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MODELING

OF CROP CULTIVATION SYSTEMS TAKING INTO ACCOUNT AGROECOLOGICAL REQUIREMENTS

MODELACIÓN DE SISTEMAS DE CULTIVO TENIENDO EN CUENTA REQUERIMIENTOS AGROECOLÓGICOS

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ABSTRACT

The growing need for sustainable agricultural production in a context of climate variability and environmental degradation underscores the importance of integrating agroecological criteria into cropping systems modeling. Therefore, this study incorporates natural system indicators, such as heat input, moisture availability, and vegetation duration, into crop yield prediction. The primary objective is to develop a mathematical model that simulates the productivity of cereal, barley, and potato crops based on the climatic and technological characteristics of agricultural landscapes. The model calculates specific coefficients of temperature, moisture, and growing season to assess crop suitability and forecast yield potential. The model's ability to reflect ecological conditions with high sensitivity was found, enabling crop yield predictions in specific geographical areas. Furthermore, the use of graphical dependencies allows for a detailed understanding of how environmental factors interact with crop physiology. This knowledge is particularly relevant for the development of agroforestry ecosystems, which not only enhance biodiversity and ecological balance but also contribute to socioeconomic resilience in rural areas.

Keywords: Sustainable agriculture, Agroecosystem modeling, Crop yield prediction, Agroforestry, climate adaptation.

RESUMEN

La creciente necesidad de una producción agrícola sostenible en un contexto de variabilidad climática y degradación ambiental subraya la importancia de integrar criterios agroecológicos en la modelización de sistemas de cultivos. Por ello, en este estudio se incorporan indicadores de sistemas naturales, como el aporte de calor, la disponibilidad de humedad y la duración de la vegetación, en la predicción del rendimiento de los cultivos. El objetivo principal es desarrollar un modelo matemático que simule la productividad de los cultivos de cereales, cebada y patata basándose en las características climáticas y tecnológicas de los agropaisajes. El modelo calcula coeficientes específicos de temperatura, humedad y período vegetativo para evaluar la idoneidad del cultivo y pronosticar el potencial de rendimiento. Se encontró que la capacidad del modelo para reflejar las condiciones ecológicas con alta sensibilidad, lo que permite predicciones del rendimiento de los cultivos en zonas geográficas específicas. Además, el uso de dependencias gráficas permite una comprensión detallada de cómo los factores ambientales interactúan con la fisiología del cultivo. Estos conocimientos son particularmente relevantes para el desarrollo de ecosistemas agroforestales, que no solo mejoran la biodiversidad y el equilibrio ecológico, sino que también contribuyen a la resiliencia socioeconómica en las zonas rurales.

EDITORIAL UNIVERSO SUR

Palabras clave: Agricultura sostenible, Modelado de agroecosistemas, Predicción del rendimiento de cultivos, Agroforestería, Adaptación climática.

INTRODUCTION

Crop cultivation systems modeling is a fundamental tool for understanding, predicting, and optimizing the behavior of agroecosystems under various environmental and management conditions. These models allow for the simulation of physiological and biophysical processes ranging from germination to harvest, incorporating climatic, soil, genetic, and agronomic management factors (Meinke, 2019)providing invaluable services to society. In response, most governments around the world are now actively developing policies to support and grow their bio-economies. This increases the expectations that society and governments have in terms of agriculture's services and performance: agriculture is not only expected to generate food for our growing populations and income for farmers, it must be part of value chains that provide raw materials that can be incorporated or converted into feed, fiber, fuel, pharmaceuticals, and other industrial products. Farmers are expected to be responsible custodians of our landscapes and their farming practices must be economically, environmentally, and socially sustainable and aligned with the broader and changing values of our societies. Often these three objectives conflict and consequently societal expectations are not met. In a world that is increasingly data rich, practicing agriculture in a way that lives up to these expectations requires tools that can help to foresee the consequences of complex interactions. Hence, this chapter explores the role of modeling and systems thinking to manage this complexity by explicitly considering three attributes of complex, adaptive systems, whereby (i. Their importance lies in offering prospective scenarios that facilitate agricultural decision-making, productivity improvements, and sustainable management practices. Furthermore, they are essential for assessing the effects of climate change, water resource variability, and technological adaptation strategies in modern agricultural systems (Nicholson et al., 2021)but how food security has been conceptualized and evaluated within agricultural systems has not been systematically evaluated. We reviewed the literature on agricultural systems analyses of food security at the household- and regional-levels, finding that the primary focus is on only one dimension of food security—agricultural output as a proxy for food availability. Given that food security comprises availability, access, utilization and stability dimensions, improved practice would involve more effort to incorporate food access and stability indicators into agricultural systems models. The empirical evidence base for including food access indicators and their determinants within agricultural systems models requires further development through appropriate short and long-term investments in data collection and analysis. Assessment of the stability dimension of food security (through time.

The emergence of the first agricultural simulation models dates back to the early 1980s (although they can be traced back to the 1940s), driven by the increasing availability of personal computing and the interest in linking climatic, soil, and biological variables. Pioneering models such as CERES, EPIC, and SUCROS laid the groundwork for today's systems, which now cover a wide range of crops and applications. Simultaneously, the USAID-funded IBSNAT project consolidated the DSSAT Suite, integrating CERES with models such as SOYGRO and PNUTGRO and establishing international guidelines for data collection, thereby strengthening global technology validation and transfer efforts (Jones et al., 2017a). These developments laid the foundation for crop modeling globally, enabling the expansion and sophistication of simulation tools (Xiao et al., 2024)but is challenged by complex climate–crop–soil management interconnections across space and over time. Here we develop a hybrid approach combining agricultural system modelling, machine learning and life cycle assessment to spatiotemporally co-optimize fertilizer application, irrigation and residue management to achieve yield potential of wheat and maize and minimize greenhouse gas emissions in the North China Plain. We found that the optimal fertilizer application rate and irrigation for the historical period (1995–2014.

But broadly speaking, crop modeling is based on a series of key concepts that integrate disciplines such as plant physiology, ecology, mathematics, and computer science. Crop models are classified according to their focus and level of detail (Holzworth et al., 2015; Jones et al., 2017b)the application of agricultural production systems modelling has rapidly expanded while there has been less emphasis on model improvement. Cropping systems modelling has become agricultural modelling, incorporating new capabilities enabling analyses in the domains of greenhouse gas emissions, soil carbon changes, ecosystem services, environmental performance, food security, pests and disease losses, livestock and pasture production, and climate change mitigation and adaptation. New science has been added to the models to support this broadening application domain, and new consortia of modellers have been formed that span the multiple disciplines. There has not, however, been a significant and sustained focus on software platforms to increase efficiency in agricultural production systems research in the interaction between the software industry and the agricultural modelling community. This paper describes the changing agricultural modelling landscape since 2002, largely from a software perspective, and makes a case for a focussed effort on the software implementations of the major models.We review the current state of agricultural systems science, focusing in particular on the capabilities and limitations of agricultural systems models. We discuss the state of models relative to five different Use Cases spanning field, farm, landscape, regional, and global spatial scales and engaging questions in past, current, and future time periods. Contributions from multiple disciplines have made major advances relevant to a wide range of agricultural system model applications at various spatial and temporal scales. Although current agricultural systems models have features that are needed for the Use Cases, we found that all of them have limitations and need to be improved. We identified common limitations across all Use Cases, namely 1:

- **Process-Based (Mechanistic) Models:** These models break down crop growth and development into individual processes such as photosynthesis, respiration, transpiration, and nutrient uptake. Each process is represented by mathematical equations that describe the underlying mechanisms. Examples include APSIM and DSSAT, which simulate processes such as carbon sequestration and water movement in the soil (Gavasso-Rita et al., 2024).
- **Empirical Models:** These are based on statistical relationships between input (e.g., temperature, precipitation) and output (e.g., yield) variables. They are simpler but less accurate under changing conditions (Elahi et al., 2024).
- **Hybrid Models:** These combine elements of both approaches, seeking to balance complexity with practicality. For example, a hybrid model may use mechanistic equations for photosynthesis and empirical relationships for biomass partitioning.
- **Functional-Structural Models (FSPM):** These focus on three-dimensional morphology and processes at the plant or organ level, complementing process-based models operating at the canopy level (Muller & Martre, 2019).

Furthermore, the increasing availability of remote sensing (Weiss et al., 2020)fibers, fuel, and raw materials that are paramount for human livelihood. Today, this role must be satisfied within a context of environmental sustainability and climate change, combined with an unprecedented and still-expanding human population size, while maintaining the viability of agricultural activities to ensure both subsistence and livelihoods. Remote sensing has the capacity to assist the adaptive evolution of agricultural practices in order to face this major challenge, by providing repetitive information on crop status throughout the season at different scales and for different actors. We start this review by making an overview of the current remote sensing techniques relevant for the agricultural context. We present the agronomical variables and plant traits that can be estimated by remote sensing, and we describe the empirical and deterministic approaches to retrieve them. A second part of this review illustrates recent research developments that permit to strengthen applicative capabilities in remote sensing according to specific requirements for different types of stakeholders. Such agricultural applications include crop breeding, agricultural land use monitoring, crop yield forecasting, as well as ecosystem services in relation to soil and water resources or biodiversity loss. Finally, we provide a synthesis of the emerging opportunities that should strengthen the role of remote sensing in providing operational, efficient and long-term services for agricultural applications techniques has prompted the assimilation of novel indices such as the leaf area index (LAI) into process models to improve the accuracy of growth and yield simulations. However, this strategy may not fully compensate for the uncertainties in remote sensing data and crop models, so the incorporation of higher-resolution datasets, such as Sentinel-2, is necessary to improve simulations in minor crops and rain-fed irrigation systems (Tiruneh et al., 2023). Thus, among the strengths of crop models, we can highlight the following:

- **Predictive capacity:** They offer detailed simulations that incorporate physiological and environmental interactions, while ML approaches excel at capturing complex nonlinear relationships.
- **Scenario versatility:** They allow for the evaluation of multiple management scenarios, climate change, and resource conservation practices, facilitating medium- and long-term planning.
- **Decision support:** When integrated into Decision Support Systems (DSS), these models provide agronomic recommendations based on quantitative simulations.

However, like any tool, they have weaknesses and limitations, as noted in the literature:

- **Data requirements:** They demand detailed climate, soil, and management data, which are often nonexistent in small-scale systems.
- **Computational complexity:** High-resolution spatial and temporal models require significant computing resources.
- **Uncertainty and validation:** Remote sensing assimilations do not fully compensate for the uncertainties

inherent in satellite measurements and model parameters (MDPI).

But beyond agronomic predictions, however, these models allow for the estimation of economic indicators (costs, revenues, profitability) and the assessment of risks in the face of climate variability, as previously noted. Net marginal return simulations, provide information for subsidy policies and agricultural insurance programs, improving the financial resilience of producers. Therefore, cropping system modeling undoubtedly offers strengths, and it is expected that in the future, simulations will be more accurate, scalable, and adaptable to diverse contexts. Nevertheless, as mention before, challenges related to data availability, results interpretation, and technological accessibility require continued attention. Consequently, it is emphasized that interdisciplinary cooperation and investment in data infrastructure can maximize the potential of these tools to promote more productive, resilient, and sustainable agricultural systems.

DEVELOPMENT

Currently, crop production using existing land resources in agriculture has caused great changes in the earth's surface. Therefore, the organization of production by using agricultural lands correctly and efficiently in accordance with agricultural requirements should be carried out on the basis of scientific justification of the agricultural system in the production process. The methods used in land cultivation in areas where crop products will be produced involve the sequential and appropriate implementation of numerous elements such as irrigation, chemical and agro-biological reclamation works, the application of fertilizers in differentiated composition and norms, and agro-ameliorative measures. The agricultural system, which has been used and preserved from ancient times to the recent past, characterizes a period characterized by population mobility and land cultivation. In general, crops are grown on lands that have been used for certain years without vegetation. Consequently, after a few years, the natural productivity of the soil and cultivated plants decreases. Often, these areas are preserved and reused without paying attention to them (Asan & Demir, 2016).

As the number of people living in the regions and their density increase, land cultivation is carried out in limited areas due to land reduction. With the establishment of permanent settlements, the use of arable land decreases. This, in turn, is characterized by greater intensity in crop production and the demand for greater volumes of crop production. At the beginning of the 19th century, the agricultural system was of great economic importance in the agricultural sector. Recently, the main goal of studying all morphological and technological features of the landscape is to form an agricultural system based on the agro-landscape. Agricultural systems with alternative indicator boundaries are attributed to such systems.

The widespread use of alternative agricultural systems is considered to be the main indicator that hinders the productivity of agricultural crops. Therefore, concepts such as "dynamically balanced" or sustainable agriculture began to spread more widely in the agricultural sector. Both of these accepted concepts should not affect the ecological balance of the environment while meeting the changing needs of the population for ecologically clean and reliable food products (Jat et al., 2010) . Among the existing systems, artificially formed agroforestry ecosystems are considered the best system. In order to maintain ecological balance, these systems are created by optimally organizing the combination of forests with different types of trees in the traditional existing ecosystem.

The development of agroforestry ecosystems in addressing urbanization problems creates conditions not only for reducing the flow of people to cities, but also from a socio-economic perspective. The use of trees for various purposes increases the efficiency of performing certain tasks. Trees in the agroforestry system help to form nitrogen nutrients in the soil, and food products are grown from additional fruit trees. In addition, trees are used to create furniture and medicines as well as feed reserves in livestock farming. The conducted analyses show that the "Agroforestry ecosystem" based system increases the level of self-sufficiency in agricultural production compared to the traditional system, and reduces the monoculture of produced products.

For a long time, certain indicators reflecting the efficiency of the "agroforestry ecosystem" have been accepted. Despite this, in the recent past, when the high achievements of scientific and technical progress were applied to production, a comprehensive approach was applied to their study. At the same time, ecological agriculture is accepted as an alternative to industrial-based agriculture. The integration of the crop and livestock production systems into this system should ensure the efficient use of natural resources in agriculture by improving the environmental situation in the long term. Agricultural production systems should reliably improve the living standards of the population working in these systems. Agroforestry ecosystems, which ensure sustainable production in sustainable agriculture, imply the optimal use of improved agricultural production areas with their high productivity, universality and uniqueness in multiple directions.

Therefore, the formation of efficient and sustainable agricultural production is based on the creation and maintenance of supporting alternatives in multiple directions:

- Creation of subsystems that will ensure adaptation in the fields of crop and livestock farming.
- Creation of subsystems for the protection and provision of biological diversity.
- Subsystems for controlling the formation and productivity of nutrients in the soil.
- Subsystems for controlling weeds, plant diseases and pests that arise in the soil.
- Subsystems for controlling the efficient use of natural resources and pastures in agriculture.
- Subsystems for controlling energy conservation.
- Subsystems for evaluating the profitability of the production system and its application.
- Subsystems for protecting the ecosystem.

The modern stage of development in agriculture, with its adaptation to environmental conditions, involves finding new opportunities for the formation of agroforestry ecosystems with a large number of components, selecting and evaluating indicators in terms of meeting agroecological requirements. These requirements are the basis for the coordination of agricultural systems with landscape features, i.e., the relief of the area, agroecological indicators, and microzonal characteristics of the territories, such as soil erosion risk (Kastanov et al., 1994). Based on the efficient use of natural resources, these systems contribute to the organization of ecologically acceptable agricultural areas in accordance with the technological characteristics of the landscape, and to the establishment of a balance between landscape-ecological and socio-economic subsystems in agricultural production (Wästfelt & Zhang, 2016).

Ecological regulation of special alternative agricultural systems, such as agroforestry ecosystems, in accordance with economic indicators allows for the implementation of measures such as expanding the composition of the biosphere by species and optimizing the technologies used in biological processes. At the same time, agroforestry systems contribute to the elimination of existing shortcomings in agricultural systems by providing a large-scale stimulus to economic and ecological development in the agricultural sector. Their basis consists of the existing environmental social organizers that will ensure the sustainable development of economic systems in the area.

In modern times, all areas of agriculture have a high level of mechanization. Although this level of mechanization has a positive effect on increasing productivity, the technical means used have a negative impact on the environment. The formation of problems with this approach to the issue has not been acknowledged for many years. In this regard, it is necessary to carefully approach the scientific ideas put forward under the title "Environmental Problems in Agriculture," which reflects the first comprehensive analysis of ecological impacts in agriculture. The most important initial indicator of environmental degradation as a result of ecological impacts is the loss of biological diversity. Despite this, the main factor here is the indifferent approach of developing countries to the loss of many species in crop and livestock farming.

The second most important indicator of environmental degradation is the excessive accumulation of nitrogen and phosphorus in groundwater and surface waters as a result of leaching from fertilized agricultural fields. All this creates a serious threat through the leaching of biogens. Negative ecological impacts such as acid rain accelerate erosion and lead to loss of soil fertility (Çelik & Acar, 2017). Deforestation is another important consequence of environmental degradation as a result of ecological impacts. Forests are one of the most important areas that play a significant role in maintaining ecological balance at the global and regional levels.

Today, they act as a source of biological resources and diversity, as well as genetic materials necessary for the production of biotechnological products. In order to reduce the negative impact on the ecosystem, developed countries continue their scientific research work toward creating new agricultural systems, taking into account their economic and social indicators. This direction is expressed in the literature as "alternative agriculture." At the initial stage of applying alternative agricultural systems, they are based on the widespread use of organic fertilizers, optimization of the production cycle, and minimal use of chemical agents in the protection of plants and animals. Along with these measures, this system envisages reducing the use of non-renewable energy sources and increasing the use of non-traditional energy sources (Asan, 2017).

Subsequently, the organic farming system began to be applied as a new direction in agriculture. In the initial stage of applying the organic farming system, the ecological efficiency of agricultural products increased significantly. In the last quarter-century, the implementation of production based on adaptive landscape management, taking into account environmental indicators and reducing impacts on the ecosystem in agriculture, is considered the most favorable system. Currently, due to the difficulties in obtaining functional information about the indicators of natural processes in certain areas, farms need theoretically reliable and tested methodological support. This allows for the prediction of the current state of activities that may cause anthropogenic impact on the environment in solving certain problems related to the ecosystem, and enables verification through the evaluation of measurements to be carried out (Karchagina, 2006).

The compliance of the ecosystem formation process in large areas of agriculture with the law of development varies depending on the geographical location of the zone and the existing altitudes. Depending on the different altitudes of the areas, certain different indicators are observed and characterized in the distribution of heat and moisture. The formation of the radiation balance is characterized by the amount of annual precipitation, its interruption, and sharp increases depending on the altitude of the zones. According to Russian scientists V.V. Dokuchayev, A.A. Grigoriev, and M.I. Budyko, this law is formed in accordance with the changing laws of the geographical situation characterizing the location of the zones. Therefore, the energy balance of the zones is characterized by the amount of precipitation and heat received. Depending on the location of the zones, the impact of anthropogenic activities on the environment in these areas occurs at all times, which leads to certain transformations in natural systems, where the role of society and nature is assessed in a complex and interconnected way (Mustafaev, 2004).

The totality of previous anthropogenic impacts affects plant production in the area, thereby reducing ecological sustainability and natural potential. The assessment of the landscape structure is carried out by measuring such indicators. It is necessary to assess the impact of anthropogenic activities on the natural system during activities in an environment surrounded by a certain natural setting. For this purpose, it is necessary to develop an integral mathematical model in accordance with the geographical laws of the zones, which allows determining the quantity of indicators that determine the accuracy and quality of measurements carried out in certain areas (Chernikov et al., 2001). This mathematical model should represent a modeling of the natural system, which allows determining quality indicators by conducting measurements in areas covered by the natural system. This mathematical model is used to measure natural climatic indicators corresponding to the location of the zones and characterizes a certain integral value of the landscape product (Burovskiy, 1995).

The plant yield of the landscape is determined based on the change in integral indicators characterized by the state of the natural system: the sum of solar radiation, which can be determined based on the average value corresponding to the specific indicator; the duration of the frost-free period, depending on the type of plant grown; the duration of the active vegetation temperature above [specific temperature] (days); the sum of the daily average temperatures; the amount of atmospheric precipitation falling during the year; the amount of atmospheric precipitation falling during the warm season; evaporation; and the duration of the vegetation period.

Next, we present the formulation of a fully developed mathematical model is accomplished by analyzing a small number of indicators of the natural system that provide potential productivity and taking into account the crop yield despite all the difficulties. The dependence between the crop yield of the area (Y) and the specific indicators of the existing natural system is determined. For this dependence, indicators such as the sum of the average daily air temperature, the duration of the vegetation period in plant production, soil fertility indicators, and the amount of precipitation are used (see equation 1).

$$Y_i = Y_{max} \cdot K_t \cdot K_w \cdot K_T \qquad (1)$$

whre:

- Y_i – is the yield of the plant according to the natural system;
- Y_{max} – is the maximum yield of the plant under good hydrothermal conditions;
- K_t – is the coefficient of the specified temperature regime during the vegetation period;
- K_w – is the coefficient of the specified moisture regime;
- K_T – is the coefficient of the specified duration of the vegetation period.

Plants have a need for various natural system parameters such as temperature, humidity, and duration of the growing season. The yield of the product depends on the temperature and humidity regime, duration of the growing season, the level of utilization of these parameters, optimization of the costs incurred, and the type of plant, resulting in the final result, see equation 2:

$$K_t = f\left(\sum t_i / \sum t_{opt}\right), K_w = f(W_i/W_{ort}) \text{ and } K_T = f\left(T_i / T_{opt}\right) \qquad (2)$$

where:

- $\sum t_i$ average daily temperature during the vegetation period;
- $\sum t_{opt}$ – average daily optimal temperature during the vegetation period;
- $W_i = O_{si}$ – amount of precipitation;
- T_i – duration of the vegetation period;
- T_{opt} optimal duration of the vegetation period.

Considering the law of tolerance in obtaining a crop product, (K_w) the level of moisture supply is approximated by a parabola, the following dependence can be used in mathematical notation according to V.V. Shabanov (Shabanov, 1981), see equation 3:

$$K_W = \left(\frac{E_i - E_{min}}{E_{opt} - E_{min}}\right)^{\beta} \left(\frac{E_{max} - E_i}{E_{max} - E_{ek}}\right)^{\beta\left(\frac{E_{opt}-E_{ek}}{E_{ek}-E_{min}}\right)} \quad (3)$$

where:

- E_{opt} is the biological optimal water requirement of the plant;
- E_{ek} the ecological water requirement of the plant;
- E_i the actual water requirement of the plant;
- E_{min},E_{max} the water requirement of the agricultural plant correspon-ding to the lower and upper limit norm equal to zero yield.
- γ_i is an indicator characterizing the deviation from the moisture supply of the plant.

In the written formula, the first part of the equation characterizes the full compliance of the moisture supply of agricultural plants with their productivity. The second part determines the degree of influence of the water supply norm on plant yield, such as irrigation during the process of soil layer rotation cultivation. As can be seen, the main quality criteria for agricultural plants are considered to be the biologically active temperature and the total temperature supply. The average daily temperature during the vegetation period from sowing of the plant in spring to the ripening of the crop is considered to be equal to or higher than +3-10^{0}C, depending on the type of plant. Three types of heat supply are used for the vegetation period until the harvest of agricultural crops. The maximum temperature value is+3-10^{0}C $\sum t_i$) (depending on the type of plant. The maximum ($\sum t_{mak}$) (and minimum $\sum t_{min}$) (biologically active temperature values that ensure the use of moisture by the plant during the vegetation period are determined by the necessary heat resource of the region. The coefficient (K_t) determining the temperature regime during the vegetation period is determined as follows (Kashtanova, 2001), see equation 4.

$$K_t = \left(\frac{\sum t_i - \sum t_{min}}{\sum t_{max} - \sum t_{min}}\right)^{\beta} \left(\frac{\sum t_{max} - \sum t_{opt}}{\sum t_{max} - \sum t_i}\right)^{\beta\left(\frac{\sum t_{max}-\sum t_{opt}}{\sum t_{opt}-\sum t_{min}}\right)} \quad (4)$$

where:

- $\sum t_i$ is the actual value of the air temperature during the vegetation period;
- $\sum t_{opt}$ – the optimal value of the air temperature that will ensure the moisture of the plant during the vegetation period;
- $\sum t_{min}$ – the minimum value of the air temperature that will ensure the moisture of the plant during the vegetation period;
- $\sum t_{max}$ – the maximum value of the air temperature that will ensure the moisture of the plant during the vegetation period.

The heat supply coefficient graph is assumed to be symmetrical, despite its curved shape. The optimum air temperature for photosynthesis is assumed. The arithmetic mean value between the maximum and minimum air temperatures for photosynthesis during the vegetation period is taken, see equation 5.

$$\sum t_{opt} = (\sum t_{min} + \sum t_{mak})/2 \quad (5)$$

Determination of the coefficient of the duration of the vegetation period (K_T) . This coefficient is determined depending on the interaction of the number of days of the duration of the vegetation period with the number of days in the year(see equation 6).

$$K_T = T_i/365 \quad (6)$$

Modeling the process of measuring natural ecological system indicators in the area begins with measuring the climate impact that characterizes the functional entry into the complex. On the one hand, the climate is characterized by aridity with warming, and on the other hand, by humidification with cooling, and the dependence is formulated in the following form (see equation 7).

$$K_W = K_T(O_s, T) \quad (7)$$

where:

- Y - is the temperature value during the vegetation period.
- O_s is the amount of precipitation during the vegetation period.

The indicator characterizing heat-induced drought climate zones is expressed as follows(see equation 8):

$$1{,}2 \cdot K_t = K_T(1{,}2 \cdot T, 0{,}8 \cdot O_S) \quad (8)$$

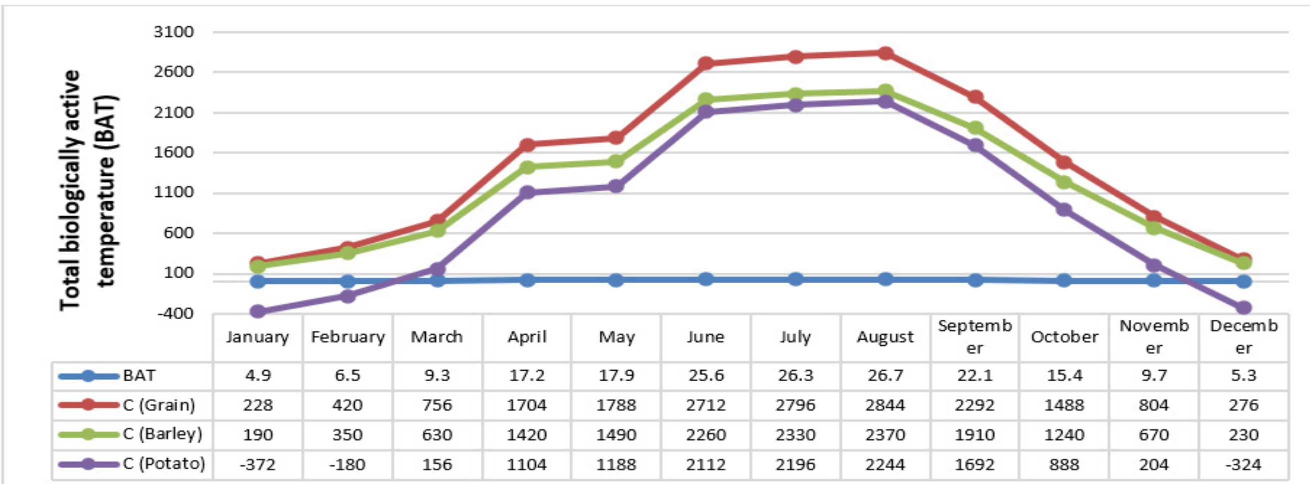
Suitable for humidification climate with cold passage it is possible to assume (Minenko & Gamazina, 2014; Tebleeva, 2000) (see equation 9):

$$0{,}8 \cdot K_W = K_T(0{,}8 \cdot T, 1{,}2 \cdot O_S)$$

$$K_t = f\left(\sum t_i / \sum t_{opt}\right), K_w = f\left(W_i/W_{opt}\right) \text{ and } K_T = f\left(T_i / T_{opt}\right) \quad (9)$$

Below we will provide an example to show the usefulness of these equations and approach. Each temperature regime is adopted taking into account the moisture content that will ensure the necessary crop production, which is based on the specific geographical indicators of the zone. Figure 1 allows predicting the exact sowing time, optimal vegetation period, and productivity depending on the change in biologically active temperature by months of the year in the production of grain, barley, and potato crops by region.

Fig 1. Annual change in biologically active temperature in crop production.



Source: own elaboration.

Considering that the temperature during sowing of grain and barley crops is above +3°C, and during planting of potatoes is above +8°C, it is considered acceptable to sow grain and barley in the region in mid-January, and to plant potatoes in the first ten days of March. Since the region is located in the foothills, it covers the period close to the harvest in August, so the maximum value of biologically active temperature falls in June and July. This correlates with the results shown in Table 1.

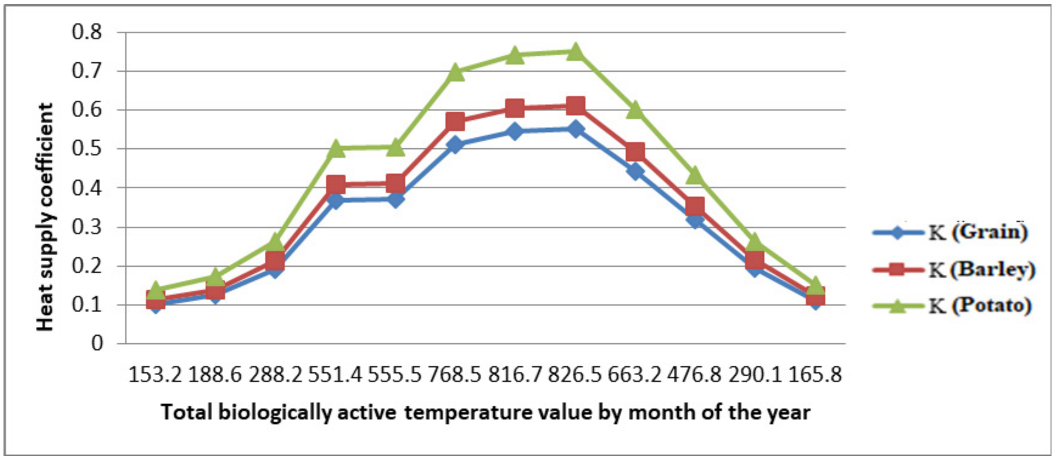
Table 1. Values of the heat supply coefficient depending on the biologically active temperature in the production of grain, barley, and potatoes in the region by month of the year.

Months	January	February	March	April	May	June	July	August	September	October	November	December
CBAT	153,2	188,6	288,2	551,4	555,5	768,5	816,7	826,5	663,2	476,8	290,1	165,8
Grain	0,102	0,125	0,192	0,3676	0,370	0,512	0,544	0,551	0,442	0,317	0,193	0,110
Barley	0,113	0,139	0,213	0,408	0,411	0,569	0,604	0,612	0,491	0,353	0,214	0,122
Potato	0,139	0,171	0,262	0,501	0,505	0,698	0,742	0,751	0,602	0,433	0,263	0,150

Source: own elaboration.

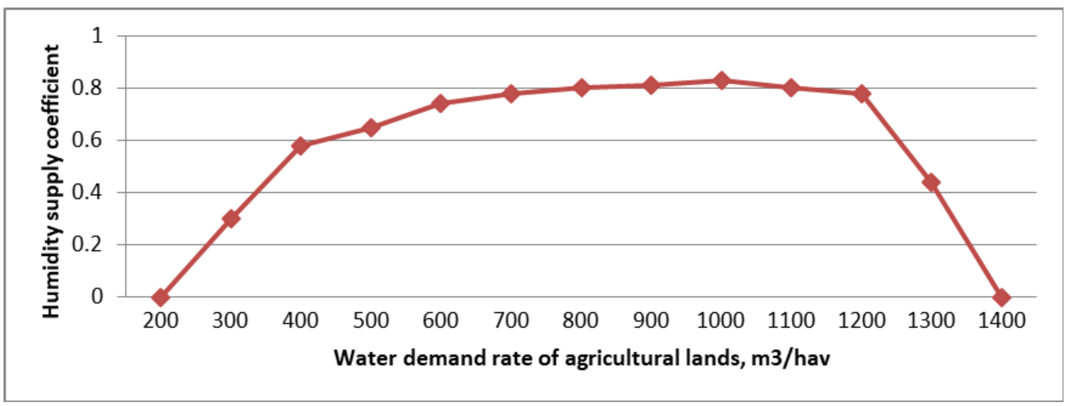
In the region analyzed, it is observed that the maximum value of the heat supply coefficient (Figure 2) varies between 0.7...0.75 for grain crops in June and July, 0.58...0.60 for barley crops, and 0.51...0.55 for potatoes during the vegetation period. The increasing change and maximum values of heat supply at the beginning of the vegetation period for cultivated plants should be taken into account when forecasting crop yields. This tipically correletaes with moisture supply coefficient (Figure 3).

Fig 2. Changes in the heat supply coefficient depending on the biologically active temperature in the production of grain, barley, and potatoes by months of the year.



Source: own elaboration.

Fig 3. Dependence of the moisture supply coefficient on the water demand rate of soils.



Source: own elaboration.

It is clear that the drought resistance of the plant depends on the increase in heat supply ($\sum t_i$).. Changes in drought resistance occur with a small indicator towards heat supply($\sum t_i$) , and for moisture lovers, with a large indicator towards moisture supply (E_i) . If the multi-year average indicators of the natural system such as moisture (E_i) and heat supply ($\sum t_i$)are known for a geographical zone, the plant product can be determined taking into account the technological characteristics of the agrolandscape in accordance with the moisture and heat supply of various cultivated plants. This methodology, which is proposed for use, covers the necessary areas in the cultivation of agricultural plants. The product obtained from plants planted in zones corresponds to the different geographical and natural ecosystems in which they are located. Thus, the e model used (1) determines the boundary condition of the criterion for measuring the integral indicators of the product in the natural ecosystem for determining the landscape product.

CONCLUSIONS

Modeling cropping systems that integrate agroecological requirements is essential for the development of sustainable and productive agriculture. Through an interdisciplinary approach that combines elements of plant physiology, ecology, mathematics, and computer science, it is possible to accurately predict the yield of crops such as wheat, barley, and potatoes, adjusting to the climatic, soil, and technological conditions of the agricultural landscape. The mathematical models developed allow for the evaluation of how factors such as temperature, humidity, and the length of the growing season influence agricultural productivity, facilitating adaptive decisions in the face of environmental changes. Furthermore, it is important to highlight the significance of agroforestry ecosystems as a strategic solution for balancing agricultural productivity with ecological conservation, by incorporating multifunctional trees that enrich the soil, diversify production, and mitigate pressure on natural resources. Similarly, the transformation toward resilient agricultural systems requires alternatives that harmonize the ecological, economic, and social functions of the agricultural landscape. To this end, we developed a model based on natural indicators that allows us to identify optimal temperature and humidity levels for different crops based on geographic location. This not only optimizes resource use but also mitigates the effects of anthropogenic activity on the environment, such as biodiversity loss, water pollution, and deforestation. However, it is important to emphasize that the success of these systems depends on a solid data infrastructure, interdisciplinary cooperation, and public policies geared toward agroecological transition, enabling efficient and sustainable long-term planning.

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