g., such measures include changes in crop management, such as increase/ decrease of irrigation use and pest control;

- ***Change of use:*** where the continuation of an economic activity becomes impossible or very risky, a change in use can be considered. For example, a farmer can substitute a crop for another more resistant to drought, in the same way, farmland can be reverted to grasslands or wildlife refuges;

- ***Research:*** the adaptation process can also be advanced with research on new technologies and new adaptation methods;

- ***Promote behaviour change through education and information:*** knowledge dissemination through education and information campaigns is a form of adaptation. Such activities have received little recognition in the past, but are now gaining in relevance as the need to involve more people, sectors and groups in the environmental adaptation.

Adaptation Measures Examples

Water Management Adaptation Case: The Tamera Water Retention Landscape in Alentejo (Portugal).
Tamera is a farm of 154 ha located in Alentejo, the most arid region of Portugal. The impact of the climate change in this area is demonstrated by significant trends of increasing erosion and desertification in an area that, only a few decades ago, the streams flowed with water all year round. Nowadays, the streams swell only during the rainy season and afterward they become dry again, this situation is expected to exacerbate since the system has fallen completely out of balance. From 2006 the Tamera farm is developing a “Water Retention Landscape” (WRL) model in order to counteract the desertification process. The WRL model is composed of a system of lakes and other retention systems such as terraces, swales and rotational grazing ponds. The aim of this system is the restoration of the full water cycle: the rain which falls in the WRL area is retained by vegetation or in water bodies and recharges the groundwater, in this way, there is no rainwater runoff. This water management system has created a regenerative basis for autonomous water supply that supports the regeneration of topsoil, forest, pasture, wild fauna and food production.

From 2006 to 2015, 29 lakes and retention spaces were constructed and the area of water bodies was increased from 0.62 ha in 2006 to about 8.32 ha in 2015 (Fig. 1.2). After 2015, the project shifted from the construction of water management bodies to mainly focus on other interventions aiming to support water infiltration, vegetation growing and soil formation, such as swales, planting of ditches, mulching with wood chips and charcoal, and check and maintenance of dams. The main benefit of this project is to reduce the vulnerability to climate change and improve the water management. There are also a large number of co-benefits such as increased carbon storage, increased productivity and diversification of agricultural products, recreational value of lakes, increased biodiversity, increased numbers of visitors due to new water-related events, and improvement in the quality of life of local inhabitants. For example, the area of woodland has increased from 9.34 ha to 19.50 ha mainly in areas previously occupied by natural grasslands. This has led to an overall increase in carbon storage of 9.4% per year between 2006 and 2014 (EEA, 2018).

Figure 1.2: Tamera EcoVillage, Portugal.

Reduction of Urban Heat Stress case: Antwerp´s thermal mappings (Belgium).
In order to understand and tackle the problem of heat stress in its urban areas, the city of Antwerp (Belgium) has commissioned the research organization VITO to create urban maps able to produce reliable scenarios related to temperatures and thermal comfort in the city. VITO applied, under the framework of Copernicus European Health service, the "UrbClim" climate model to map the air temperatures and urban heat island (UHI) extent with a horizontal resolution of 100m (Fig. 1.3).

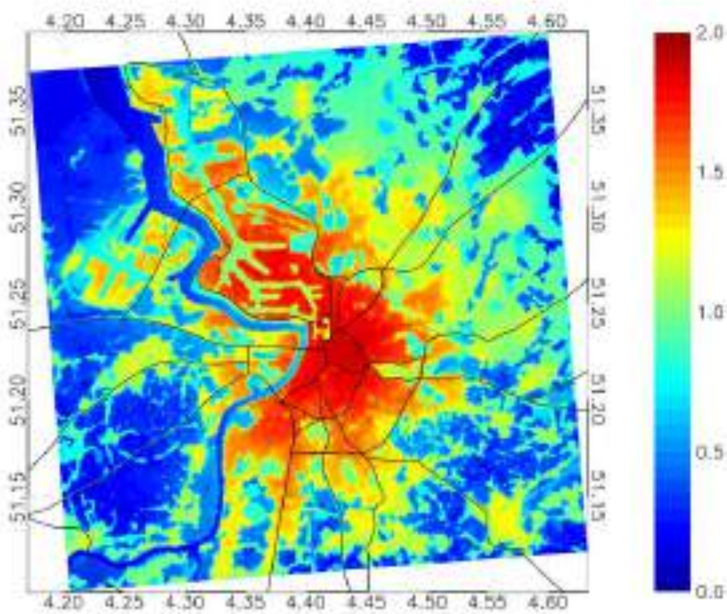


Figure 1.3: Result of VITO's urban climate UrbClim model for the city of Antwerp and its surroundings.

The research results indicate that Antwerp experienced in 2008-2017 twice as many heatwave days (defined as days with a maximum temperature over 30°C and a minimum temperature over 18°C) than the rural surroundings, exposing urban residents to much higher levels of heat stress compared to people living in the nearby rural areas (ClimateAdapt, 2020). To tackle the problem of heat stress in the city, different adaptation measures were created, such as:

- **Creating climate proofing buildings to reduce the local heat stress:** for all new or renovated roofs with a slope of less than 15% and a surface area of more than 20m², it is compulsory to install a green roof on top;

- **Establish early warning systems for climate change adaptation and disaster risk reduction:** such systems are in place to monitor, forecast, and warn people about e.g. tropical cyclones, floods, storms, tsunami, tornadoes, severe thunderstorms, volcanic eruptions, extreme heat and cold, forest fires, drought, etc.;

- **Inform the citizens about the issue and create awareness campaigns;**

- **Improve the monitoring and forecasting systems to minimise the health impacts on the population:** this includes the installation of telemetric network and weather RADARS and the establishment of a monitoring system that provides real-time information on water levels and couples it with data on current precipitation and weather forecasts.

The main impact of the research on heat stress in Antwerp was to raise awareness about this topic at the political level, generating funding and policy initiatives to tackle this problem. In fact, the results of this research were included in the *Antwerp's Climate 2030 plan*, a climate mitigation and adaptation strategy in the framework of the Covenant of Mayors initiative.

Mitigation
Tackling climate change through mitigation is a scientific and political challenge, which requires a high level of trust and cooperation between countries and scientific institutions. Following the OECD's report *"Climate Change Mitigation: Policies and Progress"* (2015), by the year 2050, if the greenhouse gas emissions would not be reduced by 40-70% compared to 2010 levels, terrestrial temperatures would most likely register significantly higher increases, increasing the risk of serious and irreversible effects on ecosystems, having significant impacts on agriculture and human health. National and international mitigation policies were agreed in the last decade by countries and governments, this includes climate change plans, carbon and energy taxation, emission trading systems, renewable energy support policies, regulatory standards and policies to reduce emissions and offer clean energy alternatives.

In order to have a clearer understanding of climate change mitigation policy, it is important to understand that each country has different starting points due to its national social and economic status. In fact, there is a huge variation on the level of gross domestic product (GDP) per capita and the greenhouse gas emissions from country to country. In global terms, if we need to understand from where most of the greenhouse gas emissions come from, we can consider the following sectors:

- **Energy (electricity, heat and transportation)** represent over the 70% of global greenhouse gas emissions;

- **Land use/ land use change, agriculture and forestry** represent the 18.4% (especially livestock and manure animals that produce a high carbon footprint);

- **Direct Industrial Processes** represents the 5.2% of total greenhouse gas emissions, especially in the cement and chemicals production;

- **Wastewater and landfills** produce 3.2% of the total greenhouse gas emissions.

The benefits of climate change mitigation initiatives are not merely related to the protection of the environment but can represent efficient national policy making strategy. Renewable energy and clean energy technology can contribute to a country's energy security, air quality, population health improvement, flood protection, conservation of biodiversity and of the ecosystem. Moreover, in some national cases the effects of the mitigation initiatives could reduce poverty, increase energy access, improve food and water security and promote a sustainable rural economic development.

Mitigation Initiative Examples

National Climate Action Plan (Ireland)

Ireland´s first statutory mitigation strategy has as a main objective the transition to a decarbonised, climate resilient and environmentally sustainable economy by 2050. To support this ongoing work, the Plan also includes over 100 individual actions for various Ministers and public bodies to take forward the mitigation initiative. The document outlines the emissions profiles, policy frameworks and strategies to achieve climate change mitigation at the national level, and in each of the following sectors (GOV.IE, 2017):

- **Decarbonising Electricity Generation:** describes the policy context within which action is being taken in the electricity sector to achieve a low carbon energy by 2050. These measures are complemented by the longer-term policy framework provided by the Energy White Paper Ireland's Transition to a Low Carbon Energy Future;

- **Decarbonising the Built Environment:** focuses on the action being taken to improve energy efficiency and reduce greenhouse gas emissions associated with Ireland's building stock;

- **Decarbonising Transport:** describes the profile of the national transport sector and its multiple objectives within Ireland's economy. As part of the longer term vision for the sector, this National Mitigation Plan sets out an ambition that all new cars and vans sold in Ireland from 2030 will be zero emission capable;

- **An Approach to Carbon Neutrality for Agriculture, Forest and Land Use:** describes the range of actions being taken to advance the long-term vision for this sector of an approach to carbon neutrality which does not compromise capacity for sustainable food production.

Beyond the policies, the Irish government introduced a carbon tax in 2010 that applies to all fuels used in sectors not covered by the Emissions Trading System of the European Union. The tax initially applied to liquid and gaseous fuels at the rate of EUR 15 per tonne of CO_2 and it was extended to solid fuels in 2013. The 2021 budget implemented the government commitment to raise the carbon tax by EUR 7.50 per tonne of CO_2 per year over the decade. This would allow the tax rate to reach EUR 100 per tonne of CO_2 by 2030 (OECD, 2021).

At the same time, the government committed to use the revenue from the carbon tax to prevent fuel poverty, ensure a just transition for displaced workers and finance climate-related investment. In line with this commitment, the government allocated part of the carbon tax revenue to enhance some social welfare schemes in 2021, such as benefits for children and people living alone. This increase is expected to mitigate the impact of the carbon tax on vulnerable households. In addition, some million of carbon tax revenue was allocated to finance the newly established national Just Transition Fund for the Midlands. The Fund provides financial support for retraining workers and for business projects that can generate sustainable jobs in a region that is being affected by the phase out of peat extraction and use (OECD, 2021).

The Air Quality and Climate Change Strategy of the Community of Madrid (2013-2020), ***"Plan Azul+"*** **(Spain)**

Plan Azul+ was a local level strategy aimed at reducing air pollution, helping to mitigate the effect of climate change, and defining adaptation strategies. The main objective was to ensure the quality of the air breathed by Madrid-dwellers. These actions were designed to help turn the city of Madrid into an urban environment characterised by a high quality of life while consolidating a shift in the city towards a sustainable urban model (Ayuntamiento de Madrid). The actions of *Plan Azul+* were characterised by their cross-cutting nature and have been designed with the foremost objective of reducing air pollution while considering other additional elements aimed at effecting a change from a conventional development model to a sustainable one, for example:

- **Road traffic:** reducing the presence of private cars and incorporating new technologies to the city's vehicle pool. Not only will GHG emissions be taken into account but also black carbon emissions from traffic;

- **Residential, commercial and institutional sector (RCI):** energy efficiency, the progressive electrification of energy demand, and generation from renewable sources on a national scale were the main lines of action to achieve the proposed objectives;

- **Other modes of transport:** the reduction of greenhouse gas emissions from the Spanish electricity mix during the Plan's implementation period that would enable indirect emissions of CO_2 to be reduced in railway and metro transport. Meanwhile, AENA (the main society of air traffic management in Spain), had set up a Carbon Management Plan for the period 2016-2021 which aimed to reduce greenhouse gas emissions from airport activities;

- **Waste:** the optimization of the waste collection service, together with other actions focused on reducing consumption and promoting composting on a neighbourhood scale, would reduce emissions associated with this sector.

During the 8-years plan it was achieved a reduction of CO2 equivalent emissions in the transport sector of almost 15% and also, the reduction of global equivalent CO2 emissions of 10% compared to 2005 (Portal Transperencia, 2020).

Even if *Plan Azul+* officially is terminated the review reports suggested for the future local policy makers to reinforce some strategies of the plan and extend it at a national level. Some of the actions that should be reinforced are:

- Promotion of electric mobility, as the main option for the decarbonisation of transport;

- Sustainable governance, that is, the establishment of decision-making processes that take into account the sustainable variable;

- Adaptation Policies to climate change, since it is necessary to know the vulnerability of the different systems and propose the necessary means to enhance their resilience.

Even if good results have been obtained by the *Plan Azul+* strategy, many measures of the plan still need to be reinforced. The long-term effect of the implementation of *Plan Azul+* in Madrid city would bring an appreciable decline in air-pollutant emissions, and would lead to better air quality and remarkable health-related benefits: it´s estimated that more than 500 all-cause premature deaths could be postponed annually (Izquierdo et al., 2020).

1.4 Conclusion

Minimizing and compensating the effects of climate change on our planet is, nowadays, a high priority for contemporary society. Everyone can support and take part in strategies to protect our planet, starting from reducing emissions in your own life, learning about climate change, to supporting climate-smart policies, institutions that are embracing adaptation and mitigation projects. This work aimed to be an introduction to different aspects of climate change: the effects of water vulnerability in agriculture, crop growth technologies, global strategies to solve problems related to climate change. Moreover, strategies of mitigation and adaptation were introduced to the reader, starting from the international *Aquacrop* model against water vulnerability in crop production applied in different countries (who are cooperating under the PONTOS project) to more local initiatives enforced to adapt and mitigate the effect of climate change in urban settings like cities (ex. Madrid and Antwerp) and rural areas (ex. Tamera eco-village). One of the aims of the present research is to raise the reader's interest to learn about strategies against climate change effects in order to support and advocate for smart policies and projects to be applied to our daily life. The final message is that our planet can continue to thrive if we all work together and adapt to our changing world.

2. MATERIALS AND METHODS

2.1 The Ukrainian Pilot area (PONTOS-UA)

The Ukrainian Pilot area is located in the Lower Dniester Basin, covering the Dniester Delta and the adjacent estuary (Southern Ukraine) with a total area of roughly 1800 km2 (Fig. 4), including the Lower Dniester National Nature Park (LDNNP). The Dniester is the largest river in the Western Ukraine and Moldova, draining to the northern shore of the Black Sea along with the Danube, Dniepro and Southern Buh Rivers. Of its total length of 1,380 km, 925 km (68%) lie within the borders of Ukraine and 652 km in Moldova. The area of the Dniester Basin is 72,100 km2, with 52,700 km2 (or 73.1%) being within Ukraine, and 19,400 km2 (26.9%) extending into the territory of Moldova (OSCE, 2005). The Lower Dniester Basin is located within the Black Sea Lowland, consisting of steppe plains. Unlike other sections of the Basin, the topography of this area is one of a gently dipping plain, which has promoted the development of extensive wetland area in the river floodplain, dissected by branches, ancient river beds that are frequently flooded (OSCE, 2005). On the other hand, this character of area topography is considered to be conducive to sedimentation (OSCE, 2005). The hydrographic network of the Lower Dniester Basin is weak (0.2 km/km2). Flow velocities show an increase, from 0.2-0.4 m/s in the deeper sections to 0.5-0.9 m/s in the sandbar sections. The river depths range from 1.6-2.5 m in the bar sections to 4.8 m in the deeper sections, reaching from 10 m to 16 m in some locations. The width of this section of the Dniester River is in the range 100 m to 200 m. The river valley slopes are asymmetrical: the altitudes of the right slope decrease from 150 m to 50 m, whereas the left slope altitudes fall from 70 m to 30 m in the downstream direction. It has precipitous banks with clayey soil, covered with pussy-willow woods, willow bushes and wild grass.

Figure 2.1: Ukrainian pilot area (PONTOS-UA) and the territory occupied by the Lower Dniester National Nature Park (dashed area).

In the arid area of the Lower Dniester Basin, soil structure comprises southern black soil and chestnut soil exhibiting signs of elevated salinity levels (OSCE, 2005). It is noteworthy that approximately 67% of the Dniester Basin area within Ukraine is occupied by agriculture, the majority of which is arable farmland (78% vs. Ukraine's average of 66%).

Figure 2.2: Studied agricultural fields within the PONTOS-UA (sunflower field in 2021 - violet-highlighted; winter wheat field in 2021 – green-highlighted).

The agricultural Pilot fields are located in the vicinity of research station "Petrodolinskoe" (46°27'22.12''N; 30°20'9.94''E), 8 km far from the Dniester river and 27 km southeast of Odesa (Fig. 2.2). The soil is a black soil (FAO definition: Chernozems Vermi-Calcic, CH vec) (Table 2.1), and representative for the south of Ukraine (Medinets et al., 2016). The study fields were under intensive agricultural management for more than 200 years, although a detailed history of the agricultural management is unknown. Before autumn 2006 the area was managed by a 'state collective farm' and then after by different farmer organizations. Over the last years both fields the following crop rotation scheme have been used:

Table 2.1: The physicochemical characteristics of the field sites. Data are averages of 4 measurements per year for the period Dec 2006 – Oct 2009 (after Medinets et al., 2016)

Parameter	1st layer (0-27 cm)		2nd layer (27-44 cm)		3rd layer (44-60 cm)		4th layer (60-74 cm)		Number of observations
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	N
pH	6.96	0.49	7.09	0.41	7.79	0.57	8.48	0.24	33
Bulk density ($g\ cm^{-3}$)	1.29	0.15	1.43	0.05	1.48	0.09	1.53	0.10	33
Clay (%)	59.43	0.04	60.64	0.73	60.90	0.15	55.15	0.24	4
Sand (%)	11.59	0.21	9.10	0.98	11.93	0.23	9.76	0.43	4
Silt (%)	28.98	0.17	30.26	0.39	27.17	0.21	35.09	0.23	4
Moisture (% by volume)	31.13	3.11	33.49	2.64	31.60	3.42	31.21	2.25	33
SOM (%)	3.12	0.23	2.65	0.46	2.04	0.59	1.20	0.46	33
TOC (%)	1.81	0.13	1.53	0.27	1.19	0.34	0.65	0.23	33
Inorganic C (%)	0.01	0.04	0.01	0.04	0.13	0.25	0.90	0.66	27
TN (%)	0.18	0.05	0.17	0.06	0.18	0.10	0.13	0.04	33

The southern areas of the Basin lie within the Black Sea Climatic Sub-Zone, which is part of the Atlantic/Continental Steppe Climatic Region. Winters are usually mild and unstable, with frequent thaws. In springs, the moderately continental air masses gradually transform to tropical ones, with warm and sunny weather settling in May. Annual air humidity pattern is fully synchronized with the temperature pattern, with maximum humidity levels/temperatures recorded in July, and respective minimums in January. Annual precipitation also varies between 400-500 mm in the Lower Dniester Basin (OSCE, 2005). The climate of the study site is temperate continental, with an annual average air temperature of 10.5°C (period of 2000-2014), an annual minimum mean of 8.4°C and an annual maximum mean of 12.5°C; total average annual precipitation is 432 mm (Medinets et al., 2016).

2.2 In-situ measurements and sampling

A combination of historical and measured in the framework of the PONTOS project datasets was used as an input data for modelling in this assessment. Own historical in-situ data on agro-meteorology and physicochemical properties of soil retrieved within previous national and EU projects were utilized. Within this assessment we have also conducted site-specific measurements of agro-meteorological parameters.

Due to the synergy between projects (namely UNEP-GEF Torads INMS and EU-funded PONTOS) we managed to install the Automatic Weather Station GrowPro, Davis Inc. (Fig. 2.3) in the sunflower field to measure wind speed & direction, evapotranspiration (ETO), air temperature, precipitation amount from June 2021 to July 2022 as well as soil temperature & moisture loggers TOMST with a resolution of 15 min at 3 soil layers (0-12cm, 30 and 50 cm) in both studied fields (Fig. 2.4).

Figure 2.3: Automatic Weather Station GrowPro (Davis Inc.) installed in PONTOS-UA and real-time Weather Link application.

Figure 2.4: Soil temperature & moisture loggers TOMST installed in sunflower and winter wheat fields within the PONTOS-UA pilot.

Aquatic vegetation sampling and analysis

We sampled the three representative plots in two studied fields at crop maturity stages in 2021 within the PONTOS project. We used a 50x50 cm plastic frame upon crop sampling to extract the vegetation biomass inserted in the frame area. Further on, the samples were qualitatively and quantitatively analysed in the ONU's laboratory. Plant quantity, fresh (wet) biomass and dry biomass of total plants, its vegetation parts and seeds following drying out at 80°C in an oven were measured in the samples.

2.3 Remote sensing measurements

Air-born mapping and data processing

Within the PONTOS project the ONU conducted a regular mapping of crop development on the studied fields using the unmanned aerial vehicles (UAVs) over 2021. Two types of UAVs were used: i) DJI Phantom 4 Pro v.2.0 with RGB sensor (1" CMOS with effective pixels 20 MP), purchased by the ONU within the PONTOS project, and ii) DJI Phantom 4 Multispectral equipped with 6 sensors (VisRGB, Blue: 450 nm ± 16 nm; Green: 560 nm ± 16 nm; Red: 650 nm ± 16 nm; Red edge: 730 nm ± 16 nm; Near-infrared: 840 nm ± 26 nm; each having 1/2.9" CMOS with effective pixels 2.08 MP).

Free software was used for high resolution mapping: 1) DJI GS Pro on Mac OS for the Multispectral UAV and 2) DJI Pilot on Android for the RGB UAV. The operational height of flight during mapping was set on 120 m above the ground for the RGB UAV and 50 m for the Multispectral UAV to get an accurate set of high resolution georeferenced images of the agricultural fields. The retrieved sets of images were pre-processed to combine into corresponding orthophotomosaics using the specific software Pix4Dmapper, purchased by the ONU within the PONTOS project. Further on the Normalized Difference Vegetation Index (NDVI) were calculated in processed orthophotomosaics according to the equation:

$$NDVI = (NIR - R) / (NIR + R)$$

where R is red spectrum and NIR is near infrared red spectrum.

Space-born data processing

The Sentinel Hub was used to retrieve Sentinel-2 satellite images and calculate NDVI values for selected fields at selected dates.

2.4 Modeling

In this study we used a highly reliable and constantly upgrading free AquaCrop model developed by the Food and Agriculture Organization of the United Nations (FAO), which can simulate crop growing cycle, water balance, biomass accumulation and crop yield production (FAO, 2022). The official Aquacrop web-page (FAO, 2022) says: "AquaCrop is a crop growth model developed by the Land and Water Division of FAO to address food security and to assess the effect of environment and management on crop production. AquaCrop simulates yield response to water of herbaceous crops, and is particularly suited to address conditions where water is a key limiting factor in crop production. When designing the model, an optimum balance between simplicity, accuracy and robustness was pursued. To be widely applicable AquaCrop uses only a relatively small number of explicit parameters and mostly-intuitive input-variables requiring simple methods for their determination. On the other hand, the calculation procedures is grounded on basic and often complex biophysical processes to guarantee an accurate simulation of the response of the crop in the plant-soil system". This model can be used as a planning tool and to assist management decisions in both irrigated and rainfed agriculture. AquaCrop is particularly useful for:

- understanding crop responses to environmental change (i.e. as an educational tool)
- comparing attainable and actual yields in fields, farms and regions
- identifying constraints to crop production and water productivity (e.g. as a benchmarking tool)

- developing irrigation schedules for maximum production (e.g. seasonal strategies and operational decision-making, and for climate scenarios)
- developing strategies under water-deficit conditions to maximize water productivity through:
- irrigation strategies (e.g. deficit irrigation)
- crop and management practices (e.g. adjusting planting dates, cultivar selection, fertilization management, the use of mulches, and rainwater harvesting)
- studying the effect of climate change on food production (for example by running AquaCrop with both historical and future weather conditions)
- analysing scenarios useful for water administrators and managers, economists, policy analysts and scientists (i.e. planning purposes)
- supporting decision-making on water allocations and other water policies.

Certainly, the Aquacrop has some limitations:

- AquaCrop can simulate daily biomass production and final crop yields for herbaceous crops with single growth cycles only.

- AquaCrop is designed to predict crop yields at the single field scale (point simulations). The field is assumed to be uniform without spatial differences in crop development, transpiration, soil characteristics or management.

- Only vertical incoming (rainfall, irrigation and capillary rise) and outgoing (evaporation, transpiration and deep percolation) water fluxes are considered.

AquaCrop uses a relative small number of explicit parameters and largely intuitive input variables that are either widely available or can be determined using simple methods. Inputs consist of weather data, crop and soil characteristics, and management practices that define the environment in which the crop will develop. Soil characteristics are divided into soil profile and groundwater characteristics, and management practices are categorized as field management or irrigation management practices (Fig. 2.5).

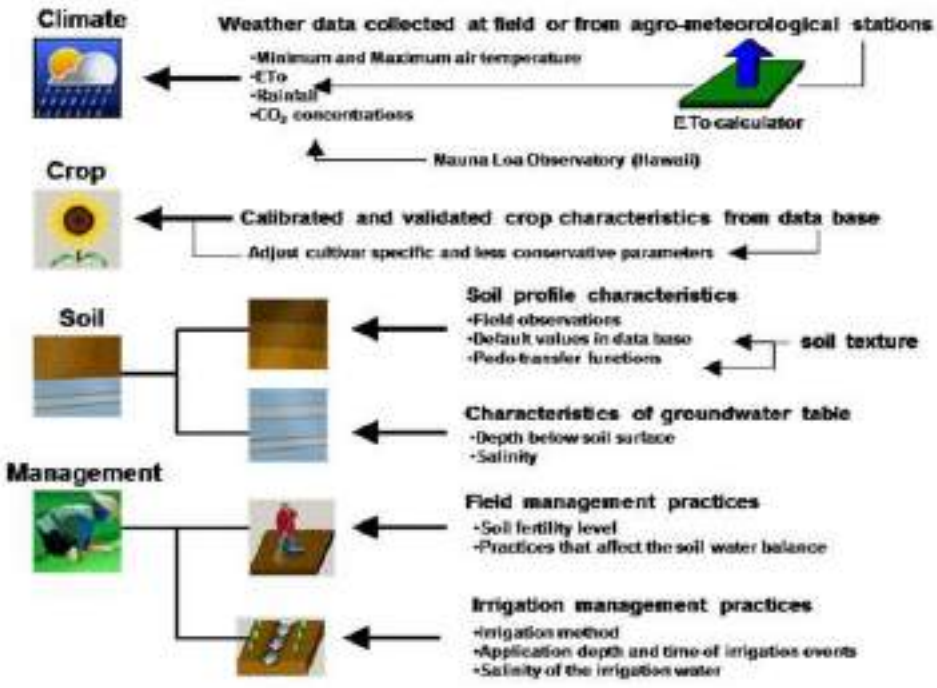


Figure 2.5: Classified input parameters required for Aquacrop model run (FAO, 2022)

However, to increase the credibility of model results especially on accurate estimation of water use, balance and stress indexes taking into account spatiotemporal heterogeneity of soil water contents, the in-situ soil water content monitoring in the soil profile within a corresponding field/ area is required (Linker et al., 2018; Tsakmakis et al., 2019).

3. PRODUCTIVE MOISTURE CONTENT IN AGRICULTURAL LANDS UNDER CLIMATIC CHANGES

Study of agro-climatic conditions of winter wheat cultivation and the tendencies in climate changes have been performed using the indicators observed daily at the meteorological post of Odesa State Agriculture Research Station (Odesa SARS) from 1970 to 2021 (air temperature, total rainfall, number of days with precipitation, gradation of precipitation). To determine the weather conditions influence on the winter wheat yields, the results received by Odesa SARS in the course of a long-term agrochemical stationary experiment carried out in 1973-2021 were used.

3.1 Changes of the Black Sea Steppe Climate Conditions

The climate of the Black Sea steppe is characterized by a natural deficit and extreme unevenness of rainfall. With an average annual rainfall of 478 mm, the fluctuation range is from 250 to 700 mm. Lack of precipitation in combination with high air temperatures leads to the occurrence of air and soil droughts, which significantly reduce and sometimes practically destroy the harvest when combined, as it has happened in 2003, 2007, and 2020.

Our analysis of climate indicators showed that there was a long period of warming in the Black Sea Steppe area, starting from 1999 (Fig. 3.1). During the entire cycle of analysis, two air temperature formation periods (T,°C) were singled out: period I (1970–1998) – stable cyclical formation (T=9.9 °C); period II (1999–2020) is a positive trendocyclic formation (T=11.9 °C) (Fig. 3.1); in general, for the period 1970-2020, the average annual air temperature was 10.7 °C. Thus, during 1999 - 2020, the average annual temperature increased by 1.2°C.

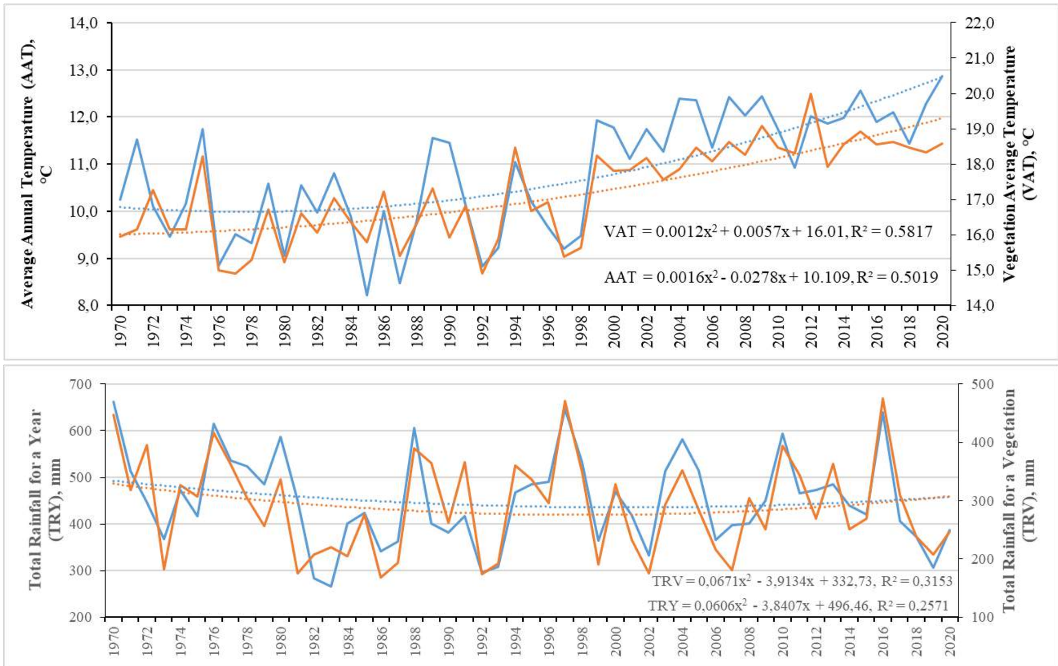


Figure 3.1: Long-term dynamics of air temperature (a) and atmospheric precipitation (b) (meteorological post of Odesa SARS, 1970 – 2020).

Since 2000, the average air temperature in Odesa Region was consistently higher than the climatic norm every year, its anomalies ranged from 0.8°C to 2.7°C (Fig. 3.2). This phenomenon was noted by climatologists throughout the territory of Ukraine (Balabukh, 2010, Vozhegova et al., 2021, Balabukh et al., 2014).

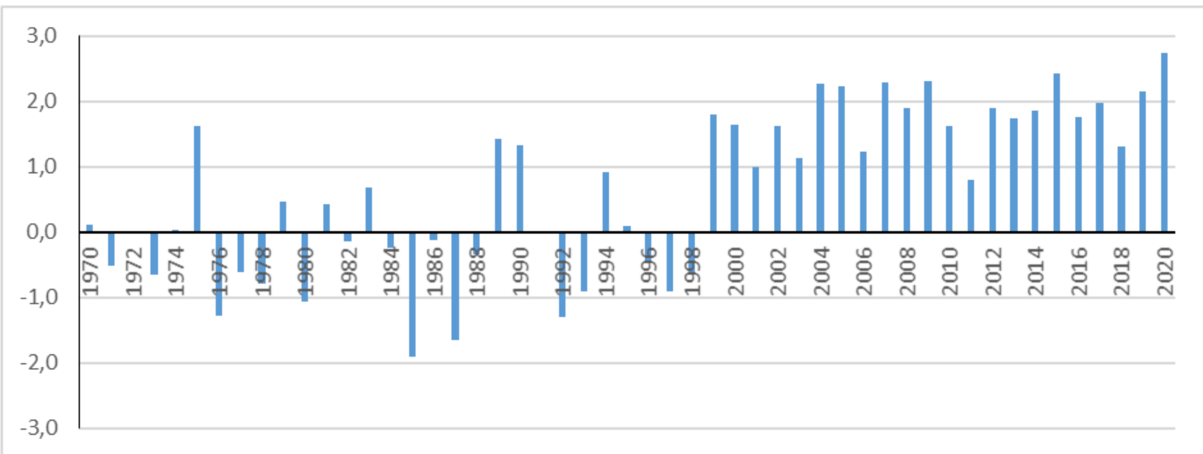


Figure 3.2: Anomalies of the average annual air temperature in the Black Sea Steppe for the period 1970–2020 relative to the climatic norm of 1961–1990.

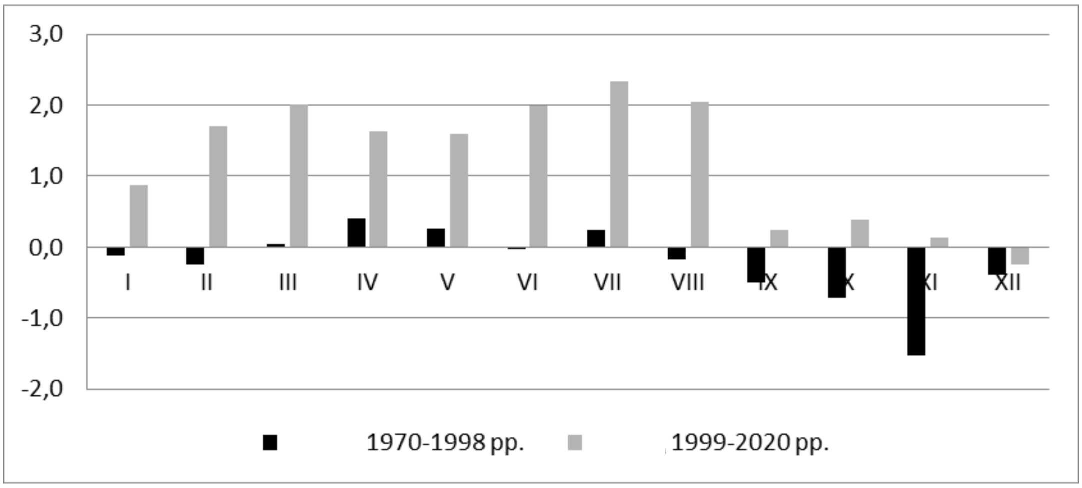


Figure 3.3: Anomalies of average monthly air temperatures (°C) relative to climatic norm of 1961–1990.

Average indicators of the thermal regime for a year are formed by average monthly temperatures, and almost all months of the calendar year (Fig. 3.3) starting from 2000 are characterized by growth compared to the climatic norm. The largest deviations from the norm were noted in February and the spring and summer months. In the period from 1970 to 1998 there was a slight increase in temperatures from III to VIII months. It should be noted that the average January temperature over a 51-year period increased from (-2.1°C) in 1970–1987 to (-0.8°C) in 1988–2020, and the average July temperature grew from 21.5 to 23.7°C.

During the period of long-term total rainfall (O) observations the norm was 456.8 mm (Fig. 3.1). We singled out 3 main cyclic time periods of formation: period I (1970-1980) - significant maximum variation deviations at the beginning of the period and a negative trend component at the end of the period, in most cases (73%) the values were higher than the norm (mean O = 511.3 mm, max O = 662.2 mm, min O = 368.3 mm); period II (1981-1993) – a negative trend component, in most cases the values (75%) were below the norm (mean O = 384.8 mm, max O = 605.6 mm, min O = 266.4 mm); period III (1994-2020) showed a slight stabilization of precipitation, in 56% the values were higher than the norm and there was a positive trend component at the end of the period (mean O = 454.6 mm, max O = 646.4 mm, min O = 332.3 mm).

There are no significant changes in precipitation relative to the climatic norm, there is a redistribution of the amount of precipitation in some months and seasons. The same pattern is also observed all over Ukraine (Morozov et al., 2012; Kulbida et al., 2013). As it can be seen from the diagram (Fig. 3.4), a positive trend in the amount of precipitation per day of the rainy period was revealed. However, analysis of the number of days with precipitation showed a sharp decrease over the past 29 years from 86.2 days (1970–1992) to 61.5 days (1993–2020).

Statistical analysis of precipitation and its quality during the winter wheat growing season during the 51-year cycle of observations is presented in Table 3.1. The average amount of precipitation during the growing season was 450.8 mm with a probability of 70.6%. The average number of days with precipitation and their distribution according to gradation had a high degree of reliability.

Table 3.1: Results of Statistical Processing of Water Availability During the Winter Wheat Vegetative Season in 1971–2021.

Indicator		Total precipitation, mm	Number of days with precipitation, total	Days acc. To precipitation gradation, % of total quantity						mm/ day
				<1 mm	1-4.9mm	5.0-9.9mm	10.0-19.9	≥20 mm	≥50 mm	
Medium		450.8	72.1	21.4	38.0	20.8	13.5	5.4	0.9	6.65
Minimal		232.5	30	0	20.8	6.2	4.9	0	0	3.1
Maximal		671.1	111	56.1	58.6	38.3	28.9	24.0	5.3	17.65
Standard error		14.6	2.7	1.9	1.2	1.1	0.8	0.6	0.16	0.37
Standard deviation		104.6	19.4	13.3	8.7	7.6	5.6	4.1	1.14	2.63
Kurtosis		-0.38	-0.14	-0.29	-0.02	0.01	-0.24	7.09	3.21	6.6
Skewness		0.02	-0.08	0.41	-0.06	0.61	0.47	2.11	1.54	2.1
Probability level	%	70.6	81.2	89.1	97.5	94.1	95.9	97.8	99.5	99.3
	degree	probable			very probable					

Unproductive precipitation of less than 5 mm of rainfall at a time accounted on average for 59.4% of the total; 5 to 19.9 mm - 34.3%, and more than 20 mm - 6.3%, including those over 50 mm - less than one percent (0.9%).

At the same time, the asymmetry that characterizes the density of distribution in relation to the average distribution has mostly small values, except for precipitation indicators of more than 20 and 50 mm and the amount of precipitation per day in the rainy period (Fig. 3.4). The positive skewness in the distribution of these indicators over the years indicates the expansion of its right branch, that is, their numerical values increase over the years.

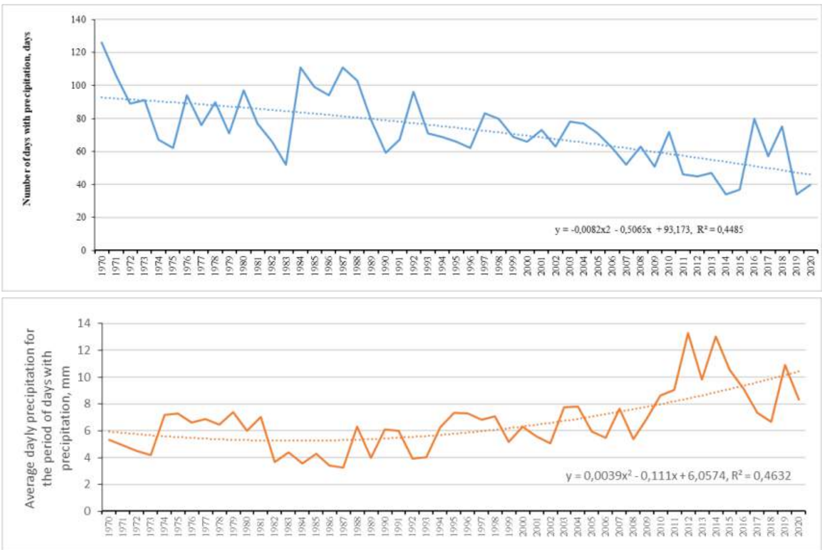


Figure 3.4: Long-term dynamics of precipitation days (top) and the mean daily precipitation for precipitation days (bottom) according to the meteorological post of Odesa SARS (1970 – 2020).

3.2. Agro-Climatic Conditions of Winter Wheat Cultivation

Global climatic change entail the changes in crop cultivation conditions (Balabukh et al., 2013; Khakhula, 2013; Lukaschuk, 2012). Systematization and assessment of provision with moisture of winter wheat vegetative cycle decade after decade (Fig. 5) enabled us to reveal the tendencies in the changes that were taking place more precisely. Thus, the average ten-year amount of precipitation varied within a fairly narrow range from 494.5 mm to 457.0 mm, while the total number of rainy days at the beginning of the 21st century decreased by 20 days, and in the last decade amounted to 53 days only (Fig. 3.5a).

The number of days with precipitation below 1 mm decreased significantly: from 25.3% (1971-1980) to 7.8% (2011-2021); the share of precipitation from 1 to 5 mm remained practically at the same level (39.4-38.2%) with small fluctuations. The percentage of days with 5-9.9 mm and 10-19.9 mm precipitation increased in the last of the analyzed periods to 25.5% and 18.7% respectively against 16.0% and 13.1%. Against the background of a sharp decrease in the number of days with precipitation during the vegetative season, the share of days when more than 20 mm fell at one time increased (from 5.5 to 8.9%), as well as that of days with more than 50 mm (from 0.7% to 1.4%).

Since 2000, in most years (20 out of 22 or 91%) the winter wheat vegetative period included 70 to 38 days with precipitation (Table 3.2), among which precipitation up to 5.0 mm was from 58.5 to 39.1%, while before the number of rainy days exceeded 70 and reached 107 during 26 out of 29 years (89.7%), and the share of days with precipitation up to 5 mm varied from 73.3 to 80.8%.

Table 3.2: Structure of Years by Precipitation Regime Characteristics During Winter Wheat Vegetative Seasons

1971-1999 n=29		2000-2021 n=22		Total precipitation, mm	Total number of days with precipitation	Days acc. To gradation of precipitation, % of the total						mm/day of rainy period
quantity	%*	quantity	%*			<1 mm	1-4.9 mm	5.0-9.9 mm	10.0-19.9	≥20 mm	≥50 mm	
5	9.8	0	0	457.4	107	41.3	32.0	14.3	9.2	2.5	0.7	4.6
9	17.7	1	2.0	514.4	84	25.2	36.5	17.4	14.8	5.4	0.6	6.0
3	5.9	1	2.0	340.9	88	41.1	39.7	13.9	7.7	2.3	0	4.9
9	17.6	11	21.6	470.1	70	17.0	41.5	21.1	13.9	5.5	1.0	6.7
3	5.9	3	5.9	420.5	54	14.9	36.9	25.6	14.7	6.9	1.0	7.9
0	0	6	11.6	378.9	38	6.1	33.0	31.2	19.2	8.7	1.8	9.4

*% of the total sum of the sampling

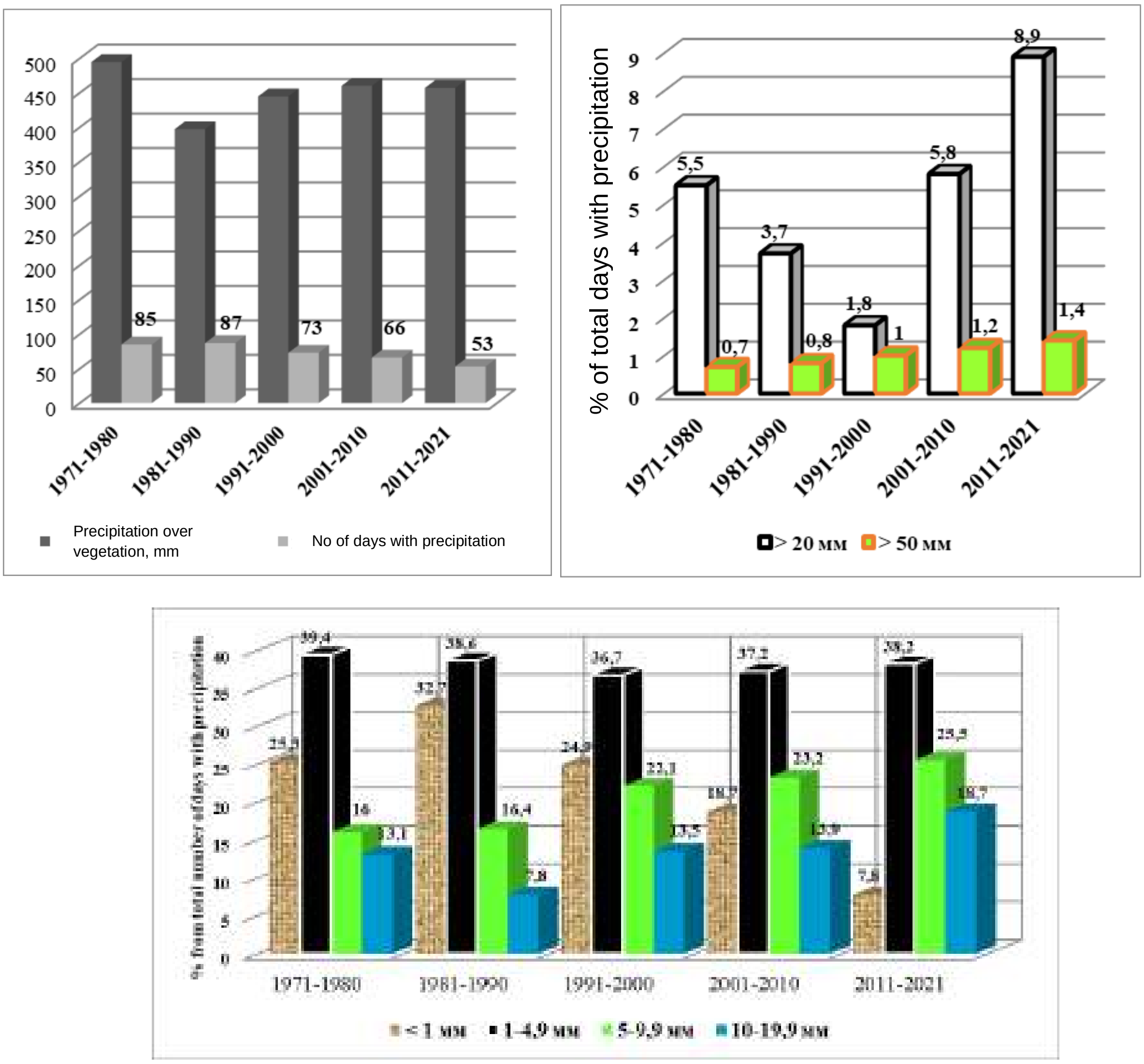


Figure 3.5: Analysis of number and structure of precipitation for decades of winter wheat vegetative periods.

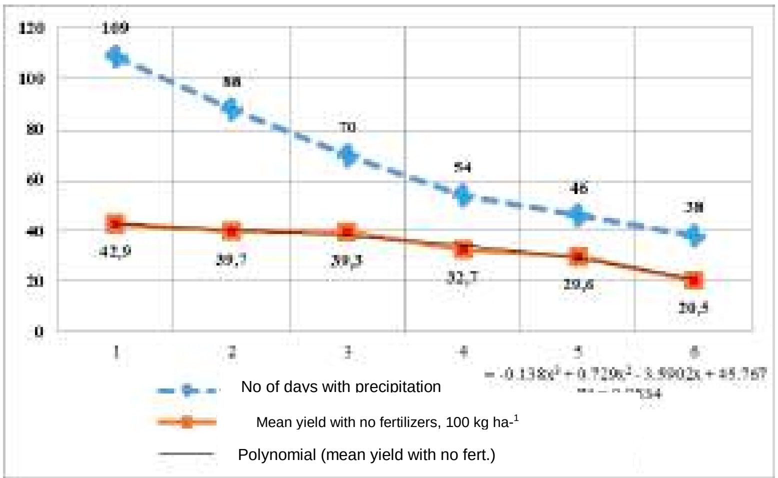


Figure 3.6: Winter wheat yield without fertilizers application and total number of rainy days in growing season.

Winter wheat yield without fertilization demonstrated high dependence on the quantity of days with precipitation: the determination coefficient was equal to 0.98 (Fig. 3.6). At the same time the gain in grain yield when the fertilizers were applied had medium scale inverse dependence on this parameter (r=-0.56) (Table 3.3): the bigger the number of rainy days during the growing period, the lower was the gain compared to the control field where no fertilizers were applied. The size of gain in yield varied within broad limits from 2.8 to 13.0 centners per hectare.

The correlation analysis (Table 3.3) proved the main tendencies of meteorological factor influence on winter wheat productivity and yield gain formation due to fertilizers. Presence of the reverse connection between yield gain and the share of days with non-productive (up to 5 mm) precipitation (R=-0.72) and the direct connection with the number of days with precipitation (r=0.73-0.76). Factor analysis result has shown that the input of natural fertility into the winter wheat yield gain formation under the conditions of the Black Sea Steppe is 13.7%, the input of fertilizers is 52.1, and the share of integrated input of weather conditions vary from 25.1 to 30.9%.

Table 3.3: Pair correlation coefficients between winter wheat yield gain and the indicators of provision with moisture during vegetative period.

Indicator	R	R^2
Yield gain – precipitation during vegetative period	0.64	0.410
Yield gain – number of days with precipitation	-0.56	0.314
Yield gain – % of days with precipitation <1 mm	-0.61	0.372
Yield gain – % of days with precipitation of 1-4.9 mm	-0.72	0.518
Yield gain – % of days with precipitation of 5-9.9 mm	0.56	0.314
Yield gain – % of days with precipitation of 10-19.9 mm	0.76	0.578
Yield gain – % of days with precipitation ≥20 mm	0.73	0.533
Yield gain – % of days with precipitation ≥50 mm	0.76	0.578
Yield gain – mm/day	0.80	0.640

3.3 Dynamics of Productive Moisture Supply for Winter Wheat and its Yield

Precipitation and temperature regime indicate the supply of productive moisture in soil, which influence significantly the productiveness of a crop.

As is known, water is part of living organisms, which takes part in almost every process related to plants development. Water is one of the most important biophysical reagents in soil formation, especially in the formation of soil fertility, the significance of which is comparable, according to the definition of H.M. Vysotskyi, only with the blood of a living organism. The amount of water reaching the land surface is measured in mm of water layer: 1 mm of precipitation per hectare corresponds to 10 tons of water. To create 1 g of dry matter, plants need from 200 to 1000 g of water. So, to generate 400-500 tons of dry matter, plants need 40-50 thousand tons of water or at least 400-500 mm of precipitation per vegetative season.

A decrease in soil moisture is observed in the Black Sea Steppe zone against the background of climatic changes, especially during the period of winter crops sowing, as well as from the restoration of vegetation to the beginning of grain filling. As our observations have shown, in the last 10-15 years the one-meter layer of the soil is reaching a moisture reserve level satisfactory for Chornozems (black soils), which is 147-155 mm, only in spring, when the vegetation resumes.

However, during the steam elongation period the moisture reserve is mainly at the level of 31 to 112 mm, which corresponds to unsatisfactory and is a critical shortage (Tkachenko, 2015). As an example, the dynamics of productive moisture reserves under the winter crops in the 2020–2021 agricultural year is presented, when the moisture reserve during the entire autumn period, both in the topsoil (0-20 cm) and in the meter-deep layer, was practically "dead", and therefore wheat seedlings sprouted only in January. During all other development stages they also did not reach the level of satisfactory content.

Table 3.4: Productive Moisture Content Dynamics in the Meter-Deep Soil Layer under Winter Wheat.

Soil layer, cm	02.10. 2020	04.11. 2020	15.03 2021	01.04.2021	22.04. 2021	08.06.2021	30.06. 2021
0-10	0	0	15.4	16.0	15.6	14.0	7.9
0-20	0	1.4	30.7	32.6	31.8	28.9	16.2
0-50	0.8	9.0	70.6	74.1	70.7	65.3	27.7
0-100	2.0	1.0	130.1	139.0	131.7	122.5	48.9

Analysis of precipitation in 2020 had shown an insufficient quantity or zero precipitation during most period of winter crops' active vegetation, which told negatively upon the yield.

Thus, the average yield of winter wheat after the forecrops fluctuated within the limits that did not correspond to the classical idea about the quality of the forecrops: the yield after peas was 16.3 centners/ha, after corn – 18.3 centners/ha, after sunflower – 11.2 centners/ha, and after stubble considered to be the worst predecessor - 19.0 centners/ha. (Fig. 3.7).

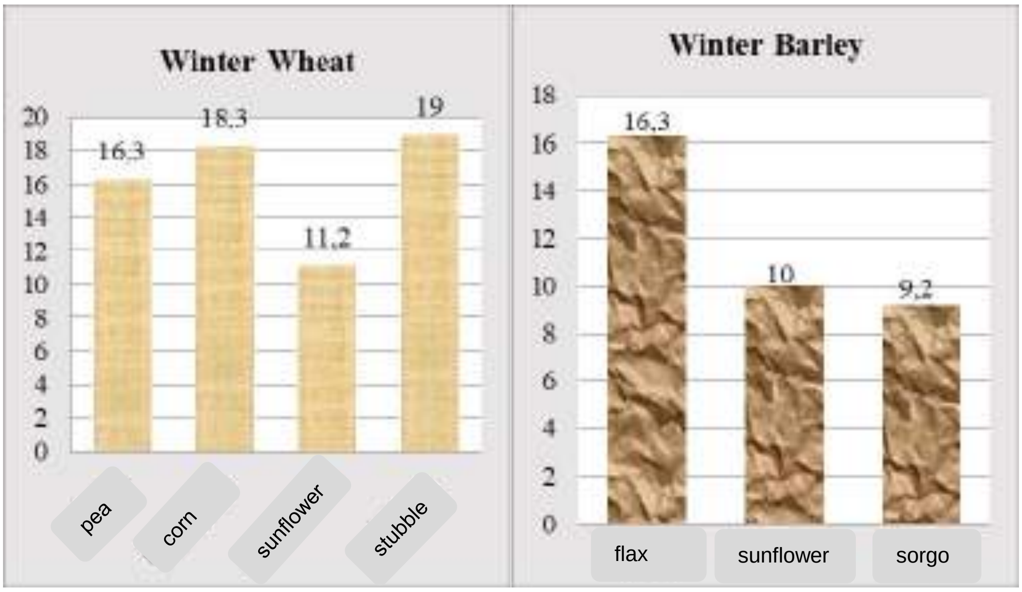


Figure 3.7: Winter grain crops average yield depending on forecrops (centners/ha).

Depending on varieties, the average winter wheat yield ranged from 23.4 centners/ha (Zysk variety) to 9.0 centners/ha (Slaven variety) (Fig. 3.8). However, on our opinion it is too early to judge the adaptation potential of varieties to stressful conditions during vegetative season based on results of one year. The results should be systematized and analysed over a long period of observation.

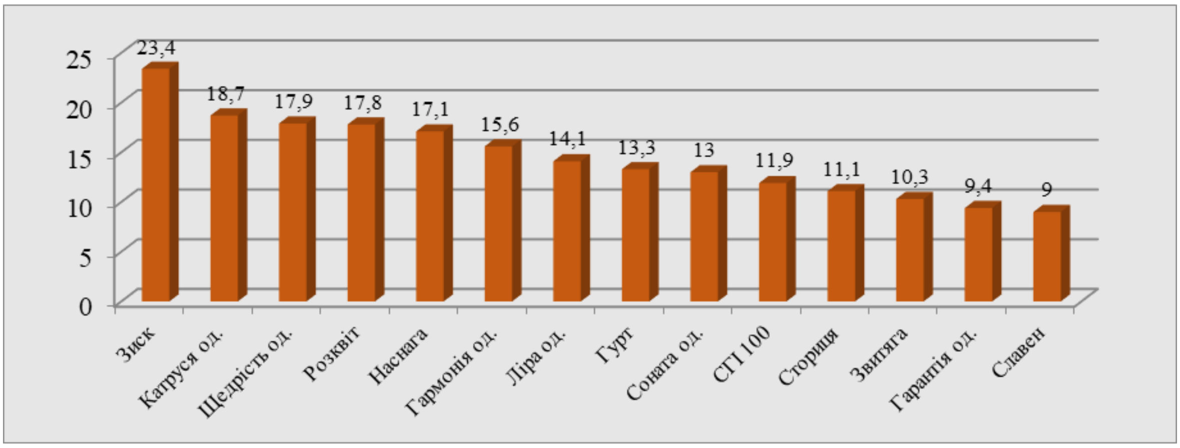
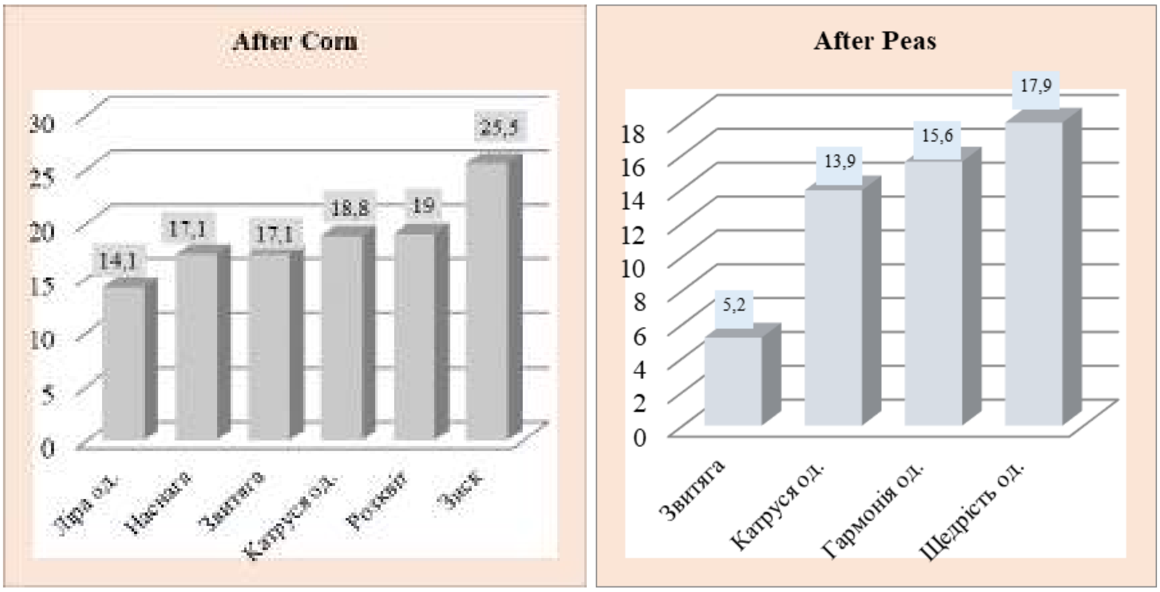


Figure 3.8: Winter wheat average yield by varieties, centners/ha (cultivar variety name are in Ukrainian; English transliteration from left to right: Zysk, Katrusya Odeska, Schedrist Odeska, Rozkvit, Nasnaga, Garmoniya Odeska, Lira Odeska, Gurt, Sonata Odeska, SGI 100, Storytsya, Zvytyaga, Garantiya Odeska, Slaven).



Поменять: (3) Zvytyaga, Slaven, Garantiya Odeska, Storytsya, SGI 100, Sonata Odeska, Gurt, Zysk, Rozkvit (4) Zvytyaga, Rozkvit, Katrusya Odeska, Zysk

Figure 3.9: Winter wheat yield depending on forecrop and variety, centner/ha (left: Lira Odeska, Nasnaga, Zvytyaga, Katrusya Odeska, Rozkvit, Zysk; right: Zvytyaga, Katrusya Odeska, Garmoniya Odeska, Schedrist Odeska).

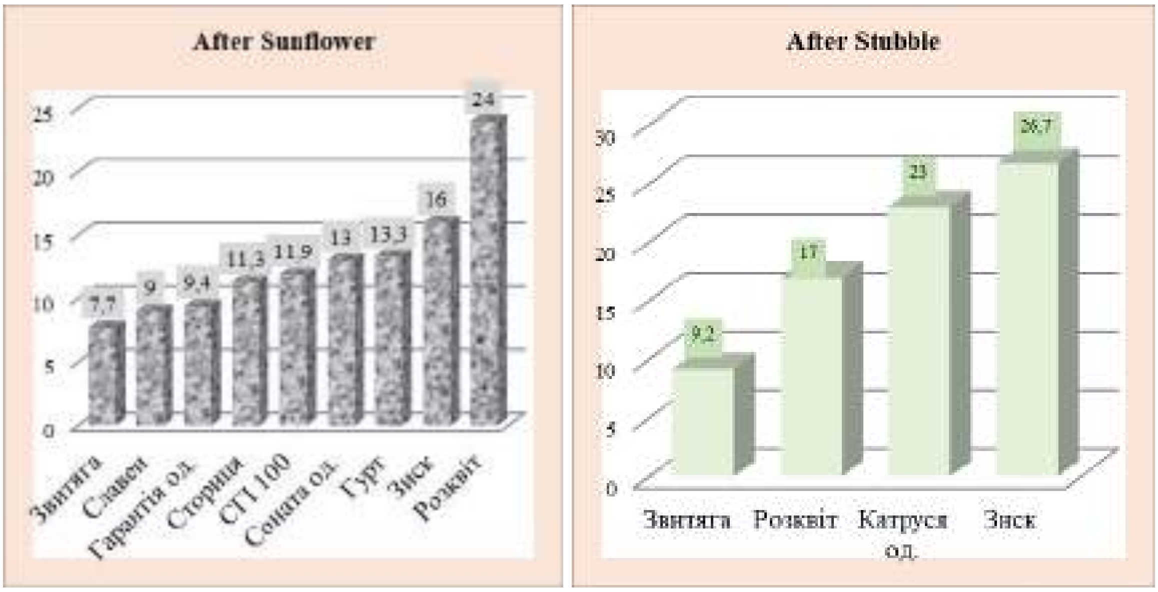


Figure 3.10: Winter wheat yield depending on forecrop and variety, centner/ha (left: Zvytyaga, Slaven, Garantiya Odeska, Storytsya, SGI 100, Sonata Odeska, Gurt, Zysk, Rozkvit; right: Zvytyaga, Rozkvit, Katrusya Odeska, Zysk).

If we consider the productivity of winter wheat varieties in terms of their forecrops (Fig. 3.9, 3.10), the maximum yield after peas in the current weather conditions was obtained when growing the Shchedrist Odeska variety (17.9 centners/ha), the minimum (5.2 centners/ha) with the Zvytyaga variety. After corn the maximum yield was received out of the Zysk variety (25.5 centners/ha), the minimum (14.1 centners/ha) – with the Lira Odeska variety. After sunflower the best result was demonstrated by the Rozkvit variety (24 centners/ha), the Zvytyaga variety gave the minimum yield (7.7 centners/ha) and after the stubble only 4 varieties were grown, of which the Zysk variety had the highest yield (26.7 centners/ha) and the Zvytyaga variety the lowest (9.2 centners/ha).

In order to establish mutual dependencies in the pairs ‘precipitation – moisture content in soil’, ‘yield – moisture content in soil’, and ‘yield – hydrothermal index’ we performed correlation analysis, which showed that the moisture content in the soil layer from 0-10 to 0-50 cm was 64.0-72.3% dependent on the amount of precipitation, at that the coefficients of correlation were 0.80-0.85 respectively. The dependence of winter wheat yield on the hydrothermal conditions of the growing season from March to the second decade of June is almost at the functional level (r= 0.98-0.99), and the productive moisture content in the soil is most important in April and the first two decades of May, which coincides with the critical phases in the formation of their productivity: r= 0.56-0.60 compared to 0.35 - 0.40 in other periods.

Status quo of Ukraine in the world wheat market will depend significantly on the ability of the agrarian sector to get adapted to the changing weather conditions as weather conditions are one of irreplaceable factors of stable growth of its productivity.

Most of the country’s acreage under winter wheat (58.8%) is situated in the Steppe zone. Winter wheat occupies the first place within the pattern of crops in the Black Sea Steppe zone in general and Odesa Region in particular, contributing significantly to the region’s economy. At the same time the region demonstrates the sharpest weather and climate changes (see Fig. 3.11).

Figure 3.11: Fields of the State Enterprise "DG Andriivske", Odesa SARS of the National Academy of Agrarian Sciences of Ukraine, showing the signs of crops drying out in spring 2020.

Climatic changes take place all over the planet. The Black Sea Steppe zone, including its part in Odesa Region, has been demonstrating significant alteration of thermal regime, moisture regime and precipitation characteristics, both during a calendar year and winter wheat vegetative season:

- since the beginning of the 21st century, the average air temperature in Odesa Region is every year higher than the climatic norm. The deviation varies within the interval from 0.8oC to 2.7oC, the biggest deviations were registered in January and July. Average temperature of January for the 51-year period grew by 1.3°C, Average temperature of July – by 2.2°C;
- average annual precipitation ( ) for the period of observations made 456.8 mm and the average precipitation for winter wheat vegetative season totalled to 450.8 mm with 70.6% probability;
- there have been no significant changes in precipitation relative to the climatic norm in the last 20 years, but there is a redistribution of the amount of precipitation in some months and seasons; the number of days with precipitation decreases on average to 61.5 days, and in the last 10 years - to 53 days in comparison with 85 days during the winter vegetation of 1971–1980 or with the average of 86.2 days for the calendar years 1970–1992;
- during the winter wheat vegetation period, precipitation characteristics in terms of their gradations changed noticeably: on average for 2011–2021, the share of days with precipitation of less than 1 mm decreased from 25.3% (1971–1980) to 7.8%; the share of

days with precipitation of 1 - 5 mm remained practically at the same level (39.4-38.2%); the percentage of days with precipitation of 5-9.9 mm and 10-19.9 mm increased by 1.6 and 1.4 times respectively, the number of days with rainfall of more than 20 mm in one go increased by 1.6 times, and the number days with rainfall exceeding 50 mm doubled;

- the productivity of winter wheat grown without fertilizers had a high degree of dependence on the number of days with precipitation (R^2= 0.98), and of that grown with fertilizers showed an average level of dependence at R^2= 0.68, while the increase in grain yield when using fertilizers demonstrated inverse dependence of a medium degree (r=-0.56): the more rainy days was in a vegetative season, the smaller the yield gain was compared with the control field where no fertilizers were applied;

The same situation was also observed in most of the previous years and, in combination with the predicted aridification of climate in the south of the country, it can cause detrimental consequences for farmers in the absence of irrigation.

4. PROPOSED WORKFLOW & RESULTS

The methodology devised for PONTOS project aims to estimate initially the daily water balance in a single field level and then upscale it to the study area level. A generic flow chart is presented in Fig. 4.1, while the below subsections describe in detail the following process.

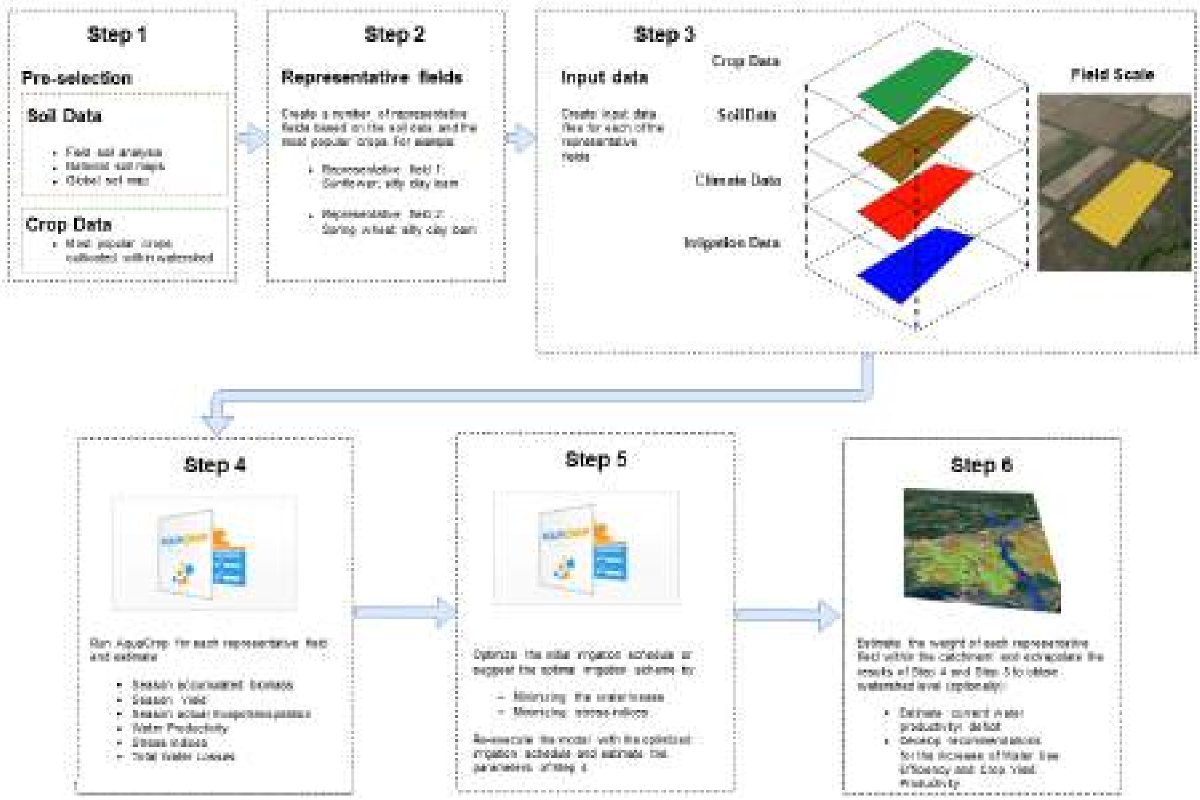


Figure 4.1: Proposed workflow chart developed within the PONTOS project (Medinets et al., 2021; Tsakmakis et al., in prep.)

4.1 Step 1: Pre-selection of representative conditions

Typically, it is suggested to use regional/ national/ global digital maps or atlases of soil types/ textures with the relevant scale and/ or rely on field research data to select the most representative lands for study in the area of interest. Due to the fact that national soil atlases of Ukraine are quite outdated, based on Soviet-era data and lack proper details at a field scale, the only option in our particular case was to use data from soil surveys conducted in Odesa region by the chair of Soil Science of the Faculty (SSF) of Geology and Geography of Odesa National I.I. Mechnikov University (ONU). Initially, a number of typical fields are defined for the study area. The typical fields are characterized based on their soil texture and the cultivated crop. Specifically, taking into account the 2019 crop map (Fig. 4.2; EOS, 2021) and the field data provided by SSF ONU. Among the typical crops, we selected winter wheat and sunflower as those were the most populated in Odesa region as for 2019 (EOS, 2021). The dominated soil texture was silty clay loam (see also Table 2.1).

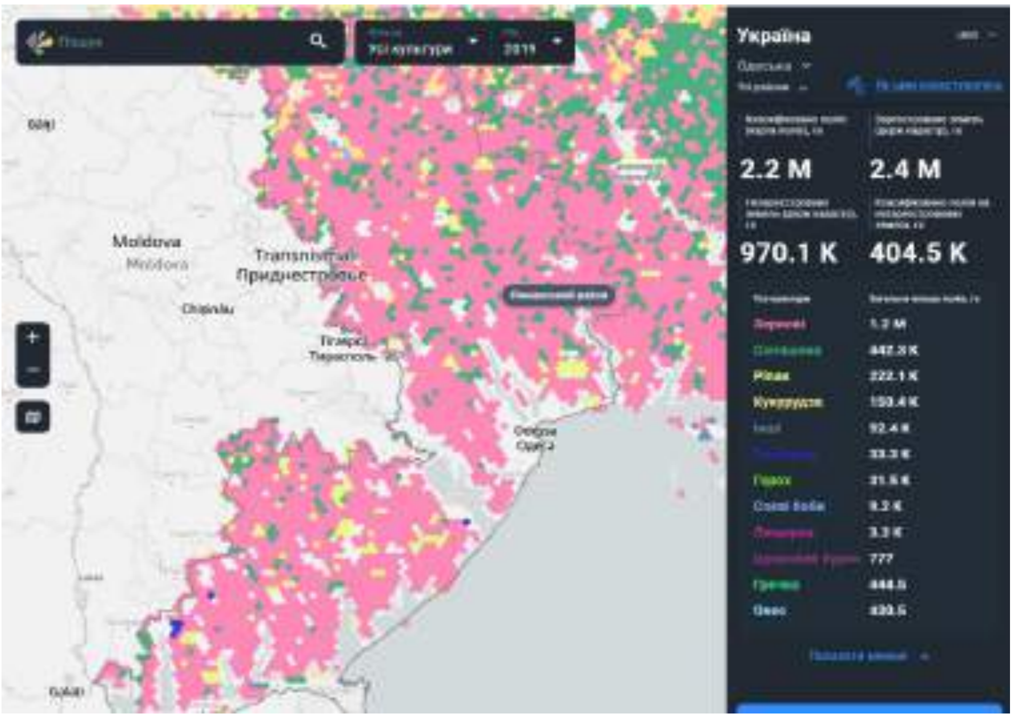


Figure 4.2: Areas of crops grown (ha) in Odesa region as of 2019 (in Ukrainian) (EOS, 2021) [pink color: cereals, mainly presented by winter wheat; green color: sunflower].

4.2 Step 2: Choosing the representative fields

We selected two representative fields with a known agromanagement history located not far from the Petrodolinskoye Research Station of the ONU (Odesa region) in the catchment of the Dniester river (Medinets et al., 2016). This agricultural area is known to be exposed to higher N deposition (>20 kg N ha^{-1} yr^{-1}) since 2016 (Medinets et al., 2020a) with a large share of organic constituents similar to that observed in the coastal areas of the Black Sea (Medinets, 2014). Crop details and agromanagement characteristics are shown in Table 3.1; studied field photos are presented in Fig. 4.3.

Table 4.1: Crop details and agromanagement characteristics in the studied fields.

#	Crop	Season	Variant	Sowing date	Density, th. s. ha^{-1}	Harvest date	Harvest, t ha^{-1}
1	Winter wheat	2020/21	DVS SN-Kombin	01.10.2020	3000	11.08.2021	3.35
2	Sunflower	2021	Limagrain 5542	19.04.2021	55	10.09.2021	3.15
3	Winter wheat	2021/22	DVS SN-Kombin	29.09.2021	3500	06.07.2022	3.00

Figure 4.3: Studied sunflower (left) and winter wheat (right) fields.

4.3 Step 3: Collecting input data to be used for simulation

This step is the most difficult, long-lasting and responsible, because the more accurate input data шi collect, the more relevant and credible model results will be obtained. Combining accuracy, simplicity and reliability, the AquaCrop, a field-crop-water-productivity simulated model fed by relatively small number of input variables is actively used around the globe and in the EU-countries (FAO, 2021; Foster et al., 2017). The quality and quantity of input data determine the default model performance accuracy, as well as allow to substantially improve the model credibility after calibration (Tsakmakis et al., 2019, 2021).

Crop data includes agromanagement data, such as crop type and cultivar, sowing date, seeding density and types provided by a farmer (Table 4.1), as well as other predefined parameters available for selection in the model database. It is noteworthy that field data on leave area index (LAI)/ green canopy cover (CC) and wet/ dry biomass substantially increase the model accuracy. Green CC might be indirectly calculated through Normalized Difference Vegetation Indices (NDVI) obtained from aerial or satellite imageries (Tsakmakis et al., 2021). In this study we monitored the NDVI evolution with the multispectral UAV (Fig. 4.4) and Sentinel-2 images (Fig. 4.5, 4.6). Mean NDVI measured at field site with multispectral UAV coincided well with those of Sentinel 2, when measured at the closed period of time (Fig. 4.7). We found that the maximum DNVI for winter wheat was detected in May 22 and for sunflower – in June 26 followed by maturity stage and then gradual senescence period.

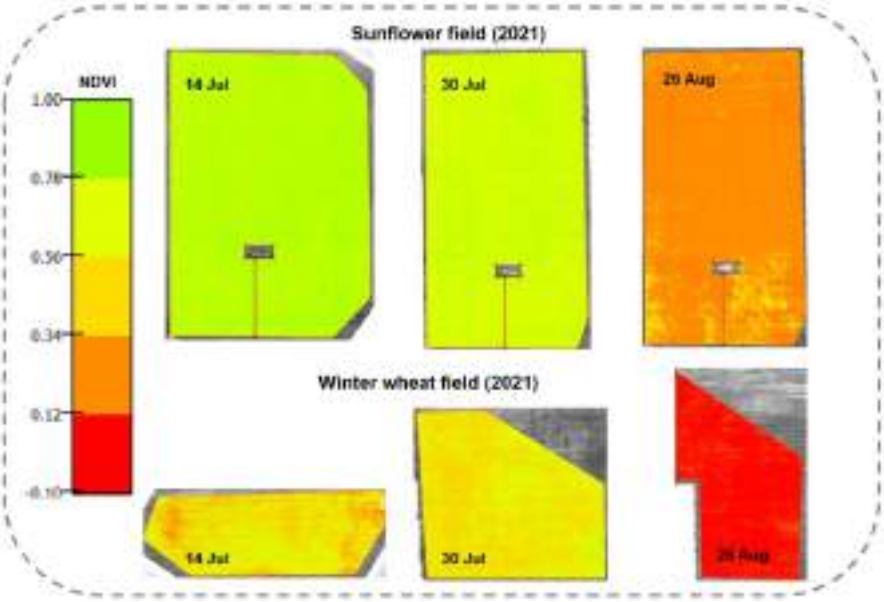


Figure 4.4: High resolution NDVI maps derived from multispectral UAV-mosaics for sunflower (top) and winter wheat (bottom) fields in July-August 2021 within PONTOS-UA.

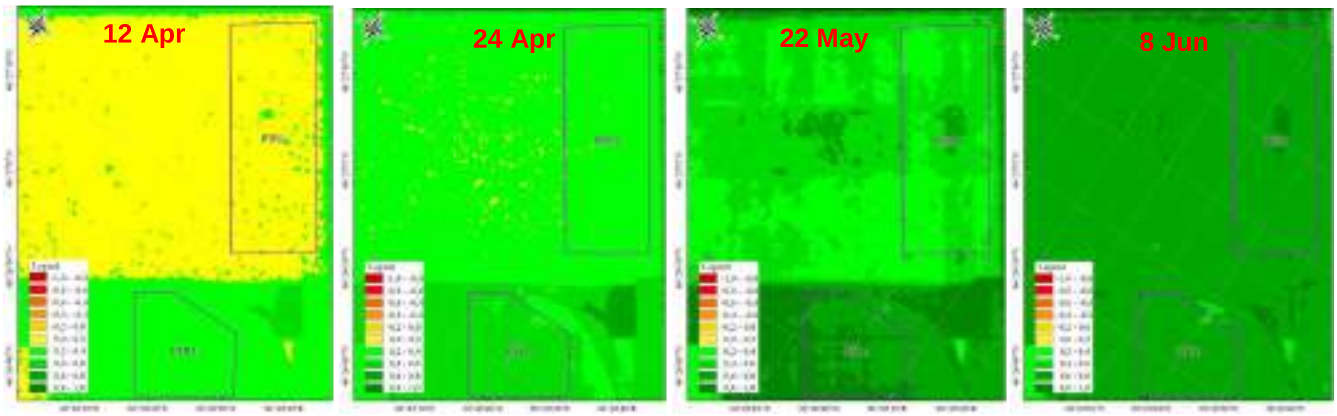


Figure 4.5: NDVI maps derived from Sentinel-2 images for sunflower (top; PTR1) and winter wheat (bottom; PTR2) fields in April, May and June 2021 within PONTOS-UA.

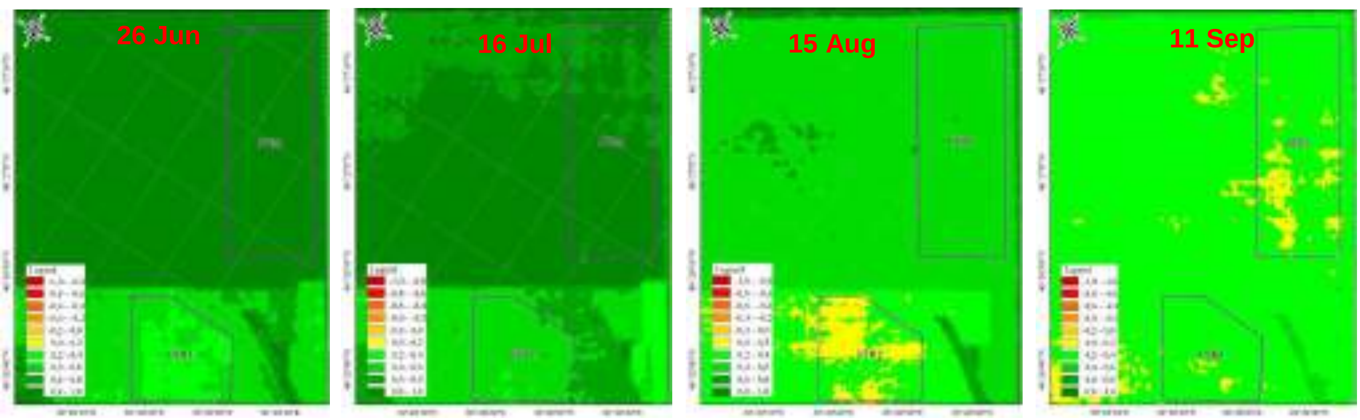


Figure 4.6: NDVI derived from Sentinel-2 images for sunflower (top; PTR1) and winter wheat (bottom; PTR2) fields in June, July, August and September 2021 within PONTOS-UA.

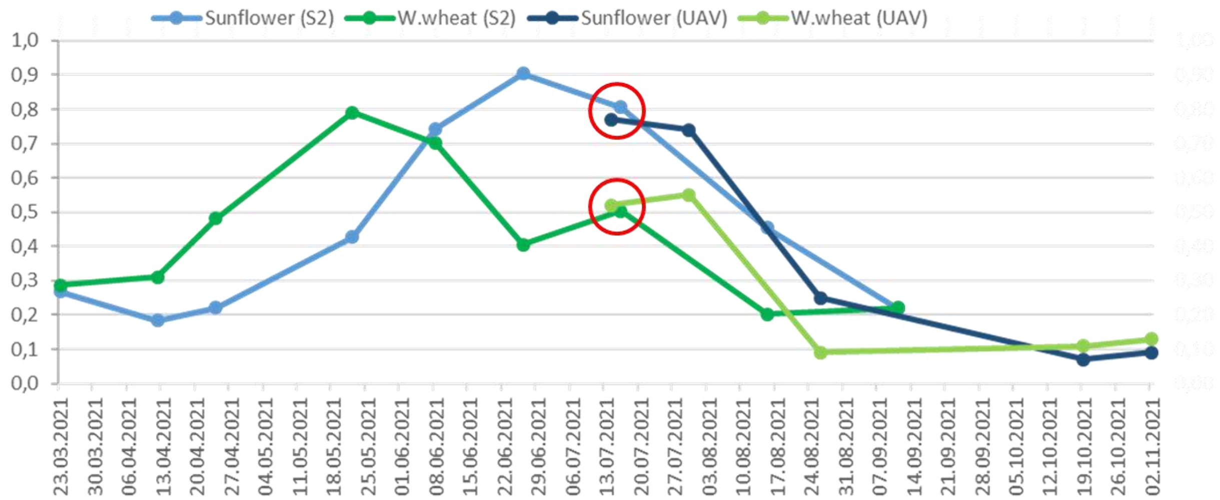


Figure 4.7: Comparison of NDVI values derived from multispectral UAV and Sentinel-2 for sunflower and winter wheat in 2021 within PONTOS-UA [red circles represent matches of close measurement dates].

We collected crop samples at a maturity stage of development to determine dry biomass per m^2 for yield and vegetation parts (Fig. 4.8, 4.9). Yields of sunflower and winter wheat measured by us in-situ in representative plots on July 30th was larger (5.87 and 4.60 t ha^{-1} respectively) than the final average yields reported by the farmer (3.15 and 3.35 t ha^{-1} respectively). The same tendency took place in 2022: 3.00 t yield ha^{-1} reported by farmer vs 4.00 t yield ha^{-1} directly sampled in the field. It might perhaps be explained due to harvesting was later on in two weeks for wheat and more than month for sunflower and may also include losses upon harvesting and transportation.

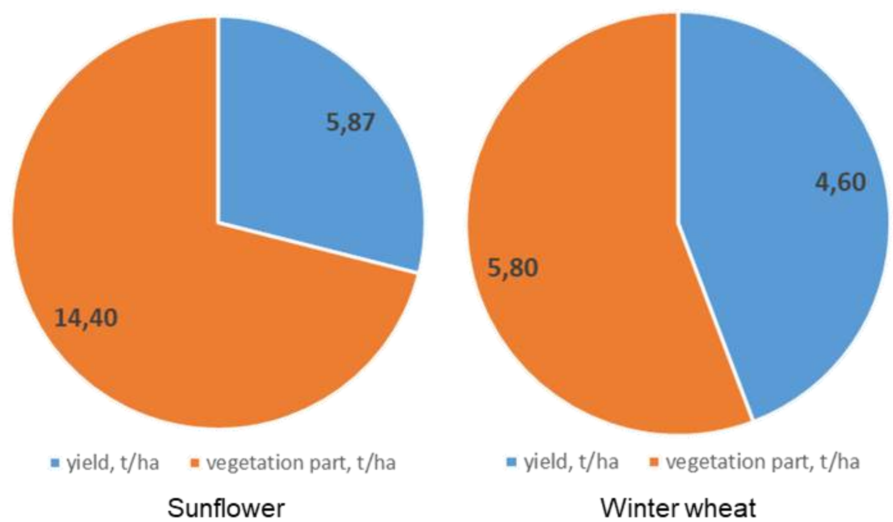


Figure 4.8: Dry biomass of yield and vegetation parts of sunflower (left) and winter wheat (right) sampled on July 30th, 2021.

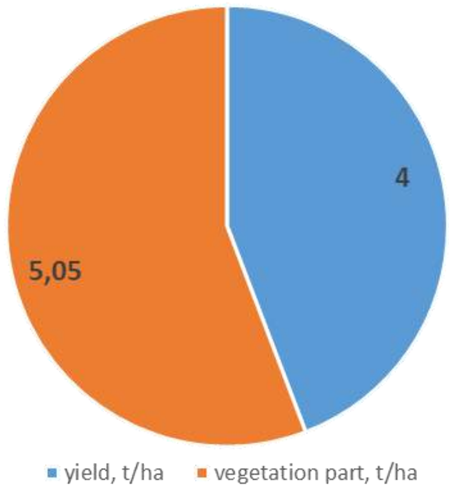


Figure 4.9: Dry biomass of yield and vegetation parts of winter wheat sampled on June 30th, 2022.

Soil data includes soil types, texture, hydraulic and physicochemical properties, which might be either obtained from detailed national databases/ digital maps or measured *in-situ* (preferable option). The properties of studied soil are presented in Table 1. Perhaps, the most critical parameter to be monitored in the field is soil water content, which spatiotemporal variation across field area and in soil profile within the root zone significantly impacts the model outputs. In our study we have been using microclimate loggers TMS-4 (TOMST s.r.o., Czech Republic) for soil temperature and water content (SMC) measurements with a resolution of 15 min placed at 3 soil layers: 6, 30 and 50 cm (Fig. 4.10).

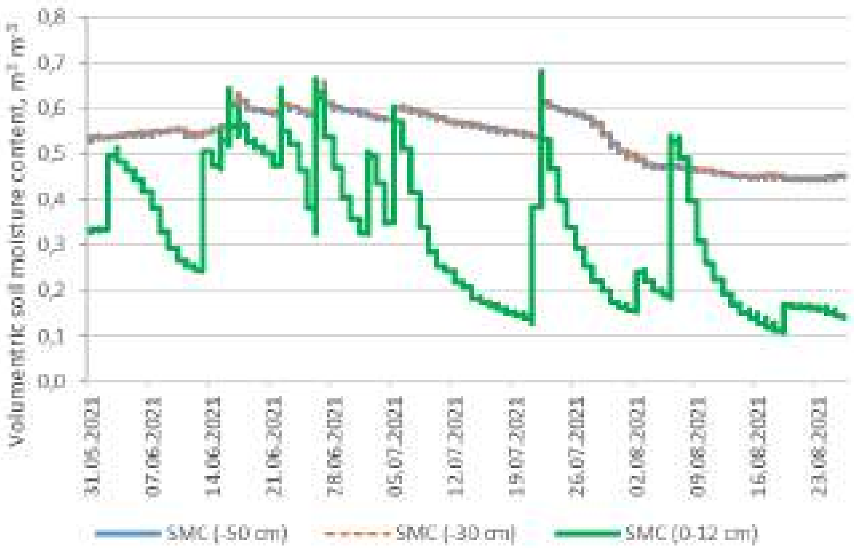


Figure 4.10: Dynamics of continuously monitored soil moisture content in 3 soil layers under sunflower in 2021 (15-min averaged data).

Fig. 4.10 shows how sensitive the topsoil SMC (0-12 cm) to rainfall events, the length of dry period and the hat intensity afterwards. We reported a decline of upper layer SMC from 59% (July 5th, 2021) via 20% (July 14th, 2021) to 14% (July 21st, 2021) and even faster from 66% (July 22nd, 2021) to 16% (August 1st, 2021). At the same time, lower depth SMC (30 and 50 cm) were shown to be subjected to rain and temperature fluctuations in less extend never decreased lower than 45%. This is an important characteristic of the studied Black soil with silty clay loam texture showing a flag to farmers which crop types and cultivar varieties should be consider to survive under rainfed management at changing climate with an extended dry period.

Climate data includes daily minimum and maximum air temperature, relative evapotranspiration, precipitation and ambient concentration of CO_2. Meteorological data can be obtained from either a local automatic weather station (AWS) or the closest meteorological station of a national network (if located close enough to studied area), while CO_2 data are usually taken from the AquaCrop database (referred to Mauna Loa station) if there is no Eddy Covariance tower measuring CO_2 concentration/ flux nearby. In our study, we used a combination of a high spatial resolution modeled NASA data based on historical meteodata from Jan 2020 to May 2021. Since Jun 2021 we have been used in-situ measured data derived from a Davis VantagePro2 GroWeather station (Davis Instruments Corp., USA) with a real-time data access through the web application, which was installed in the middle of the sunflower field. The continuous dataset, including precipitation, air temperature, relative humidity, wind speed and direction, evapotranspiration (ETO), was obtained (Fig. 4.11, 4.12). In contrast to a very dry spring-summer 2020 caused by massive rainfed crop damage in the region, the year of 2021 was extremely wet (annual precipitation was 1.8 time higher compared to the long-term average; Table 4.2) resulted in infrastructure damages in the upper part of the Dniester basin and negative impacts on agriculture downstream due to flooding/ soil over-moistening.

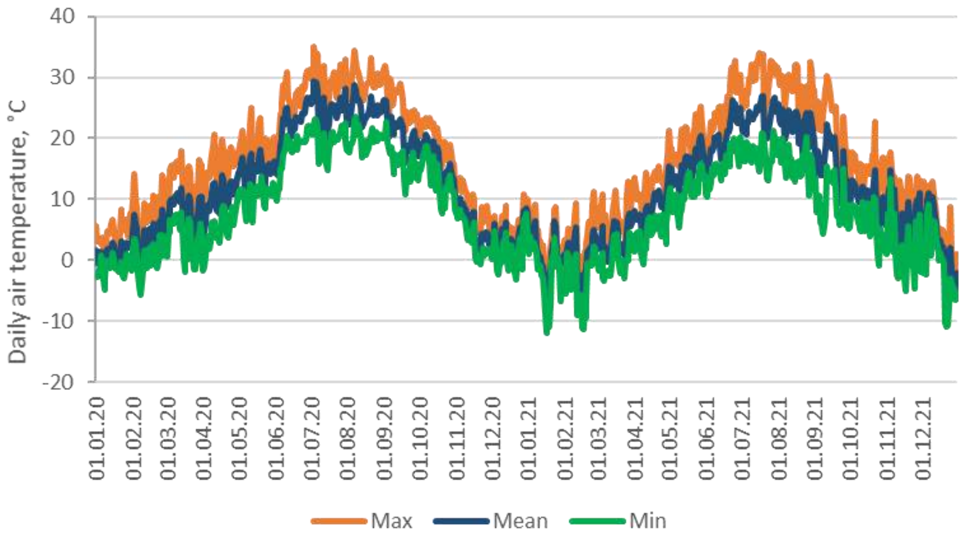


Figure 4.11: Daily air temperature (mean, maximum and minimum) measured *in-situ* by automatic weather station.

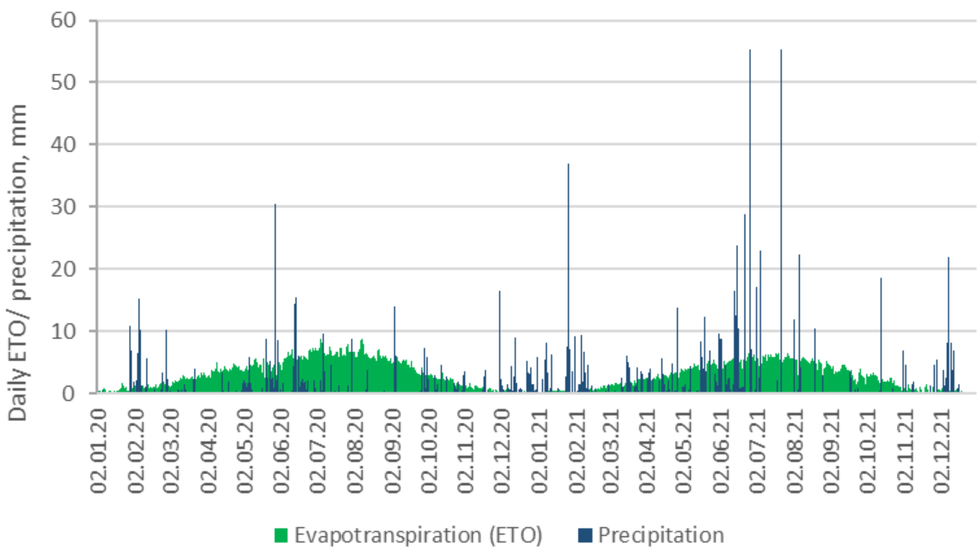


Figure 4.12: Daily precipitation and evapotranspiration measured *in-situ* by automatic weather station.

Table 4.2: Annual and vegetation season means of climatic parameters (air temperature (T), precipitation (rain) and evapotranspiration (ETO)) in a studied area.

Year	Mean air T, °C	ETO, mm	Rain, mm
2000-2014	10.5	-	432
2020	13.1	1178	420
2021	10.8	933	771
W. wheat 2020-21	10.3	749	748
Sunflower 2021	19.2	657	443
W. wheat 2021-22	9.1	535	188

Despite the fact, that at the moment the available meteodata for the study area are based solely on the measurements of one station (point meteorology), an option for spatial meteorology data is included in the methodological framework for a potential future increase in the meteorological stations network in the area. This future incorporates R programming language *meteoland* package (De Cáceres et al., 2018). The package uses as inputs (a) the coordinates and elevation of each station; (b) the measured weather data of each station in daily basis and (c) a digital elevation map of the area. Successively, the package interpolates weather variables using truncated Gaussian filters, which consist in defining spatial weights W(r) at radial distance r from a target point p using:

$$W(r) = exp\left(-a\left(r / R_p^{\ 2}\right)\right) - exp(-a) \tag{1}$$

If $r \leq R_p$; else W(r)=0

where r the radial distance from p, R_p the truncation distance and a is a shape factor.

The package returns a NetCDF-CF file with a spatial resolution equal to that of the provided digital elevation map.

4.4 Step 4: AquaCrop simulation and Step 5: Model optimization

Collected input data for certain fields were applied to run the model for simulation of the following parameters: accumulated biomass, yield, actual evapotranspiration, water productivity, water stress indices and total water losses. In total, we have simulated crop yield and water productivity of (i) sunflower over 2021 growing season (Fig. 4.13), (ii) winter wheat over 2020/2021 growing season (Fig. 4.14), (iii) winter wheat over 2021/2022 growing season (Fig. 4.15) to be used as a baseline for further agromanagement optimization.

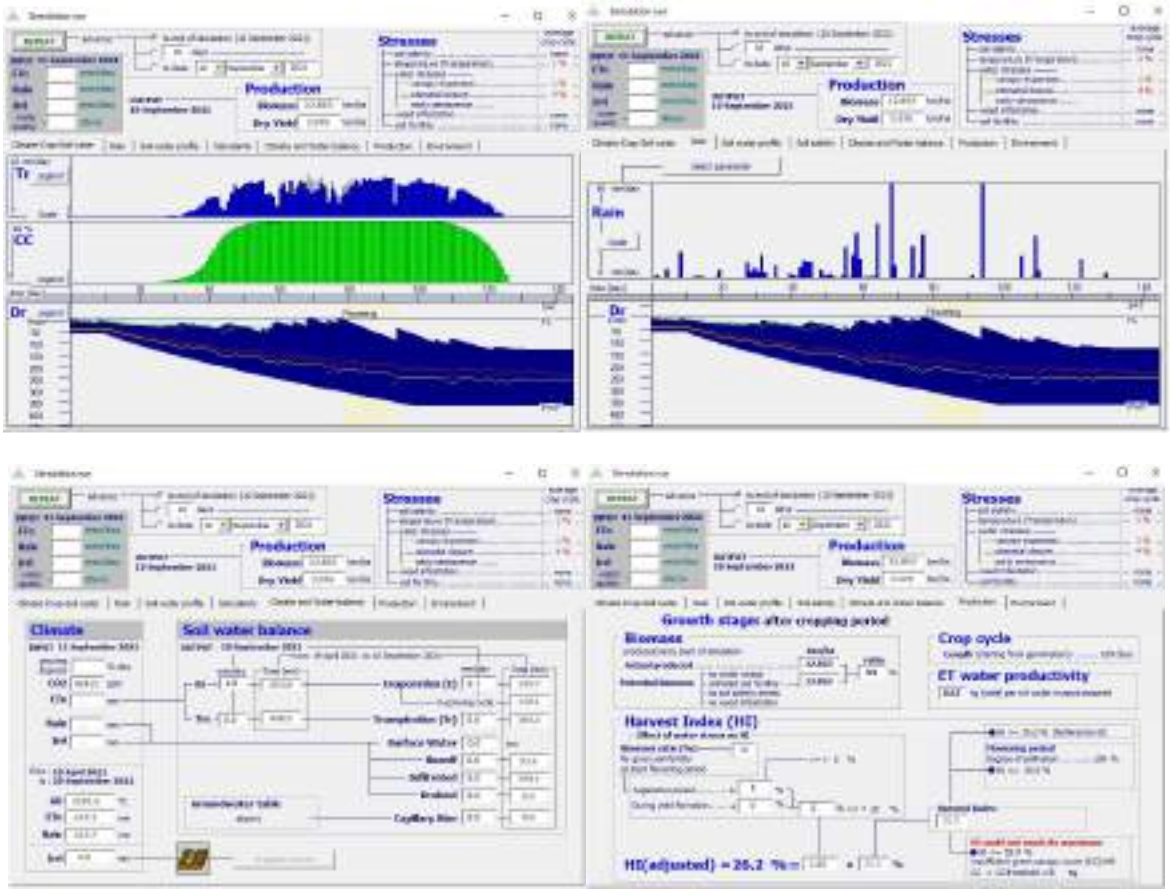


Figure 4.13: Simulation data on sunflower using real agromanagement data and in-situ agrometeorological parameters measured over 2021 growing season.

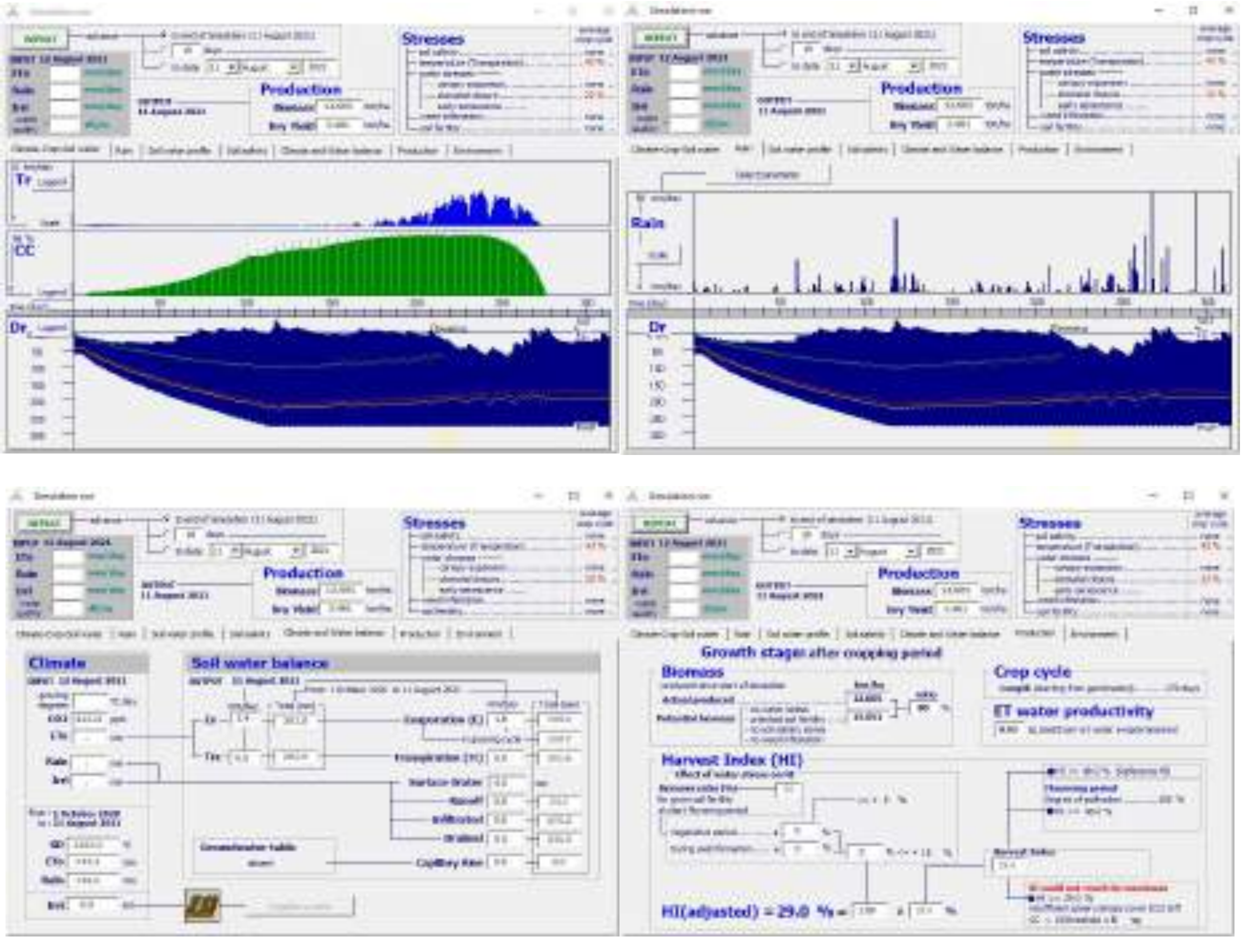
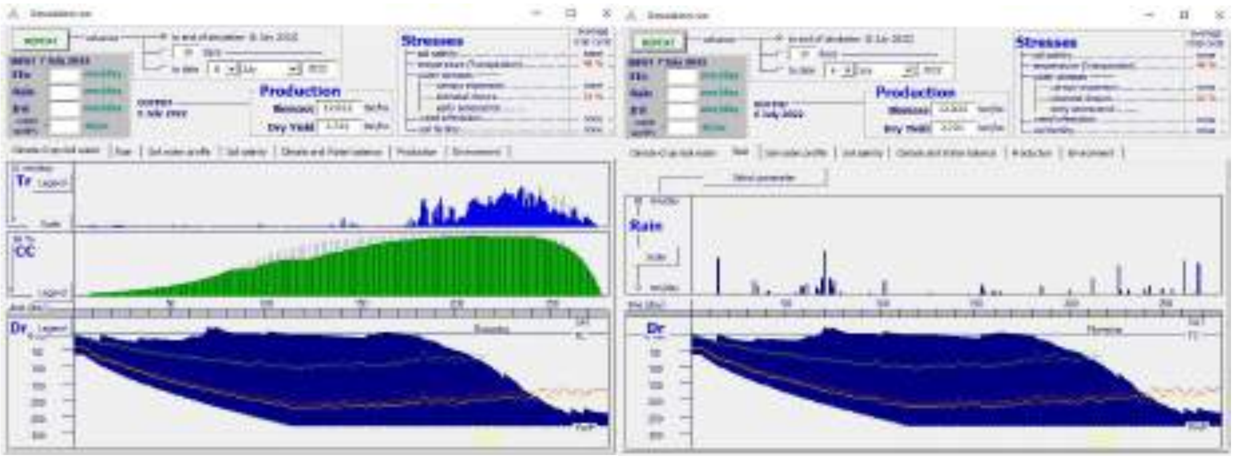


Figure 4.14: Simulation data on winter wheat using real agromanagement data and in-situ agrometeorological parameters measured over 2020-2021 growing season.



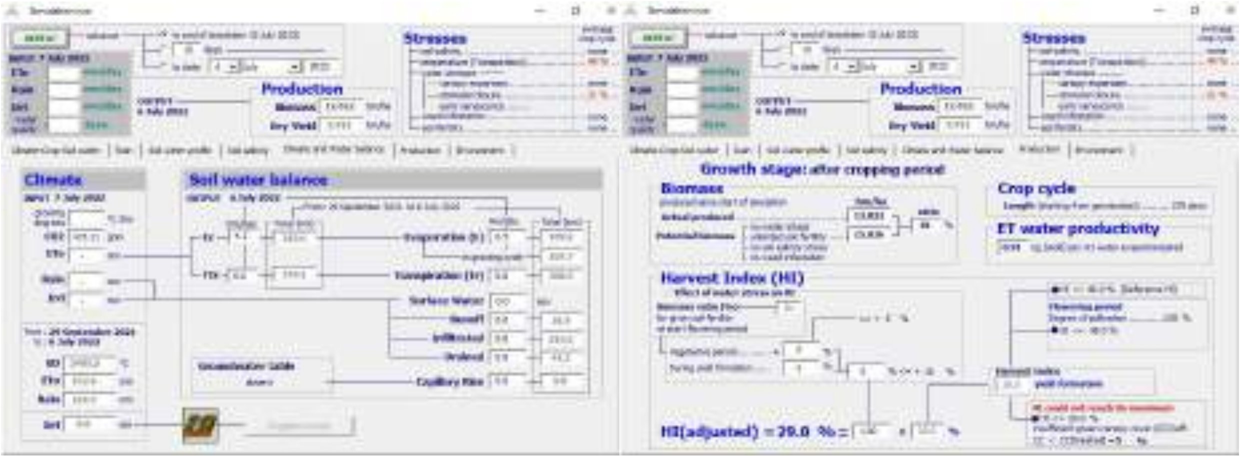


Figure 4.15: Simulation data on winter wheat using real agromanagement data and in-situ agrometeorological parameters measured over 2021-2022 growing season.

At an optimization step we analyzed the obtained model results to optimize the water loss/ diminish water deficit and reduce water stress indices. Then after to re-run the model using different scenarios of optimized irrigation scheme and agromanagement practice in order to re-evaluate model outputs and find the best options for minimizing water losses and sustaining yield production. In this assessment we compared model results obtained with and without in-situ measured high temporal resolution SMC data, which were used as a baseline scenario. Then we estimated 1 alternative scenario with sprinkler irrigation for sunflower and 4 alternative scenarios for winter wheat.

We found that adding in-situ measured SMC data increased credibility of simulation. E.g. Aquacrop model showed higher stomatal stress with real SMC data that with ‘default’ (ideal) ones (which did not reflect a real field condition) for sunflower and winter wheat (Table 4.3-4.5).

Sunflower

The rainfed agromanagement scheme used by a farmer in 2021 for sunflower under given climatic condition was proven by a model simulation to be quite efficient in terms of both yield forming and water losses (Table 4.3). Simulated yield was from 7 to 8% larger than that reported by the farmer for the entire field, but still less than directly measured in the field plots. The ratio of actual to potential biomass (Brelative) was quite high (92.8%) with harvest index of 26.2% (out of 35% possible maximum). Crop was subjected to a light temperature stress of 1% and stomatal stress of 4% to avoid water losses through transpiration. ET Water Productivity for yield part was quite effective under such climatic condition: ca. 0.67 kg yield produced per m^3 water evapotranspired. Sunflower is well known to form a taproot system more than 3 m deep; the main mass of the roots is developed in 15-45 cm depth within a diameter of 1.5-3.0 m. Those peculiarities of its root system allow sunflower to effectively consume soil moisture form deep layers, which makes it one of the most drought-resistant plants; another advantage feature is that sunflower leaves may accumulate moisture from dew. Also, in pers. comm. with farmer we learnt that there were attempts to grow sunflower on irrigation. Sprinkler irrigation use often had no difference or even gave a lower yield compared to rainfed system. In this study we simulated additional 100 mm surface irrigation (via sprinkler) and found that indeed this caused to decrease of yield (by 11%) and water productivity (by 6%) compared to rainfed management due to increased water losses via evaporation (Table 4.3). At the same time subsurface drip irrigation was not tested, but might be recommended and seems to be reliable in case if substantial annual rainfall decline prior to the vegetation season.

Table 4.3: In-situ measured, reported by framer and simulated by AquaCrop model data on biomass, dry yield, harvest index (HI), actual to potential biomass ratio (Brelative), precipitation (rain), irrigation, temperature stress (T_str), stomatal stress (Sto_str), water productivity (Wpet) for sunflower during 2021 growing season [w/o: without; w: with; SMC: soil moisture content; sprinkler: surface sprinkler irrigation].

Sunflower	Biomass, t ha^{-1}	Yield, t ha^{-1}	HI, %	Brelative, %	Rain, mm	Irrigation, mm	T_str, %	Sto_str, %	Wpet, kg m^{-3}
Field (in-situ 30 Jul)	**20,27**	**5,87**	**29,00**						
Field (farmer 10 Sep)	**-**	**3,15**	**-**						
AquaCrop (w/o SMC)	13,56	3,44	25,3	98	444	0	1	1	0,66
AquaCrop (w SMC)	**12,86**	**3,38**	**26,2**	**93**	**444**	**0**	**1**	**4**	**0,67**
AquaCrop (sprinkler)	**11,93**	**3,00**	**25,1**	**86**	**444**	**100**	**1**	**5**	**0,63**

Winter wheat

We monitored winter wheat growing in two distinctively different seasons: wet one of 749 mm precipitation over 2020-2021 and dry one of 188 mm precipitation over 2021-2022. In both cases our direct in-situ measurements of yield were higher than reported by farmer (Table 4.4, 4.5). Logically, the yield in drier season was 10-13% lower than in wetter one. Simulations with real field SMC data showed that yield formation was 8% less in a dry year. In both seasons temperature stress was high (43% in a wet warmer vegetation season vs 49% in a dry colder vegetation season), while stomatal stress was more than doubled in a dry season (21% vs 9%) under rainfed system. In this study we tested 4 different scenarios: two irrigation amount (300 and 500 mm) with two different irrigation types (surface sprinkler and sub-surface drip). We showed that fractional sub-surface dripping irrigation simulated for a *'wet vegetation season'* was much effective and may increase yield by 310 and 520 kg ha^{-1} if watering with 300 and 500 mm respectively compared to sprinkler irrigation, which may increase crop yield by 70 and 150 kg ha^{-1} respectively. According to the model simulation use of subsurface irrigation is supposed to increase harvest index to 30.6-31.6% and ET water productivity to 1.08-1.18 kg yield with evapotranspiration of 1 m^3. Similar simulation results we obtained for a *'dry winter wheat season'*. Fractional sub-surface drip irrigation increased yield by 400 and 540 kg ha^{-1} at a total dose of 300 and 500 mm respectively compared to sprinkler irrigation, which potentially increased crop yield by 80 and 210 kg ha^{-1} respectively. According to the model simulation the application of sub-surface irrigation is supposed to increase harvest index to 29.9-30.5% and ET water productivity to 1.03-1.08 kg yield at evapotranspiration of 1 m^3.

Simulation results showed higher water productivity due to higher water use efficiency (WUE) as well as higher yield due to lower stomatal and temperature stresses for fractionally irrigated winter wheat compared to rainfed ones in Odesa region over two different (wetter and drier) vegetation seasons (Table 4.4, 4.5). Moreover, winter wheat under sub-surface drip irrigation were demonstrated to be more productive in yield formation (by 6-8%) and substantially sustainable in water productivity (by 13-16%), especially under dry vegetation season of 2021-2022, than sprinkler irrigation. However, taking into account the peculiarity of southern Black soil (dense texture and high level of soil organic matter) and importance of winter cereals for Ukrainian economics the targeted agro-ecological studies are urgently needed to estimate in-situ the

Table 4.4: In-situ measured, reported by framer and simulated by AquaCrop model data on biomass, dry yield, harvest idex (HI), actual to potential biomass ratio (Brelative), precipitation (rain), irrigation, temperature stress (T_str), stomatal stress (Sto_str), water productivity (Wpet) for winter wheat during 2020-2021 growing season [w/o: without; w: with; SMC: soil moisture content; drip: sub-surface drip irrigation; sprinkler: surface sprinkler irrigation].

Sunflower	Biomass, $t\ ha^{-1}$	Yield, $t\ ha^{-1}$	HI, %	Brelative, %	Rain, mm	Irrigation, mm	T_str, %	Sto_str, %	Wpet, $kg\ m^{-3}$
Field (in-situ 30 Jul)	10,40	4,60	44,2						
Field (farmer 11 Aug)	-	3,35	-						
AquaCrop (w/o SMC)	14,04	4,27	30,4	93	749	0	43	4	1,05
AquaCrop (w SMC)	13,80	4,05	29,3	92	749	0	43	8	0,93
AquaCrop (drip 1)	14,01	4,25	30,3	93	749	300	37	4	1,06
AquaCrop (drip 2)	14,15	4,45	31,4	94	749	500	36	3	1,10
AquaCrop (sprinkler 1)	13,96	4,14	29,7	93	749	300	41	7	0,96
AquaCrop (sprinkler 2)	14,02	4,21	30,0	93	749	500	38	5	1,00

Table 4.5: In-situ measured, reported by framer and simulated by AquaCrop model data on biomass, dry yield, harvest idex (HI), actual to potential biomass ratio (Brelative), precipitation (rain), irrigation, temperature stress (T_str), stomatal stress (Sto_str), water productivity (Wpet) for winter wheat during 2021-2022 growing season [w/o: without; w: with; SMC: soil moisture content; drip: sub-surface drip irrigation; sprinkler: surface sprinkler irrigation].

Sunflower	Biomass, $t\ ha^{-1}$	Yield, $t\ ha^{-1}$	HI, %	Brelative, %	Rain, mm	Irrigation, mm	T_str, %	Sto_str, %	Wpet, $kg\ m^{-3}$
Field (in-situ 06 Jul)	9,05	4,00	44,2						
Field (farmer 06 Jul)	-	3,00	-						
AquaCrop (w/o SMC)	13,32	3,89	29,2	84	188	0	49	17	0,91
AquaCrop (w SMC)	12,82	3,72	29,0	81	188	0	49	21	0,91
AquaCrop (drip 1)	13,60	3,95	29,0	86	188	300	46	15	0,97
AquaCrop (drip 2)	13,83	4,10	29,6	87	188	500	45	12	1,00
AquaCrop (sprinkler 1)	13,15	3,81	29,0	83	188	300	48	19	0,91
AquaCrop (sprinkler 2)	13,40	3,95	29,5	85	188	500	47	17	0,93

efficacy of sub-surface drip irrigation on crop productivity/ quality and WUE as well as its impact (of water amount and its quality) on soil properties/fertility (e.g. mineralization, oxygen content, root disease agents) in middle-/ long-term prospective.

4.5 Step 6: Results extrapolation (optional) and recommendations

The extrapolation of the obtained results from the representative fields to a larger area of interest (district, region, watershed) taking into account the sowing area under the studied crops (identified with digital maps or satellite images) might be an important option. Also, the *status quo* of the current agro-practices under current climate conditions in the region should be highlighted as well as recommendations for farmers and policymakers aiming at improvement of WUE, diminish of water stress and thus increase of crop yield ought to be outlined and spread in all levels from regional administration to farm.

Monitoring of soil properties and crop conditions, along with tillage activity mapping, helps researchers and farmers to assess land use, predict harvests, monitor seasonal changes and assist in implementing policies for sustainable development. Sentinel data can also be used for monitoring the drought induced changes of agricultural production and pasture productivity, as well as monitoring the decline in land productivity and soil degradation due to excessive cultivation, pasturage or improper irrigation. Agricultural maps allow for independent and objective estimates of the cultivation extent in a given area or a growing season, which can be used to support the efforts to ensure food security in vulnerable areas. Sentinel-2 data might be used for classification of land cover types, validation of cropland area data, and, therefore, extrapolating the AquaCrop simulation results for winter wheat and sunflower cropland in Odesa region. This extended analysis might be conducted for those mentioned and other populated crops in the region and beyond on demand or in future projects/ initiatives. This will allow to better understand the overall irrigation water demand on different levels (local, regional, sub-catchments, catchment). For instance, Sen2r package can be used in order to continuously and automatically obtain the indices and monitor the changes related to the agricultural production and water stress such as MSAVI2, NDVI, NDWI, and NDWI2 (Fig. 4.16).

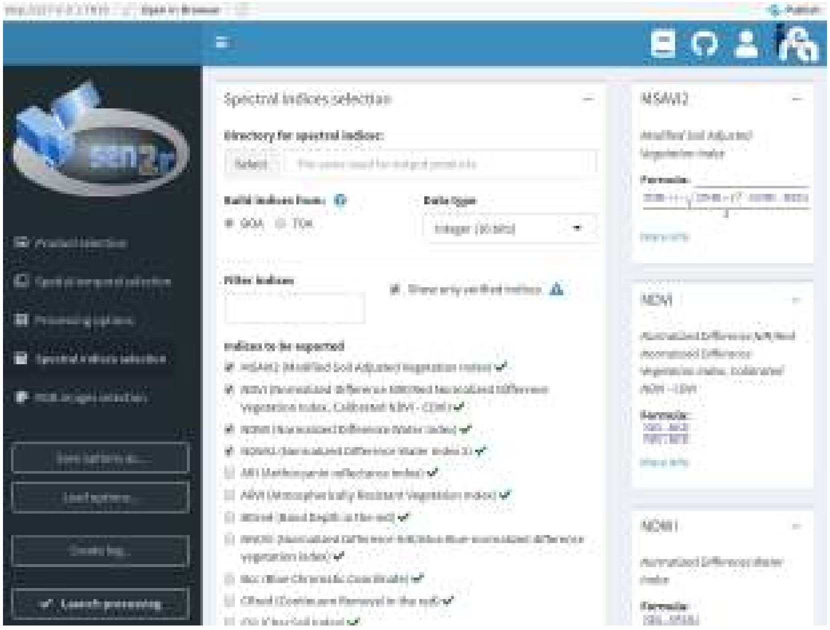


Figure 4.16: Spectral indices selection in Sen2r package GUI.

Sen2r is a scalable and flexible R package to enable downloading and preprocessing of Sentinel-2 satellite imagery via an accessible and easy to install interface. It allows the execution of several preprocessing steps which are commonly performed by Sentinel-2 users: searching the Sentinel-2 archive for datasets available over a spatial area of interest and in a defined time window, downloading them, applying the Sen2Cor atmospheric correction algorithm to compute surface reflectances, merging adjacent tiles, performing geometric transformations, applying a cloud mask, computing spectral indices and color images.

Despite a number of previous programs and plans aimed to increase water use efficiency in the agricultural sector and environmental protection of water ecosystems in Odesa region, the practical implementation of measures is still inefficient.

Problems related to the agricultural water balance, productivity, and water stress are related to the following factors:

- poor condition of water supply infrastructure,
- water allocation and intersectoral distribution issues,
- unfavorable soil conditions,
- inefficient farmer practices,
- lack of measures aimed at adapting to climate change.

Our assessment with the presented workflow was focused on the last two points above trying to estimate the credibility and efficacy of irrigation for traditionally rainfed crops in the current climatic conditions in the region. Using the AquaCrop model, and climatic, crop, irrigation, soil, groundwater, and other characteristics from ground monitoring and satellite data sources, it was estimated that irrigation application is likely a vital option to sustain the growth of traditionally rainfed crop (winter wheat), which subject to water stress under climate change condition in becoming drier Odesa region. With this regards the improvement/ repairment of abandoned/ damaged/ inappropriate irrigation infrastructure in the regional is of highly priority for food security. Water deficit makes crops more sensitive to fungal and bacterial diseases, resulting in intensification of chemical treatment (pesticides), which leads to more environmental problems in such a sensitive ecosystem as Dniester delta basin. Therefore, the future basin development activities and measures must be aimed at solving the water use efficiency problems in agricultural sector and the irrigation practices should become knowledge- and evidence-based taking into account the climate change trends.

Copernicus products, combined with continuous field monitoring data and management information from farmers, is highly important for monitoring the changes in agricultural lands under changing climate and for planning relevant measures to address the challenges. The tools such as Sen2r package are assisting in automation of data receiving and monitoring, saving the time and resources for analytical and decision-making tasks.

CONCLUSIONS

The implementation of such a workflow for agricultural water balance assessment based on the combination of in-situ measurements, aerial observations, space-born data and model simulations will allow us to (i) estimate the current water productivity/ water deficit at sunflower and spring wheat cultivation, (ii) extrapolate results to a larger area of interest, (iii) develop recommendations for farmers and policymakers based on model simulations on how to improve WUE, avoid the effects of water stress in plants and increase yield production at field-to-regional scale.

Using the AquaCrop model, and climatic, crop, irrigation, soil, groundwater, and other characteristics from ground monitoring and satellite data sources, it was estimated that irrigation application is likely a vitable option to sustain the growth of traditionally rainfed crop (winter wheat), which subject to water stress under climate change condition in becoming drier Odesa region, while not really required for sunflower. The results of Aquacrop simulations showed higher water productivity and higher yield due to lower stomatal and temperature stresses and increased WUE for fractionally irrigated winter wheat system compared to rainfed crop system in Odesa region over two different (wetter and drier) vegetation seasons. We estimated that winter wheat under sub-surface drip irrigation formed higher yield (by 6-8%) and had higher water productivity (by 13-16%) than sprinkler irrigation. With this regards the improvement/ repairement of abandoned/ damaged/ unappropriate irrigation infrastructure in the regional is of highly priority for food security.

We ensure that this workflow, combining Copernicus products and continuous field monitoring data, and obtained model-derived estimates for typical crops can be highly relevant to support sectoral agencies and regional authorities in knowledge- and evidence-based planning the limits of water supply for irrigation purposes and the food security strategy based in the Odesa region suffering from climate extrema over last years.

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