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ASSESSING THE EFFICIENCY OF USING PRECISION FARMING TECHNOLOGY AND REMOTE MONITORING OF WEATHER CONDITIONS IN THE ACTIVITIES OF AGRICULTURAL ENTERPRISES

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The object of this study was the technology of precision agriculture and remote monitoring of weather conditions. The task to evaluate the effectiveness of using precision farming and precision irrigation technologies in the activities of agricultural enterprises under different conditions, in particular, different climatic and weather conditions, has been considered. To solve the task, a hardware-software system for smart irrigation and remote monitoring of weather conditions in the activities of agricultural enterprises during the cultivation of agricultural crops was designed and described. Results of the system's performance were analyzed in the activities of the Ukrainian agricultural company, which grew potatoes of various varieties in the Kyiv oblast (Ukraine) from 2021 to 2023. The results show that the average yield of potatoes of different varieties without irrigation for three years of observation was 29.74 t/ha, with irrigation – 48.99 t/ha, and with smart irrigation – 55.26 t/ha. At the same time, in the latter case, water, human, and financial resources were saved. The increase in yield with smart irrigation compared to yield with conventional irrigation over the three years of observation was on average 12.8 %. According to the results of the implementation of the hardware-software system for smart irrigation and remote monitoring of weather conditions in Ukraine, the effect of the possible implementation of this system by agricultural companies in the Republic of Kazakhstan was analyzed. The forecast of the average yield of potatoes for the period from 2024 to 2026 was built based on the model of linear weighted moving average, taking into account corrections in the case of using smart irrigation. Data on potato yield from 1990 to 2023 were chosen as the basis. The use of smart irrigation according to the described technology could increase the yield of potatoes of various varieties on average from 31.71 t/ha to 35.78 t/ha in comparison with the forecast values of yield without irrigation at the level of 19.25 t/ha. This confirms the need to apply the transfer of precision farming technologies to increase the yield of agricultural crops, in particular potatoes, and the productivity of agricultural companies

Keywords: efficiency of agricultural enterprises, yield of agricultural crops, smart irrigation, precision farming technologies

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1. Introduction

It is known that irrigation is an artificial process of supplying water to agricultural land to provide plants with the moisture necessary for their growth and development. This method is used when plants are grown that require a special regime of soil moisture or when natural precipitation is not enough to provide optimal conditions for growing crops. In general, agricultural enterprises use several main types of irrigation: surface, drip, sprinkler, and subsoil. Depending on the type of agricultural crop and other factors, one or another type of irrigation is chosen. It should also be understood that the use of any type of irrigation is associated with the consumption of water and energy resources. In addition, the irrational use of water resources can not only lead to unjustified financial costs of the agricultural enterprise but also harm the optimal growth of crops. This can directly affect the yield and disease level of plants.

With the development of precision farming technologies, the demand for installing irrigation systems has increased in such a way as to ensure the optimal way of growing crops while minimizing the costs of the enterprise for water, energy, human resources, etc. Therefore, irrigation in precision agriculture is a technology that uses modern tools and data to optimize the irrigation process, enabling the efficient use of water resources and increasing yields. Implementing such a system in the activities of agricultural enterprises at different levels, depending on the degree of implementation, may be associated with the use of various components. The first most important component that is mandatory in such systems is the installation of sensors for measuring soil moisture. Also, more system systems can use global positioning systems and geographic information systems, using satellite images or drones to assess the condition of crops and determine optimal areas for irrigation. In this process, it is important to develop high-quality software that will make it possible to calculate crop irrigation rates depending on sensor indicators and taking into account the type of crops, soil characteristics, etc. In general, the installation of irrigation systems based on precision farming technologies contributes to the efficient use of water resources, reducing water supply costs and increasing the yield of agricultural crops.

There are a number of agricultural crops for which the need for controlled irrigation is increasing sharply. The expediency of using irrigation systems based on precision farming technologies when growing especially vegetable crops and potatoes is due to their high demand for moisture supply conditions. For example, unlike other agricultural crops, the root system of vegetables has a weak absorption power and therefore they can provide themselves with water only if there are sufficient reserves of it in the soil. In addition, 2/3 of physiologically active root branches are located, as a rule, in the upper (up to 30 cm) layers of the soil, which are most prone to fluctuations in moisture reserves and frequent drying out. It should be noted that, in addition to the amount of irrigation, obtaining an effect from the yield of such crops depends on the choice of the time of the start of irrigation during the day. In addition, information about the weather conditions in the region in which the agricultural land is located is important, in particular, the level of cloudiness, precipitation, humidity in the air, etc.

Similar irrigation systems using precision agriculture technologies have been installed by many agricultural enterprises in the last decade. In particular, in Ukraine, all large agricultural holdings used these technologies in one form or another. However, even relatively small agricultural enterprises also used elements of smart irrigation and received an increase in yield, sometimes significant. The agricultural sector of the Republic of Kazakhstan is interesting from the point of view of improving the agricultural sector through the introduction of smart technologies, in particular smart irrigation. The Republic of Kazakhstan is a strong producer of food in Central Asia, especially in the cultivation of cereals, despite difficult natural conditions such as a harsh continental climate and limited water resources. Also, the Republic of Kazakhstan has large areas of land that are suitable for growing grain and vegetable crops. The growth of the agricultural industry in the Republic of Kazakhstan to the level of one of the largest grain exporters in the world is an important component in ensuring the security of the region under the conditions of food shortages in the world. Over the past decade, the government has allocated funds to modernize the agricultural system, in particular through the introduction of precision farming and smart irrigation technologies. This region is also interesting because of difficult climatic conditions, which complicate, unlike Ukraine, the process of growing agricultural crops, ensuring irrigation, harvesting, etc.

The planned use of the transfer of smart irrigation technologies in precision agriculture allows the agricultural enterprise to accurately plan production, optimize the use of resources, in particular water, and manage risks. This is especially important under difficult climatic conditions, a significant shortage of food in the world, and the instability of the agricultural market. Investigating the effect of implementing smart irrigation technologies under some conditions, it is possible to calculate yield estimates, water consumption under other conditions for specific crops. Different conditions mean different climatic conditions, soil types, weather conditions, etc. This makes it possible to ensure the sustainability of agricultural enterprises. Therefore, studies aimed at determining transfer possibilities of smart irrigation technologies in the activities of agricultural enterprises are relevant.

2. Literature review and problem statement

The basis for the application of precision farming technologies in the activities of agricultural enterprises is to ensure high yields of agricultural crops and reduce financial costs and resources involved in various stages of cultivation. The direction of application of precision farming technologies, in particular smart irrigation, is intensively developing. In particular, work [1] describes a statistical yield model taking into account weather conditions when growing cereal crops. According to the authors, the accuracy of such a model is about 95 %. This is a good result. However, under the conditions of a sharply continental climate, such as in the Republic of Kazakhstan, even small mistakes in making decisions regarding the cultivation of agricultural crops can lead to irreparable losses in yield. Therefore, such an accuracy indicator should be increased. Work [2] describes a dynamic-statistical biomass model for forecasting the yield of agricultural crops. The model works well under different climatic conditions. However, for its adjustment, it is necessary to separately study the values of the indicators, which vary significantly depending on the region in which the agricultural land is located. This is related to the involvement of additional financial and human resources.

When analyzing the scientific literature on the use of smart irrigation, several main areas should be highlighted: water resources management in the process of smart irrigation, soil monitoring, weather monitoring.

Most current research on smart irrigation and water management suggests the use of sprinklers. This is the most used irrigation system. In particular, work [3] describes a model of greenhouse management using sprinkler irrigation. However, the work considers a limited range of agricultural crops that form the basis of agriculture in one of the regions of Colombia. In [4], an approach to automated smart irrigation based on water is proposed, but it is mostly suitable for Indian crop cultivation practices. There are also separate studies on the use of drip irrigation. In work [5], a neural network is used to optimize the schedule of drip irrigation of agricultural crops. The system proposed in [5] has advantages due to its intelligence, low cost, and portability, which makes it suitable for greenhouses and farms, but it is difficult to implement. Paper [6] presents an automatic drip irrigation system for providing water to farms based on water level data using an Android application, WSN and GPRS modules. An algorithm was developed, according to which the sensor values are continuously fed to the ARDUINO microcontroller. The system described in work [6] is well suited for implementation in areas with a shortage of water resources, due to high savings. Robotic systems based on spray irrigation are proposed for use in [7]. It is also proposed to design Internet of Things devices with sensor complexes that allow decisions to be made on the irrigation of certain lands based on the processing of statistical data [8].

Another area of research that is important for the organization of a system of precision agriculture and smart irrigation is the measurement of soil conditions. Most of the studies describe probes for measuring soil moisture but the details of the measurement and the features of the equipment's operation are not described. In particular, work [9] presents a system that can manage irrigation according to needs. This system consists of temperature, humidity, and PH sensors, which inform the user about the condition of the field and accordingly the user can control the system. Work [10] also describes a smart irrigation system using the MQTT protocol. In works [9, 10] there is an image of the device, but they do not indicate the model and manufacturer.

Regarding weather monitoring, various studies focus on specific weather indicators that help smart irrigation systems and precision agriculture work in general. In particular, in work [11], with the help of ZigBee technology, artificial intelligence and decision support technology, a study of the technology of applying the agricultural Internet of Things for humidity monitoring was carried out. Paper [12] proposes an automation system based on the Internet of Things (IoT), a geographic information system for increasing the efficiency of water use. However, the basis of the work in the part of the research of weather conditions is only the relative humidity of the air. Work [13] describes the process of designing a system of precision agriculture using a wireless network of sensors with the analysis of weather conditions, in particular the level of precipitation. Works [14, 15] describe smart irrigation technologies using Internet of Things systems and analysis, in particular, of the level of natural light required for the vegetation of agricultural crops.

For the implementation of smart irrigation systems, the most popular nodes are Arduino UNO, Node MCU, Arduino Mega, Raspberry (Pi 2 Model B, Pi 3 Model B+) [16]. In terms of the use of communication technologies, the high popularity of Wi-Fi, GSM, ZigBee, GPRS, LoRa, etc. technologies can be observed. Paper [16] indicated that in a large number of studies, end users access data obtained in the process of monitoring or for system control through applications or websites. Most of these communications are carried out through mobile devices using wireless technology. Work [17] describes the classification of IoT middleware taking into account various interface protocols. For the most part, MySQL or SQL database management systems are used to implement smart irrigation systems.

In general, the described approaches for implementing smart irrigation should be part of precision agriculture systems based on technology transfer. In work [18] it was established that the use of technology transfer, in particular, precision farming technologies, makes it possible to improve the efficiency of agricultural enterprises, in particular, to increase the yield of agricultural crops and, accordingly, to enhance the profitability of enterprises.

The tasks of evaluating the efficiency of using precision farming and precision irrigation technologies in the activities of agricultural enterprises under different conditions, in particular, different climatic, weather conditions, etc., have not been researched in detail. In particular, the use of precision farming technologies to influence the yield of agricultural crops was not researched in detail. The use of such means, in particular hardware-software systems, for their transfer under different climatic and weather conditions has been also insufficiently investigated.

3. The aim and objectives of the study

The purpose of our work is to evaluate the effectiveness of the application of precision farming technologies in the activities of agricultural enterprises, in particular the transfer of precision farming technologies, part of which is a hardware-software system for smart irrigation and remote monitoring of weather conditions. This will make it possible to increase the productivity of the agricultural enterprise when growing agricultural crops.

To achieve the goal, the following tasks were set:

– to describe the components of the hardware-software system for smart irrigation and remote monitoring of weather conditions for use in the activities of agricultural enterprises when growing agricultural crops;

– to verify the effectiveness of applying the hardware-software system for smart irrigation and remote monitoring of weather conditions to increase the yield of agricultural crops under the conditions of technology transfer.

4. The study materials and methods

The object of our study is the evaluation of the effectiveness of applying precision farming technologies and smart irrigation technologies in the activities of agricultural enterprises, in particular the transfer of precision farming technologies. The hypothesis of the study is to verify the fact that the use of technology transfer of precision agriculture, in particular, smart irrigation, makes it possible to obtain higher efficiency, in particular, greater productivity of agricultural enterprises.

The work uses methods of quantitative analysis, in particular, the use of statistical tools for the analysis and forecasting of time series of crop yields. These tools are necessary in order to show the effectiveness of the use of precision agriculture technologies, in particular, smart irrigation, in the activities of agribusinesses.

In this study, there is a certain simplification since other factors, except for the cultivation of agricultural crops, were not considered in the activity of the agro-industrial system. The basis of the study is the verification of the effectiveness of the implementation of the hardware-software system of smart irrigation and remote monitoring of weather conditions in Ukraine and the assessment of possible gains from the transfer of this technology in the Republic of Kazakhstan. At the same time, the statistical indicators of the yield of specific crops that were analyzed in the Republic of Kazakhstan, taking into account climatic conditions, were taken into account. The data were obtained from the official statistics of the Bureau of National Statistics of the Agency for Strategic Planning and Reforms in the Republic of Kazakhstan [19] and the Aerospace Committee of the Ministry of Digital Development, Innovation, and Aerospace Industry of the Republic of Kazakhstan [20].

Also, this study is part of the state budget-funded program in the Republic of Kazakhstan on the topic of development of tools and methods for precision agriculture. The Ukrainian company IT-Lynx [21] was involved in the study of the effectiveness of technology transfer in the Republic of Kazakhstan. This company develops and manufactures a range of on-board equipment for monitoring moving objects, peripherals and sensors for various purposes, which are used, in particular, in agriculture.

5. Research on the effectiveness of precision farming technologies and smart irrigation technologies

5. 1. Components of the hardware-software system for smart irrigation and remote monitoring of weather conditions

The hardware-software system for smart irrigation and remote monitoring of weather conditions is designed to enable accurate and continuous monitoring of various agrometeorological parameters. This system is used in agriculture to optimize the conditions for growing crops. It allows farmers and agronomists to receive timely data on weather conditions and current soil conditions, which helps make informed decisions about irrigation, fertilization, and crop protection. This, in turn, helps increase productivity, reduce resource costs, and minimize negative environmental impact. The conceptual model of the architecture of the hardware-software system is shown in Fig. 1.

At the heart of the hardware part of the system is an online weather station designed to collect data from various sensors, process them, and transmit them to the central server. This weather station is equipped with sensors that measure key parameters: temperature, air humidity, wind speed and direction, precipitation, and other important meteorological indicators. The system provides continuous monitoring and high accuracy of measurements, which enables prompt response to changes in weather conditions. The collected data is processed in real time and transferred to a central server, where it is stored and analyzed. Thanks to this, users can access up-to-date information via the Internet from anywhere in the world. This significantly increases the efficiency and effectiveness of decision-making in the field of agriculture, natural resource management, and other areas that depend on weather conditions.

Soil moisture is one of the most important indicators of plant growing conditions collected by the online weather station because it directly affects their growth and development. Optimal humidity provides plants with the necessary amount of water for the processes of photosynthesis, transpiration, and metabolism. A lack of moisture can lead to withering and death of plants, a decrease in their resistance to diseases and pests, as well as to a decrease in yield. On the other hand, excessive moisture can cause rotting of roots, deterioration of soil aeration, and development of pathogenic microorganisms. Therefore, monitoring and maintaining the optimal level of soil moisture are key factors in successful farming, ensuring stable and high yields.

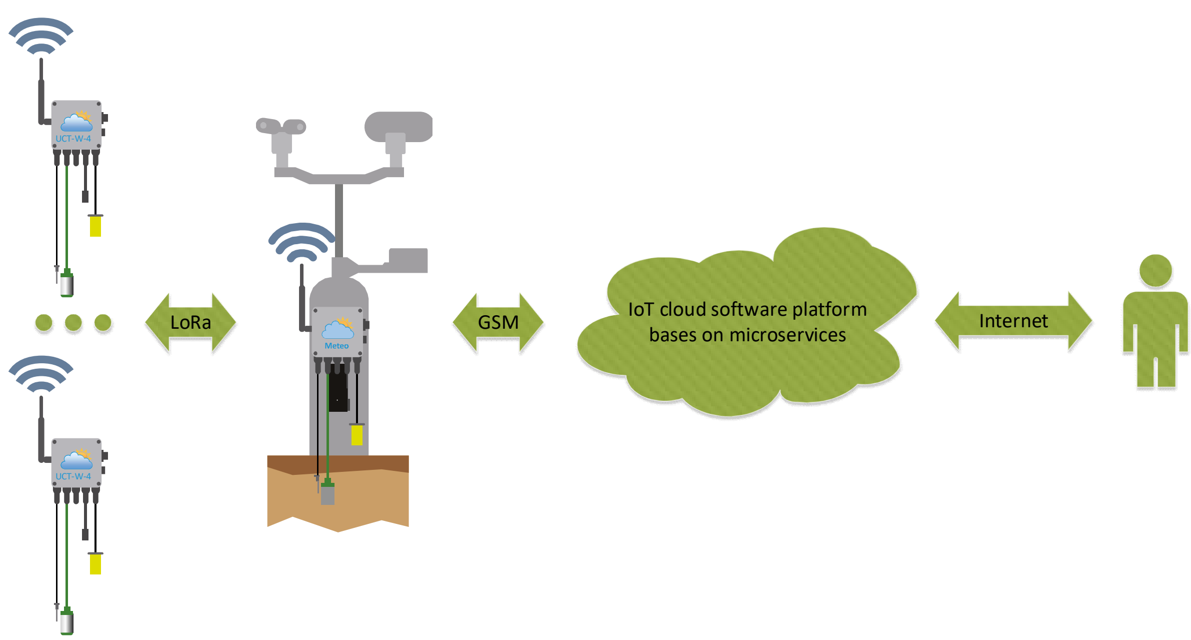

Fig. 1. Conceptual model of the architecture of the hardware-software system for smart irrigation and remote monitoring of weather conditions

The DVG-3 sensor is used in this system to measure the percentage of volume content of water in a soil sample. Volumetric water content is the volume of soil water contained in a unit of total soil volume. The presence of moisture in the soil significantly affects its dielectric constant since the value of the dielectric constant of water is significantly higher (at least 20 times) when compared to other soil components. The bulk moisture sensor uses electrical capacitance to measure the dielectric constant of the surrounding soil. The electronic circuit inside the probe measures the temperature and converts the measured capacitance into a voltage proportional to it. Current temperature and voltage information can be read using a standard 1-Wire digital interface.

The DVG-3 sensor operates at a frequency of 70 MHz, which makes it possible to minimize the influence of salinity and soil structure and can be used to measure volumetric moisture from 0 to 100 % in almost any environment, including mineral soil, peat, thermal insulation, and sawdust The high frequency of operation of the sensor ensures the accuracy of measurements and makes it possible to use it effectively in a variety of conditions. This makes this sensor a versatile tool for monitoring soil moisture, which is an important aspect for optimal water management in agriculture. General view of the sensor is shown in Fig. 2.

Fig. 2. General view of the DVG-3 volumetric soil moisture sensor

In the case of complex field configurations, which require the measurement of soil moisture data not only near the weather station but also in remote locations, special wireless modules are used. Modules that collect data from sensors and transmit them to a weather station using LoRa data transmission technology. The UCT-W-4 wireless module provides a convenient, fast, and reliable way to monitor information from various sensors located up to 3 km line of sight from the base weather station. Up to 4 different sensors can be connected to one UCT-W-4 wireless module for remote monitoring. Unlike wired sensors, sensors with a wireless UCT-W-4 module can be installed anywhere without additional costs for laying cables. This device does not interfere with the operation of machines and units, which ensures its wide application in agricultural practice. LoRa data transmission technology is characterized by very low energy consumption and a long range. Information from the wireless module is transmitted to the main controller via a radio channel, and if the data is transmitted every hour, the module can work for about a year without replacing the batteries. Operating at a frequency of 868 MHz, the module does not require licensing on the territory of Ukraine. The general view of the UCT-W-4 wireless module, equipped with three DVG-3 volumetric soil moisture sensors, is shown in Fig. 3.

The software part of the system is designed for data collection from online weather stations, their storage, processing, and display to the user. The web-based system provides access to data from anywhere in the world, allowing the user to view and analyze information using any computer with Internet access. The method described in study [22], which makes it possible to determine the deviation of the main signal parameters, can be used to monitor and improve the reliability of wireless communication between the components of the smart irrigation system. This will enable stable data transfer between sensors, controllers, and other devices. Users are given the opportunity to monitor all data received from weather stations, and the system supports collecting data from an unlimited number of weather stations into one account. In addition to viewing data in real time, the software makes it possible to view the history of measurements by hours and days, which facilitates detailed analysis and making informed decisions on managing agrometeorological conditions.

Fig. 3. General view of the UCT-W-4 wireless module equipped with three DVG-3 volumetric soil moisture sensors

The general view of the software part of the hardware-software system is shown in Fig. 4. The screenshot shows data on weather conditions for the month. Daily fluctuations in air and soil temperature, as well as air and soil humidity, are clearly visible on the charts. These data enable users to observe the dynamics of changes in climatic parameters and analyze their impact on agronomic processes. In addition, the software part provides an opportunity to view the values of atmospheric pressure, wind speed and direction, which is important for a comprehensive analysis of meteorological conditions. Precipitation is represented in the form of a bar chart that clearly demonstrates the intensity and distribution of rain over time. Fig. 4 shows an increase in soil moisture after heavy rains, which confirms the relationship between the amount of precipitation and the state of soil moisture.

Therefore, this hardware-software system for smart irrigation and remote monitoring of weather conditions can be used in the activities of any agricultural enterprise in different countries. Currently, there are data on its successful use in the activities of agricultural enterprises in Ukraine. The research method is to evaluate the effectiveness of its possible use in the activities of agricultural enterprises in the Republic of Kazakhstan, taking into account climatic conditions.

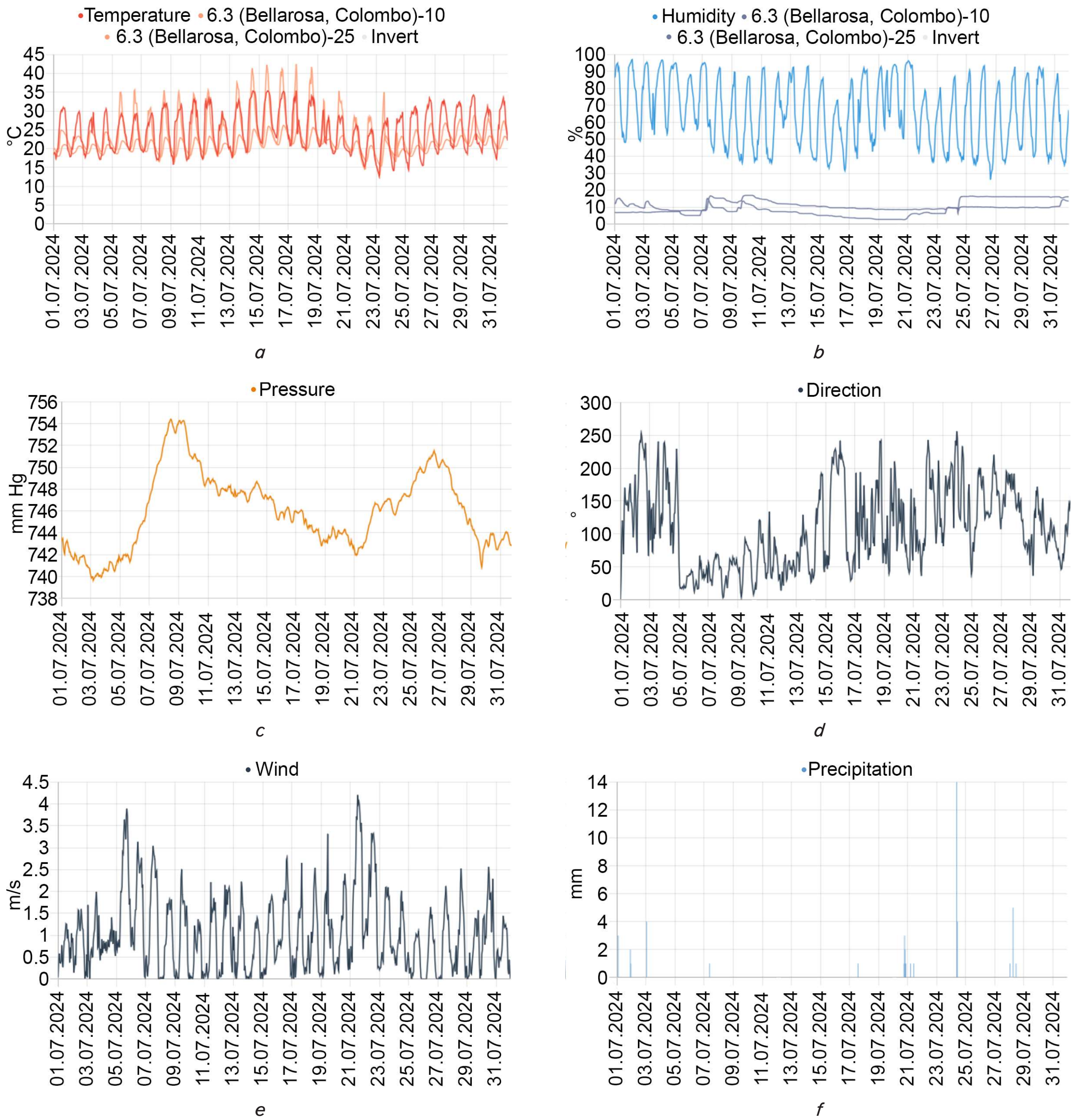

Fig. 4. General view of the software part of the hardware-software system for smart irrigation and remote monitoring of weather conditions: *a* – temperature indicators, *b* – humidity, *c* – pressure, *d* – direction, *e* – wind, *f* – precipitation

5. 2. Evaluating the effectiveness of validating the hardware-software system for smart irrigation and remote monitoring of weather conditions to increase productivity

The described hardware-software system for smart irrigation and remote monitoring of weather conditions was used in the activities of one of the agricultural enterprises in the Kyiv oblast (Ukraine), which specializes in growing potatoes. Since the yield and planted areas are a commercial secret of the agro-enterprise, the provided data are distributed anonymously. Potato cultivation statistics were collected in 2021–2023. In 2021, the company experimented with growing fifteen varieties at once, some of them with different planting dates. This was done to establish optimal varieties and growing conditions in the future. Relatively small areas were planted. Some areas were not irrigated separately. Some areas were joined together. Also, two areas were allocated for testing the hardware-software system for smart irrigation for the varieties "Tiras" and "Arizona". The average yield in 2021 at all sites of the enterprise was 37.36 t/ha. At the same time, the average yield of potatoes without irrigation in 2021 was 23.33 t/ha. The average yield of potatoes with irrigation in 2021 was 48.57 t/ha. The average yield of potatoes with smart irrigation, i.e., with the use of hardware-software system for smart irrigation, in 2021 was 54.49 t/ha.

In 2022, 71.4 hectares were planted with four varieties of potatoes. Two cultivars, Queen Anne and Columba, were planted for irrigated cultivation. The variety "Libella" was planted for cultivation without irrigation. "Tiras" variety on an area of 2.4 ha was planted for cultivation with smart irrigation. The average yield in 2022 at all sites of the enterprise was 44.75 t/ha. At the same time, the average yield of potatoes without irrigation in 2022 was 37.51 t/ha. The average yield of potatoes with irrigation in 2022 was 46.10 t/ha. The average yield of potatoes with smart irrigation, that is, with the use of the smart irrigation hardware-software system, in 2022 was 50.64 t/ha.

In 2023, eight varieties of potatoes were planted on an area of 130.6 hectares. In that case, the average yield in 2023 at all sites of the enterprise was 47.11 t/ha. At the same time, the average yield of potatoes without irrigation in 2023 was 28.38 t/ha. The average yield of potatoes with irrigation in 2023 was 52.30 t/ha. The average yield of potatoes with smart irrigation, i.e., with the use of hardware-software system for smart irrigation, in 2023 was 60.64 t/ha. Tables 1–3 give the indicators of potato cultivation by this agricultural enterprise in 2021–2023. Table 4 gives the average yield of potatoes by year.

The value of the rate of irrigation in the smart irrigation hardware-software system was calculated according to the following formula [23, 24]:

$$N = \frac{hS\psi(1-\alpha)W}{\mu} \cdot 100, \quad (1)$$

where N is the rate of irrigation, m^3/ha; W is the lowest moisture content of the root layer of the soil as a percentage of the mass of completely dry soil; h is the recommended depth of soil wetting, m; ψ is the compaction density of the root layer of the soil, t/m^3; μ is the water density, t/m^3; assumed to be 1; S – the moistened part of the field area in fractions of the unit; α – the humidity coefficient of the root layer of the soil before the start of irrigation in fractions of W.

Parameter S takes into account the part of the field area that is actually moistened during irrigation. For drip irrigation, S will be less than 1 because the water is applied pointwise. For sprinklers, S=1, since water is evenly distributed over the entire field area.

The depth of moistening is taken from the need to moisten the soil volume, which contains at least 75 % of the physiologically active root branches of the plant, or it is determined by the scheme of planting plants and the placement of irrigation pipelines of the drip irrigation system. Under the condition of reasonable sprinkler irrigation for potatoes, the following irrigation rate was proposed: for the growing season N=190 m^3/ha, for flowering – N=150 m^3/ha. These values varied over the growing period as W was calculated from the moisture sensors.

Table 1

Indicators of potato cultivation by Ukrainian agricultural enterprises in 2021

Variety	Variety planted/harvested, ha	Gross harvest, t	Bunker yield, t/ha	Soil, t	Total without soil, t	Yield without soil, t/ha	Notes
Granada, planted 1	18.0	912.96	50.72	8.00	904.96	50.28	With irrigation
Rudolph	1.8	89.92	49.96	0.61	89.31	49.62	
Arizona	4.4	222.64	50.60	0.90	221.74	50.40	
Columbus	1.0	38.58	38.58	0.25	38.33	38.33	
Labella (Memphis)	1.6	43.22	27.01	0.30	42.92	26.83	
Queen Anne	1.2	29.88	24.90	0.70	29.18	24.32	
Granada, 1 and 2 repr.	17	1,083.00	63.71	10.23	1,072.77	63.10	
Granada, 1 repr.	34.0	2,088.00	61.41	11.75	2,076.25	61.07	
Granada, 2 repr.	18.0	1,160.96	64.50	17.12	1,143.84	63.55	
Granada, planted 2	20.5	1,213.26	59.18	20.33	1,192.93	58.19	
Opal	29.0	365.90	12.62	4.81	361.09	12.45	Without irrigation
Arsenal	12.0	168.58	14.05	1.86	166.72	13.89	
Connect	47.0	2,180.78	46.40	904.34	1,276.44	27.16	
Rudolph	19.0	675.58	35.56	108.04	567.54	29.87	
Labella (Memphis)	5.6	124.84	22.29	12.97	111.87	19.98	
Rodriga (RedLady)	6.2	155.52	25.08	11.82	143.70	23.18	
Queen Anne	5.5	173.64	31.57	11.99	161.65	29.39	
Columbus	4.7	126.26	26.86	7.00	119.26	25.37	
Lily	5.4	134.04	24.82	3.09	130.95	24.25	
Otolia	2.2	45.20	20.55	1.84	43.36	19.71	
Opal 2	7.4	158.52	21.42	2.89	155.63	21.03	
Granada	11.1	400.38	36.07	21.03	379.35	34.18	
Arizona	14.7	391.27	26.62	21.81	369.46	25.13	
Demo	2.2	47.92	21.78	1.58	46.34	21.06	
Arizona	3.1	198.13	63.91	2.58	195.55	63.08	Ssmart irrigation
Tiras	3.5	164.25	46.93	3.58	160.67	45.91	
In total	296.1	12,393.23	967.10	1,191.42	11,201.81	–	–

Table 2

Indicators of potato cultivation by Ukrainian agricultural enterprises in 2022

Variety	Variety planted/harvested, ha	Gross harvest, t	Bunker yield, t/ha	Soil, t	Total without soil, t	Yield without soil, t/ha	Notes
Columbus	27.5	1,281.60	46.60	41.65	1,239.95	45.09	With irrigation
Queen Anne	40.0	1,909.58	47.74	25.06	1,884.52	47.11	
Labella	1.5	57.60	38.40	1.34	56.26	37.51	Without irrigation
Tiras	2.4	123.38	51.41	2.34	121.04	50.43	Smart irrigation
In total	71.4	3,372.16	184.15	70.39	3,301.77	–	–

Table 3

Indicators of potato cultivation by Ukrainian agricultural enterprises in 2023

Variety	Variety planted/harvested, ha	Gross harvest, t	Bunker yield, t/ha	Soil, t	Total without soil, t	Yield without soil, t/ha	Notes
Opal	19.3	900.92	46.68	14.20	886.72	45.94	With irrigation
Tiras	11.4	513.20	45.02	3.4	509.80	44.72	
Arizona	9.2	528.18	57.41	0	528.18	57.41	
Granada	12.2	862.02	70.66	51.71	810.31	66.42	
Kibitz	2.2	91.70	41.68	0	91.70	41.68	
Columbus	11.4	611.42	53.63	5.92	605.50	53.11	
Queen Anne	19.7	944.72	47.96	1.91	942.81	47.86	
Melody	16.6	1,086.96	65.48	70.16	1,016.80	61.25	
Arizona	13.5	525.72	38.94	76.57	449.15	33.27	Without irrigation
Tiras	5.0	119.58	23.92	2.11	117.47	23.49	
Arizona	3.6	179.16	49.77	1.96	177.20	49.22	Smart irrigation
Tiras	4.6	202.67	44.06	2.31	200.36	43.56	
Queen Anne	1.9	55.23	29.07	1.07	54.16	28.51	
In total	130.6	6,621.48	614.27	231.32	6,390.16	–	–

Table 4

The average yield of potato cultivation by the Ukrainian agro-enterprise by years, t/ha

Indicator \ Year	2021	2022	2023
Average yield without irrigation	23.33	37.51	28.38
Average yield with irrigation	48.57	46.10	52.30
Average yield with smart irrigation	54.49	50.64	60.64

Since the cultivation of agricultural crops takes place in open ground and depending on the climatic conditions, rainfall of different intensity may be recorded in different periods of cultivation. To ensure a high yield, it is necessary to adhere to the recommended watering rates for the periods of vegetation and flowering. Forecast results and actual indicators of weather conditions in the area of the field should also be taken into account. The hardware-software system for smart irrigation and remote monitoring of weather conditions records the values of temperature, humidity, wind direction and strength, and precipitation intensity. This information was used to control irrigation. Moreover, the irrigation rate will be determined as the sum of two components: data from artificial irrigation and natural soil moistening from rain. Irrigation rates for a specific agricultural crop in different growing periods are set in advance. The hardware-software system for smart irrigation and remote monitoring of weather conditions determines, with the help of sensors, the component of natural irrigation from rain. At the same time, a rational rate of artificial irrigation is calculated, which makes it possible to obtain the maximum yield of crops.

The possibility of transferring this technology in the activities of agricultural enterprises of the Republic of Kazakhstan is considered below. A total of 321,387 entities in the agro-industrial system operate on the territory of the Republic of Kazakhstan. Since 2019, precision farming technologies have been actively used in Kazakhstan. The introduction of precision farming technologies is carried out gradually, not all components are immediately involved in the agricultural production process. Table 5 gives the yield of potatoes by year in the Republic of Kazakhstan without irrigation [19, 20].

The forecast of potato yield in the Republic of Kazakhstan is calculated according to statistical data and we adjust it taking into account the possible use of smart irrigation technology. Let the time series of yield (tons per hectare) be given for the potato crop of different varieties. This time series takes the following form:

$$Y = \{Y_1, Y_2, \ldots, Y_k\}, \quad (2)$$

where Y is a discrete time series of yield (t/ha), Y_i is the level of yield recorded at a discrete point in time (for example, annual data).

The yield forecast with horizon g is determined from the following formulas:

$$\hat{Y}_{k+1} = F\left(Y_{k-p+1}, Y_{k-p+2}, \ldots, Y_{k-1}, Y_k\right),$$

$$\hat{Y}_{k+2} = F\left(Y_{k-p+2}, Y_{k-p+3}, \ldots, Y_k, \hat{Y}_{k+1}\right),$$

$$\hat{Y}_{k+3} = F\left(Y_{k-p+3}, \ldots, Y_k, \hat{Y}_{k+1}, \hat{Y}_{k+2}\right),$$

$$\ldots$$

$$\hat{Y}_{k+g} = F\left(Y_{k-p+g}, \ldots, \hat{Y}_{k+g-2}, \hat{Y}_{k+g-1}\right), \quad (3)$$

$\hat{Y}_{k+j}$ is the forecast of point $k+j$, $j = \overline{1,g}$, g is the horizon of the forecast, F is the functional by which the forecast is calculated, p is the amount of retrospective data that is selected for the calculation of the forecast.

For example, in the case of the yield time series, to simplify calculations for F, one can choose a linearly weighted moving average, which is calculated according to the formula:

$$\hat{Y}_{k+1}=\left(\sum_{v=1}^{p}v\right)^{-1}\sum_{v=1}^{p}v\cdot Y_{k-p+v}, \quad (4)$$

where $\hat{Y}_{k+1}$ is the yield forecast one point ahead by the linear weighted moving average method. Similarly, forecasts for $j=\overline{2,g}$, taking into account scheme (3) are calculated.

Table 5

Yield of the main agricultural crops in the Republic of Kazakhstan (t/ha)

Year	Yield
1990	11.30
1991	9.90
1992	10.40
1993	9.40
1994	9.40
1995	8.40
1996	8.80
1997	8.40
1998	7.70
1999	10.80
2000	10.60
2001	13.30
2002	13.90
2003	13.90
2004	13.40
2005	15.00
2006	15.36
2007	15.58
2008	14.37
2009	16.00
2010	14.30
2011	16.72
2012	16.59
2013	18.15
2014	18.43
2015	18.55
2016	19.04
2017	19.42
2018	19.79
2019	20.34
2020	20.67
2021	20.74
2022	20.54
2023	17.00

If we calculate the forecast for the yield of potatoes in the Republic of Kazakhstan according to formulas (3), (4), taking into account the data from Table 5, then we get the results given in Table 6. These indicators for other crops were also calculated for the Republic of Kazakhstan in work [18]. The average yield increase when using a hardware-software system with smart irrigation technology in Ukraine is 85.8 %. Forecast data for the use of this technology has been adjusted to account for this increase. However, since the total yield of potatoes in Kazakhstan is lower than in Ukraine without the use of irrigation, as well as taking into account the climatic conditions of the Republic of Kazakhstan, the lower limit of the forecast yield should be established. The increase in yield with irrigation compared to yield without irrigation over the three years of observation is an average of 64.7 %. Considering the good climatic conditions for growing potatoes in Ukraine and comparing with difficult conditions in the Republic of Kazakhstan, it is reasonable to set this value as the lower limit of potato yield in the case of using smart irrigation technology in the Republic of Kazakhstan.

Table 6

Results of forecasting the yield level of potatoes in the Republic of Kazakhstan, taking into account the correction for the use of smart irrigation

Year	Predicted yield	Yield, adjusted for the use of smart irrigation (lower limit), t/ha	Yield, taking into account the correction for the use of smart irrigation (upper limit), t/ha
2024	19.40	31.95	36.05
2025	19.25	31.70	35.77
2026	19.11	31.47	35.51

Official data on potato yield in the Republic of Kazakhstan for the period from 1990 to 2023 were used to calculate the forecast [19, 20, 25]. The forecast is built on the basis of a linearly weighted moving average with a period of p=5.

Our data demonstrate that the application of smart irrigation technologies can significantly increase the yield of potatoes, which will accordingly lead to the growth of both the income part of the agricultural enterprise and the overall productivity of finished products. The yield of potatoes in this case can be obtained on average at the level of 31.71 t/ha to 35.78 t/ha in comparison with the forecast values of yield without irrigation at the level of 19.25 t/ha.

6. Discussion of results of evaluating the effectiveness of the application of precision farming technologies and remote monitoring of weather conditions in the activities of agricultural enterprises

The advantage of using smart irrigation with the use of soil moisture sensors is to optimize water resources and provide ideal conditions for plant growth. Insufficient soil moisture can stress plants, slow down their growth, and reduce yields. Plants feel a lack of moisture, which leads to wilting and insufficient absorption of nutrients. On the other hand, waterlogging of the soil also has a negative effect on plants. Excess moisture deteriorates the soil structure, causing erosion and eluviation, which reduces its fertility. Waterlogging also promotes root rot and reduced nutrient uptake, which weakens plants and makes them more susceptible to disease.

A hardware-software system has been proposed, which is an integral part of the technology of precision agriculture and remote monitoring of weather conditions. This system makes it possible, through the use of sensors for monitoring weather conditions and volumetric soil moisture, to determine the rates of irrigation of agricultural crops. This makes it possible to get a higher yield compared to irrigation without smart irrigation and no irrigation at all. The effectiveness of the use of this technology in the case of applying the technology of precision irrigation with frontal watering machines is shown, while the irrigation rates were determined according to formula (4) using the hardware-software system.

According to the results of validating the effectiveness of applying the hardware-software system, the following results were obtained. In particular, the average yield of potatoes of various varieties without irrigation for three years of observation was 29.74 t/ha, with irrigation – 48.99 t/ha, and with smart irrigation – 55.26 t/ha. The increase in yield with irrigation compared to yield without irrigation over the three years of observation was an average of 64.7 %. The increase in yield with smart irrigation compared to yield without irrigation over the three years of observation is an average of 85.8 %. The increase in yield with smart irrigation compared to yield with conventional irrigation over the three years of observation is an average of 12.8 %. Although the latter indicator is not high, the effect of using smart irrigation is significantly greater than just an increase in yield. At the same time, water resources, human resources and, accordingly, financial resources are saved.

In general, the use of smart irrigation according to the described technology will increase the yield of potatoes of various varieties on average from 31.71 t/ha to 35.78 t/ha in comparison with the forecast values of yield without irrigation at the level of 19.25 t/ha.

The study shows that the use of transfer of precision farming technologies, in particular, smart irrigation, is a key component for increasing the efficiency of agricultural enterprises in the Republic of Kazakhstan, which makes it possible to increase the yield of agricultural crops and the profitability of agricultural enterprises. Our study examined the efficiency of agricultural enterprises in terms of growing agricultural crops, in particular potatoes. Other components of the agro-industrial system were not considered.

The current study has limitations that arise from the constrains in the linear weighted moving average method for yield forecasting. The method does not take into account seasonal changes. Also, potato yield statistics are integrated and, although mostly based on non-irrigated growing data, may include other yield results from enterprises that used irrigation or other technologies.

The development of our research in the future should involve a deeper analysis of climatic conditions and weather conditions in the Republic of Kazakhstan, in order to more accurately predict the yield of agricultural crops. In addition, it is important to conduct a study on the effect of the transfer of smart irrigation technologies for the cultivation of other agricultural crops.

7. Conclusions

1. We have described a hardware-software system for smart irrigation and remote monitoring of weather conditions, its architecture, and sensors, which can be used for productive cultivation of agricultural crops. This system can calculate artificial irrigation rates taking into account data on weather conditions: temperature, humidity, pressure, wind strength and direction, rainfall intensity. Special feature of the system is that the sensors that are part of it can be placed directly in different points of the field and transmit information about the state of the field to the server through wireless interfaces. The developed hardware-software system was used in the activities of the agricultural enterprise during 2021–2023. The collected data was used to evaluate the efficiency of using precision farming technology under different conditions. So, the use of a hardware-software system for smart irrigation and remote monitoring of weather conditions allowed us to solve the task of evaluating the effectiveness of using precision farming and precision irrigation technologies in the activities of agricultural enterprises under different conditions.

2. According to the results of validating the effectiveness of the application of the hardware-software system for smart irrigation and remote monitoring of weather conditions in Ukraine, the effect of the implementation of this system in agricultural companies of the Republic of Kazakhstan was analyzed. In general, the use of smart irrigation according to the described technology could increase the yield of potatoes of various varieties on average from 31.71 t/ha to 35.78 t/ha in comparison with the forecast values of yield without irrigation at the level of 19.25 t/ha. It was established that the yield of potatoes with smart irrigation in comparison with the yield without irrigation for three years of observation was an average of 85.8 %. On the other hand, in the case of using smart irrigation technology, compared to conventional frontal irrigation with watering machines, it is possible to obtain an increase in the yield of potatoes by 12.8 %. At the same time, water resources, human resources, and, accordingly, financial resources are saved. This confirms the need to apply the transfer of precision farming technologies to increase the yield of agricultural crops, in particular potatoes, and the productivity of agricultural companies.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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