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AGROTECHNOLOGICAL AND ECONOMIC IMPORTANCE OF THE HEAT SUPPLY FORECASTING FOR THE POST-HARVEST PERIOD IN THE DRY STEPPE ZONE OF UKRAINE

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Abstract

The purpose of the study is to assess available agroclimatic resources and forecast heat supply in the post-harvest period in the Dry Steppe zone of Ukraine. Dynamic analysis of agrometeorological indices was performed by comparing the average long-term values. The correlation analysis of the agroclimatic conditions of the growing season revealed a significantly strong dependence of individual meteorological indices on the availability of heat resources in the post-harvest period. It was established that the sum of effective and active temperatures for the post-harvest period has a weak and moderate correlation with the mean monthly air temperature and atmospheric aridity index in April and May, while in June the coefficient increases. The highest correlation of the specified meteorological parameters was recorded for the period 1992–2021. Linear regression models of the dependence of the sum of active and effective temperatures during the post-harvest period with high adequacy (R^2=0.69–0.70) were developed. The models allow forecasting the temperature conditions for placing the fore crops for winter wheat. Besides, they are useful for better selection of varieties and hybrids for the post-harvest crops of sunflower and millet. As a result, 28.31% higher yields of millet, and 15.77% higher yields of sunflower in 2022-2023, comparing to 2021, were collected owing to better choice of suitable crops' genotypes. The economic effect of the methodology reached additional 220 EUR/ha for millet, and 80 EUR/ha for sunflower, respectively. The implementation of this method contributes to a more productive use of natural resources and an increase in crop productivity and profitability.

Key words *post-harvest period, hydrothermal conditions, statistical analysis, linear model, agricultural resources forecasting*

INTRODUCTION

While the technical level of agriculture improves, the importance of agrometeorological forecasts increases, and the scope of their application expands. The latter is especially true for intermediate post-harvest crops, grown under irrigated conditions [20]. Currently, Ukrainian farmers have practical experience in postharvest and cultivation of forage crops, green manure crops, and vegetables. However, the full cycle of cultivation of cereals and oil crops is of greater interest, and this question has not been adequately studied. Under such conditions, the time factor acts as an additional limiting factor, as a category that limits hydrothermal and insolation resources, and determines the possible selection of crops, their varietal and hybrid composition, and cultivation technology. Thus, the prediction of the supply of heat resources acquires high significance.

In general, the methodology for the evaluation and forecasting of agroclimatic resources is complicated due to its dynamism and uncertainty. It is also impossible to ignore current climate change [2, 4]. There are quite a lot of special studies on the assessment of agroclimatic resources from the point of view of optimising the placement and cultivation in different zones of field crops, vegetables, and fruits [14, 15, 16]. However, insufficient attention was paid to the residual post-harvest period in the Dry Steppe zone of Ukraine in these studies [1].

Forecasting the heat resources of the potential production period will contribute to the most rational use of climatic and weather conditions to ensure the highest possible probability of guaranteed achievement of the expected crop productivity. The development and mastering of forecasting methods is the basis for both adaptive cultivation technologies and rational use of agro-climatic resources [12].

There are common methods of forecasting the heat supply during the growing season, which are based on the revealed correlations between the dates of the beginning of spring and the total heat income [21, 22]. The intricacy of the computations and the need for specialized meteorological data, which is not generally available, are their main drawbacks. In our opinion, methods based on the dynamics of the temperature regime and rainfall, which determine the possibility of second crop cultivation, will have greater practical importance. The most important is the active vegetation period, which is the part of the season between dates with an air temperature of more than +10°C. The start and finish of the growing season are therefore recorded in Davitai's writings between the dates of the air temperature shift through +10°C. The study has established that there is a connection between the date of the air temperature transition through +10°C and the total amount of heat income ($\Sigma t>10°C$) there is a connection, which in most geographical areas is reflected in high values of correlation coefficients [3]. The study's scientific validation of the relationship between the length of the growing season and the timing of spring's arrival is crucial. This allows us to predict the sum of temperatures above +10°C for the growing season or its certain intervals, as well as the duration of the growing season.

Such empirical models have good reliability because they take into account the most important factors that determine not only the current growing conditions, but also the patterns of ontogenetic changes in plants [10].

Therefore, this approach could be used to predict the heat supply and the economic value of the postharvest period, since it is known that heat and moisture resources undergo significant annual fluctuations, while insolation resources are sufficient for plant photosynthesis in most areas. Thus, agrometeorological variables such cycle start and termination dates, sums of active and effective temperatures, and hydrothermal indices are more susceptible to study and model participation when assessing the heat supply of the post-harvest period. However, if the termination of the growing season in the post-harvest period is due to the transition of temperatures below the biological minimum, then the beginning relates to the harvesting of the previous crop. However, practical experience shows that it also depends on the current environmental conditions. Numerous studies have established that the speed of plant development is often determined by the course of the thermal regime, although the influence of moisture availability is also important. Thus, according to the results of the analysis of agrometeorological conditions during the cultivation of oil crops (sunflower, oil flax, safflower), the duration of interphase periods depended on the factors of the external environment, such as heat and moisture, while during the period of formation of generative organs, the greatest influence was found to be due to the hydrothermal coefficient [13].

The aim of the study is to assess the agroclimatic resources and forecast the heat supply of the post-harvest period of the Dry Steppe Zone of Ukraine to manage the cultivation of various groups of crops at the post-harvest sowing.

MATERIALS AND METHODS

The study was performed based on a scientific approach using monographic, analytical, comparative, and statistical methods. The source of the initial information is the results of observations of Kherson Hydrometeorological Centre. The analysis was carried out by comparing the average long-term characteristics of the agrometeorological parameters. The meteorological values for the period 1961–1990 and the current average values were determined as the base values recommended by the World Meteorological Organisation as a climatic norm.

To assess temperature conditions and thermal resources, the limits of temperature conditions under which plant life processes are possible are traditionally used – the temperature of the beginning of growth (biological minimum) and the maximum temperature. For promising post-harvest crops such as millet, sunflower, and soybean, the biological minimum is +10°C, which is the basis for the subsequent calculations.

Consequently, research on variations in the total active air temperature is useful for the implementation of post-harvest technology.

They compute the average monthly air temperature for the time by multiplying it by the number of days in a given month, and they compute the total monthly temperature for a portion of the month by multiplying the average monthly temperature by the number of days in this period.

Considering the high dependence of the growing season duration on climatic conditions, it is also important to assess growing conditions according to multi-year complex indicators, which reflect the influence of weather conditions on the production processes.

Thus, a wide range of coefficients are used to assess the aridity of a season or a certain period.

According to the studies, Ped proposed to use the general aridity index (Si), which is calculated as the difference between temperature anomalies, precipitation, and soil moisture storages [8, 9].

Arid conditions are reflected by positive values of Si, while humid conditions are characterized by negative values of the index. Since atmospheric aridity (Sa) plays the main role in the irrigated conditions, this part of the water balance is of decisive importance, which allows to be considered separately as the difference between temperature and precipitation anomalies (Eq. 1):

$$S_a = \frac{\Delta T}{\sigma_T} - \frac{\Delta R}{\sigma_R}, \qquad \text{(Eq. 1)}$$

where:

ΔT; ΔR – deviation of average monthly values, respectively, of air temperature (°C) and precipitation amounts (mm); σ_T; σ_R – root mean square deviation of mean monthly values, respectively, of air temperature (° C) and precipitation amounts (mm) [7].

Correlation and linear regression analysis were performed using common statistical methodology within the framework of MS Excel software environment [5].

RESULTS AND DISCUSSIONS

Analytical grouping of the indicators, statistical indices do not provide a complete quantitative description of the influence of individual factors on the changes in the level of heat supply during the period, which necessitated the use of the correlation-regression method (Table 1).

The correlational analysis of the degree and nature of the relationship between individual agrometeorological indicators demonstrates the presence of some peculiar characteristics. During 1945–2021, the sum of effective and active temperatures for July–October, as a potential post-harvest period, had a weak to moderate correlation with mean monthly air temperature for April and May, while an increase to a significant level was observed for June.

The interconnection for the July–September period is strong.

Higher values of the correlation coefficient in June and July–September were also recorded for 1961–1990 and 1992–2021 periods.

In our opinion, this is related to cyclical thermodynamic processes in the atmosphere and could be used in forecasting the availability of thermal resources in the post-harvest period.

Table 1. Correlation Connections Between the Mean Monthly Air Temperature and Thermal Conditions of the Post-harvest Period

Sum of the temperatures in the post-harvest period	Mean monthly air temperature, (° C)					
	IV	V	VI	VII	VIII	IX
	1945–2021					
$\sum T_{effective}$ (VII–X)	0.29	0.22	0.53	0.74	0.74	0.77
$\sum T_{active}$ (VII–X)	0.32	0.27	0.56	0.77	0.81	0.76

$\sum T_{effective}$ (assessed)	0.50	0.47	0.68	0.70	0.76	0.69
$\sum T_{active}$ (assessed)	0.45	0.41	0.58	0.60	0.65	0.62
	1961–1990					
$\sum T_{effective}$ (VII–X)	0.24	0.35	0.42	0.62	0.70	0.63
$\sum T_{active}$ (VII–X)	0.32	0.45	0.51	0.66	0.76	0.63
$\sum T_{effective}$ (assessed)	0.56	0.61	0.54	0.53	0.73	0.61
$\sum T_{active}$ (assessed)	0.46	0.45	0.40	0.43	0.60	0.59
	1992–2021					
$\sum T_{effective}$ (VII–X)	0.44	0.13	0.47	0.72	0.64	0.82
$\sum T_{active}$ (VII–X)	0.41	0.11	0.42	0.77	0.70	0.82
$\sum T_{effective}$ (assessed)	0.55	0.39	0.66	0.68	0.65	0.70
$\sum T_{active}$ (assessed)	0.47	0.35	0.60	0.60	0.51	0.59

Source: Own study.

Considering that the actual beginning of the post-harvest period is determined by the harvesting dates of the fore crop, which significantly depends on the hydrothermal conditions of June – the ripening period of winter wheat, the dates of its ripening were simulated using proven methods and the estimated sums of active and effective temperatures of the remaining period were determined accordingly [11].

The correlation coefficients were shown to have an increase in value for the months of April, May, and June and a minor reduction for the July–October period.

The correlation between the mean monthly air temperature in June and the sum of active and effective temperatures for the estimated post-harvest period in the analysed periods was R=0.40–0.60 and R=0.54–0.68, respectively.

In agrometeorology, complex indices are used to monitor conditions, assess the level of manifestation of individual processes, and forecasting.

The advantage is a more accurate and unbiased simulation of the change and impact of meteorological phenomena, leading to their wide practical application [6, 17, 19].

An analysis of the degree and nature of the relationship between the atmospheric aridity index and air temperatures indicates the presence of similar characteristics.

During the calendar period, a weak and moderate degree of correlation between the studied indices is recorded for April and May and moderate and significant for June. The greatest dependence of the formation of thermal resources on the conditions of July–September is observed (Table 2).

Table 2. Correlation Between Mean Monthly Values of Atmospheric Aridity and Thermal Conditions of the Post-harvest Period

Sum of the temperatures in the post-harvest period	Atmospheric aridity index (Sa)					
	IV	V	VI	VII	VIII	IX
	1945–2021					
$\sum T_{effective}$ (VII–X)	0.30	0.22	0.53	0.73	0.74	0.76
$\sum T_{active}$ (VII–X)	0.33	0.26	0.56	0.77	0.80	0.75
$\sum T_{effective}$ (assessed)	0.51	0.46	0.68	0.70	0.75	0.68
$\sum T_{active}$ (assessed)	0.47	0.40	0.58	0.60	0.64	0.61
	1961–1990					
$\sum T_{effective}$ (VII–X)	0.28	0.36	0.43	0.62	0.70	0.62
$\sum T_{active}$ (VII–X)	0.35	0.45	0.51	0.66	0.76	0.62
$\sum T_{effective}$ (assessed)	0.59	0.61	0.54	0.54	0.73	0.60
$\sum T_{active}$ (assessed)	0.47	0.45	0.41	0.44	0.59	0.58
	1992–2021					
$\sum T_{effective}$ (VII–X)	0.44	0.13	0.48	0.72	0.64	0.82
$\sum T_{active}$ (VII–X)	0.41	0.10	0.43	0.77	0.70	0.81
$\sum T_{effective}$ (assessed)	0.56	0.39	0.68	0.68	0.64	0.69
$\sum T_{active}$ (assessed)	0.48	0.35	0.62	0.60	0.51	0.59

Source: Own study.

As the index of atmospheric aridity (Sa) reflects the conditions of the spring-summer growing season of winter wheat, the grain ripening processes and, accordingly, the harvest period, the correlation coefficients with respect to the sum of temperatures for the period determined by the calculation method are significantly higher. However, even in this case, during the growing season of the fore crop, the values for June (R=0.41–0.68) were higher, compared to April (R=0.47–0.59) and May (R=0.39–0.61).

Such a regularity makes it possible to use the indicated June agrometeorological indices for forecasting heat supply in the post-harvest period. At the same time, in the reference period 1992–2021, a slightly closer relationship is observed. Considering the mentioned above, it was decided to choose this period as the base array.

Corresponding linear regression models were developed based on the obtained values of the parameters' vectors and the intercept terms (Table 3).

Table 3. Linear Regression Models for the Dependence of the Sum of the Air Temperatures in the Post-harvest Period on Mean Monthly Air Temperature and Atmospheric Aridity Index

Sum of the temperatures	Equation of the model	R^2	F_{act}	F_{theor}
$\sum T_{effective\ (VII–X)}$	$8,558+937.2a_1-353.0a_2$	0.532	5.32	0.0113
$\sum T_{active\ (VII–X)}$	$6,161+545.9a_1-199.1a_2$	0.454	3.50	0.0446
$\sum T_{effective\ (assessed)}$	$10,127+1,204a_1-424.8a_2$	0.700	13.0	0.0001
$\sum T_{active\ (assessed)}$	$23,346+2,611a_1-993a_2$	0.686	12.0	0.0002

Notes: a_1 – atmospheric aridity index (Sa); a_2 – mean monthly air temperature of June, ºC.
Source: Own study.

The mean monthly air temperature and the index of atmospheric aridity in June were established to be strongly related to heat supply in the post-harvest period of winter wheat. The linear regression equations are statistically significant, as F_{actual} is greater than $F_{theoretical}$ in all the models. Higher quality is a defining characteristic of the models that characterize the heat supply of the calculated post-harvest period, which also more accurately represents the conditions of the remaining growing season. Therefore, it is possible to recommend the use of such models for the forecast of heat supply in the post-harvest period to make a reasonable selection of crops and varieties for cultivation in such conditions.

The aridity index of the base array 1992–2021 was used to convert this mathematical model in accordance with the actual current values of meteorological indices, since the sum of active temperatures is primarily used to estimate thermal resources and conditions for plant growth and development. Therefore, by simplifying the equation using the following formula, the total active temperatures for the post-harvest period might be anticipated using the current air temperature and the amount of precipitation in June (Eq. 2):

$$Y = 496.458 + 93.589 \times T_{June} - 3.539 \times O_{June} \quad \text{(Eq. 2)}$$

where:
Y – sum of the active temperatures of the post-harvest period, ºC; T_{June} – mean monthly temperature in June, ºC; O_{June} – precipitation amount in June, mm.

The advantages of the latter model are its simplicity and easy access of the data required for calculations, as well as significant statistical accuracy of the obtained forecasts. Among the drawbacks, it should be noted that in some years winter wheat harvesting takes place later, which makes it somewhat difficult to determine the current mean monthly values of air temperature and precipitation.

The economic effect of the implementation of the model for forecasting the sum of active temperatures for Millet and Sunflower crops

We used the generated models to predict the total active temperatures for Odesa Agricultural Research Station conditions in 2022 and 2023. The forecasted values were just 3.8-4.3% different from the actual ones, which were further recorded in the field conditions in the intercourse of agrometeorological observations.

Based on the forecast of the sum of the active temperatures, millet varieties Vitrylo (early-ripening), Polto and Sonechko slobidske (middle-ripening), Myronivske 51 and Denvikske (moderately-late-ripening) were chosen for sowing in 2022-2023. As a result, average yield of millet was 2.81 t/ha, that is significantly better than average yield, harvested in 2021 – 2.19 t/ha (28.31% higher). Cultivation technology peculiarities in 2022-2023 remained unchanged compared to the reference year 2021, therefore, pure economic effect from millet cultivation reached additional 220 EUR/ha (in prices for millet in Ukrainian grain market dated January, 2024).

The same is true for sunflower, cultivated in 2022-2023 in the post-harvest crops. Using the developed models for meteorological forecasts, it was determined that considering the prognostic features of the season, the hybrid Kosmos and the variety Prometei should be selected for sowing, as they would fit best for the predicted temperature regime. As a result, sunflower yield averaged to 1.52 t/ha for Kosmos, and 1.49 t/ha for Prometei in the season 2022-2023, that is 16.92% and 14.62% higher than in the year 2021, respectively, under the same agrotechnological conditions [18]. The pure economic effect in this case reached additional 80 EUR/ha (in prices for sunflower seeds in Ukrainian grain market dated January, 2024) (Table 4).

Table 4. The economic effect of the application of the models to forecast the sum of the active temperatures in 2022 and 2023 for the conditions of Odesa agricultural research station- Case study Millet and Sunflower varieties

Varieties	**2022-2023**		**2021**		**Difference between 2022-2023 and 2021**		**Market price Euro/t**	**Income surplus Euro/ha**
	Sum of active temp. ºC	Yield t/ha	Sum of active temp. ºC	Yield t/ha	Sum of active temp. ºC	Yield t/ha		
Millet								
Vitrylo	2,364	2.32	1,986	1.85	378	0.47	355	166.9
Polto	2,364	2.80	1,986	2.16	378	0.64	355	227.2
Sonechko	2,364	2.54	1,986	2.10	378	0.44	355	156.2
Myronivske 51	2,364	3.10	1,986	2.29	378	0.81	355	287.6
Denvikske	2,364	3.29	1,986	2.55	378	0.74	355	262.7
Sunflower								
Kosmos	2,364	1.52	1,986	1.30	378	0.22	390	85.8
Prometei	2,364	1.49	1,986	1.30	378	0.19	390	74.1

Source: Own results.

Therefore, the developed agrometeorological models have practical value, are effective, reliable and useful tool to assist in right selection of hybrids and varieties for the post-harvest crops cultivation in the conditions of the South of Ukraine.

CONCLUSIONS

Predicting the amount of heat that will be available during the post-harvest phase is crucial for crop productivity planning and varietal composition selection. An evaluation of the agroclimatic conditions in June shows that the post-harvest phase is significantly and strongly dependent on meteorological indices and heat supply. The proposed models for the evaluation of the sum of active and effective temperatures are accurate enough to reflect the thermal conditions of the post-harvest crop growing season, cultivated after winter wheat harvesting. The implementation of this method contributes to the optimization of management decisions regarding the placement of crops and the development of the most productive ways of using natural resources under the irrigated conditions.

The application of the models allowed right choice of millet and sunflower varieties and hybrids for the post-harvest cultivation, that resulted in 15-30% yield output increase. More research should be conducted to improve the accuracy of forecasting models.

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