AGRICULTURAL BIOLOGY,
2020, V. 56, Iss. 1, pp. 92-102
(SEL'SKOKHOZYAISTVENNAYA BIOLOGIYA)

ISSN 2412-0324 (English ed. Online)
ISSN 0131-6397 (Russian ed. Print)
ISSN 2313-4836 (Russian ed. Online)

UDC 633.11:631.559.2:528.88

doi: 10.15389/agrobiology.2021.1.92eng
doi: 10.15389/agrobiology.2021.1.92rus

PROSPECTS FOR PRECISION MANAGEMENT OF WHEAT PRODUCTIVITY IN THE CONDITIONS OF NORTHERN KAZAKHSTAN

B.R. IRMULATOV[1], K.K. ABDULLAEV[1], A.A. KOMAROV[2] ✉, V.V. YAKUSHEV[2]

[1]*Baraev Scientific-production Center for Grain Farming,* p. Shortandy-1, Shortandinsky District, Akmola Region, 021601 Kazakhstan, e-mail irmulatov61@mail.ru, tsenter-zerna@mail.ru;
[2]*Agrophysical Research Institute*, 14, Grazhdanskii prosp., St. Petersburg, 195220 Russia, e-mail: zelenydar@mail.ru (✉ corresponding author), mail@agrophys.com
ORCID:
Irmulatov B.R. orcid.org/0000-0002-8155-7817
Abdullaev K.K. orcid.org/0000-0001-7760-4636
Komarov A.A. orcid.org/0000-0003-1430-0509
Yakushev V.V. orcid.org/0000-0001-8434-5580
The authors declare no conflict of interests
Acknowledgements:
The authors are deeply grateful to Academician Viktor P. Yakushev for insightful comments and suggestions in writing the article.
The work was performed within the framework of the program of the Baraev Scientific-production Center for Grain Farming LLP "Transfer and adaptation of technologies for precision crop production based on the 'Demonstration farms (polygons)' principle in the Akmola region".
Received October 18, 2020

Abstract

More complete realization of the wheat genetic potential will ensure increasing its yield and quality in the conditions of the Republic of Kazakhstan. Innovative agrotechnological approaches, including a precision farming system (PFS) allow the problem to be addressed. Given the large area of Kazakhstan, the incorporation of precision farming systems needs assessment of the state of its vast territories using the Earth remote sensing (ERS) technology. In this paper, for the first time in the conditions of Northern Kazakhstan, the methods of precision management of spring wheat productivity were implemented. The aim of the work was to assess the prospects for precision farming in the conditions of Northern Kazakhstan and to develop an algorithm not only for passive monitoring of the state of crops, but also for active management of the spring wheat yield using ERS. The field trials were performed on dark chestnut soils in the seasons of 2019-2020 (a special precision farming landfill, Baraev Production Center of Grain Farming) with highly productive spring wheat (*Triticum vulgare* L.) varieties of local selection, the Shortandinskaya 95 and Astana. At the first stage, the main agrochemical indicators of the test sites were characterized using a ground-based mobile complex. Soil fertility parameters were assessed using survey grids with 1, 5, and 25 ha plot grids. The data were used to identify intra-field heterogeneity and calculate fertilizer doses for differentiated application. The second stage involved crop assessment using images from the Sentinel-2 group satellites and photographs form unmanned aerial vehicles (UAV). Plant development during ontogenesis was characterized by normalized difference vegetation index (NDVI), and the yields were finally evaluated using electronic yield maps. At the third stage, the data were processed using the Stat and Microsoft Excel 2010 software package and AGROS-1 software (version 2.09-2.11/1993-2009). The main fertilizers were used at sowing and surface applied. Non-root feeding was also performed. Polymer fertilizers Vitanoll-NP (1 l/ha) and Vitanoll-micro (1 l/ha) (Agromarket-24 LLC, Russia), a complex chelated fertilizer CHF (2 l/ha) (Agrophysical Research Institute, Russia), and a humic fertilizer Stimullife (0.3 l/ha) (Agrofizprodukt LLC, Russia) were used. It was found that only one agrochemical inhomogeneity of the field was partially leveled by the PFS-based differentiated introduction of fertilizers. Soil fertility, landscape profile and hydrological parameters (soil moisture availability) are shown to dominantly affect the spring wheat yield in the arid conditions of Kazakhstan. The changes in the agricultural landscape conditions due to the slope of the terrain, allows us to trace watercourses that characterize the productive moisture availability in a particular part of the field. On the basis of remote sensing data and coupled ground measurements used to precisely assess and record soil, landscape and soil moisture conditions, an algorithm has been developed to manage the yield formation process in plants. It is shown that the more precise the data analysis, the higher the effect of crop yield management. An increase in yield was approximately 10 % for a 5-ha plot grid and 2 times more for a 1-ha plot grid. The correlation revealed between the wheat yield and NDVI is strong and uneven as depends on the spatial direction, that is, the *r* values are 0.64-0.99 along the slope transect and 0.62-0.98 broadwise the field. A significant increase in yield was obtained both due to the differentiated application of mineral fertilizers, by 9.5 % for the 5-ha grid and by 19.2 % the 1-ha grid, and due to timely non-root fertilizing, by 15-22.3 %. In general, our findings indicate the PFS prospects in the management of spring wheat productivity under the conditions of Northern Kazakhstan.

Keywords: spring wheat, Northern Kazakhstan, precision agriculture, remote sensing data, agro landscape, soil fertility, soil moisture

The Republic of Kazakhstan is one of the world's leading exporters of high-quality wheat. At the same time, the yield of soft wheat in Kazakhstan averages only 10-15 c/ha, which is due not only to natural and climatic factors but also to the imperfection of agricultural technologies. Increasing the yield and quality of wheat can be achieved by realizing its breeding potential [1, 2], which, among other things, provides resistance to pathogens [3]. It has been previously shown that, along with selection achievements, innovative agro-technological approaches, including the precision farming system (PFS), are of decisive importance [4, 5]. However, PFS technologies successfully implemented in the Russian Federation [4] and other countries [6, 7] require adaptation to the conditions of Northern Kazakhstan. Simple copying or replication of the PFS previously used in humid climates is unacceptable when it comes to the specific conditions of arid climates.

The introduction of precision farming in the conditions of Kazakhstan began relatively recently. Since 2018, LLP Baraev Production Center of Grain Farming has been developing a specialized program "Transfer and adaptation of technologies for precision farming in the production of crop products based on the principle of demonstration farms (landfills) in the Akmola Region". Scientific research is focused on a specialized precision farming landfill with an area of 3000 hectares, where precision experiments have been carried out since 2019. One of the first elements of the introduction of precision farming in Kazakhstan (taking into account its length) is the assessment of the state of the cultivation zones of agricultural plants using modern technologies of Earth remote sensing (ERS) [8, 9]. On the basis of ERS, numerous tasks are currently being solved, including the predictive and actual assessment of the state and yield of spring crops in large areas [10, 11], which implies the assessment of the areas of not only cultivated plants but also the proportion of native species [12, 13].

To identify the ERS, it is required to be bound to the terrain conditions, as well as have a connection in time and space with ground-based studies, carried out taking into account the heterogeneity of the state of the soil cover, which can be realized only in precision studies. In addition, ERS provides typical monitoring observations aimed at assessing, analyzing, and only to some extent predicting the state of soils and plants [4, 14].

In this work, for the first time in the conditions of Northern Kazakhstan, methods of precision control of the productivity of spring wheat were implemented. It was shown that with a more detailed analysis of the data (the degree of precision on a grid of 1, 5, and 25 hectares), the resulting yield increased, which is associated with a more accurate differentiated use of fertilizers. It was revealed that in the arid conditions of Kazakhstan, soil-landscape-hydrological factors associated with the reserve and distribution of soil moisture were more important. Using ERS and the normalized difference vegetation index (NDVI), a close correlation was established between the remote sensing data and the yield map. In addition, the NDVI, determined using unmanned aerial vehicles, differed in information content and efficiency from satellite images. At the precision farming landfill, using ground and coupled ERS observations, it was possible to quickly identify zones of depression in plant development in the heterogeneous space of the field, which made it possible to timely carry out the necessary correction of plant growth and development using foliar dressing.

The aim of the work is to assess the prospects for using the PFS in the conditions of Northern Kazakhstan and, on this basis, to propose an algorithm for the transition from passive monitoring measures to active control precision methods of increasing the productivity of spring wheat.

Materials and methods. The studies were carried out on dark chestnut soils typical for Northern Kazakhstan and southern carbonate chernozems in the conditions of the growing seasons of 2019-2020 (a specialized experimental landfill of precision farming (LLP Baraev Production Center of Grain Farming). The main objects were highly productive varieties of spring wheat (*Triticum vulgare* L.) of local selection. The variety Shortandinskaya 95 (improved), a subvariety of Lutescens, was bred by the method of stepwise hybridization by means of mass selection from the hybrid population [(Pirotrix 28 × Justin) × Tselinnaya 21] × (Tselinnaya 60 × Lutescens 57/76). The variety is of a medium late type, the vegetation period is 95-100 days. The variety Astana, a subvariety of Lutescens, was bred by hybridization (line Lutescens I-2959 × Tselinnaya 90), medium-early ripening type, vegetation period 80-84 days.

The growth and development of plants were assessed both with the help of traditional ground-based observations and with the data of remote sensing of the Earth coupled with them.

Previously, at the precision farming landfill, the parameters of soil fertility were determined by means of a detailed agrochemical survey according to the generally accepted method, and in some variants — according to a 1-, 5- and 25-hectare grid. A precision farming technology with variable rationing of fertilization was used for the fields with a grid of 1 and 5 hectares, and the traditional technology for the fields with a grid of 25 hectares. Soil samples were taken with an automatic Wintex 3000 drill (Wintex Agro, Denmark) using a mobile complex with GPS referencing along a diagonal route for each cell of soil sampling. The data obtained were used to identify intra-field heterogeneity and calculate the doses of fertilizers for their differentiated application.

The state of plants was assessed using satellite images using the NDVI [8, 9]. Based on a detailed study of various vegetation indices, the most informative indicators with a spatial resolution of 30 m were previously identified [15]. Monitoring by satellites of the Sentinel-2 group was carried out using the LandViewer service (https://eos.com), which allows processing and analyzing images in real time. The authors also took into account the data of unmanned aerial vehicles (UAVs) [16] Geoscan 201 Agro (Geostoroiizyskaniya LLC, Russia) equipped with two cameras — an RGB camera and a modified infrared camera. The data from the first was used to create an orthomosaic, elevation maps, 3D models, and from the second, for NDVI maps.

Field coordinates on a 1-ha grid are 51°33′5.8″N (latitude), 71°02′30.7″E (longitude); on a 5-hectare grid 51°33′17.4″N, 71°02′08.7″E; on a 25-hectare grid 51°33′14.2″N, 71°03′25.1″E. For cluster sectors (along the field slope) at constant longitude 71°02′30.7″E, coordinates for sector 1 are 51°33′15.8″N, for sector 2 51°33′54.7″N, for sector 3 51°32′43.7″N. Spring wheat cv. Shortandinskaya 95 was cultivated in the 1- and 5-hectare fields with differentiated fertilization, wheat cv. Astana according to a standard technology. All fields were located within the same soil variety on dark chestnut soils.

The control techniques of precision farming were implemented through the differentiated application of basic fertilizers in two ways, i.e., with presowing fertilization in the rows simultaneously with sowing seeds using the Bourgault complex (Bourgault Industries Ltd., Canada) and by the surface method using the Amazone ZA-M solid bulk fertilizer spreader (AMAZONEN-WERKE

H. Dreyer GmbH & Co. KG, Germany). Both of these complexes were equipped with control on-board electronics and GPS receivers, which made it possible to control fertilization with a specfied accuracy.

Corrective control of the bioproduction process was carried out by foliar feeding. Top dressing was carried out with a solution at the rate of 50-100 l of tank mixture per 1 ha using equipment for applying liquid fertilizers (self-propelled sprayer John Deere m 4030, John Deere, USA). In the experiments, the research team used polymer fertilizers Vitanoll-NP (1 l/ha) and Vitanoll-micro (1 l/ha) (Agromarket-24 LLC, Russia) [25], complex chelated fertilizer CCF (2 l/ha) (FSBSI Agrophysical Research Institute, Russia) and humic fertilizer Stimulife (0.3 l/ha) (Agrofizprodukt LLC, Russia) [26]. Operational correction of productivity was carried out at the critical phases of ontogenesis which were assessed using ERS.

Statistical analysis was performed using the Stat and Microsoft Excel 2010 standard software packages and the AGROS-1 software (version 2.09-2.11/1993-2009). The reliability of the results of field experiments based on the analysis of variance, correlation and variation analysis was determined according to the method of the field experiment [17]. ERS data were assessed based on cluster analysis [18, 19] and time series analysis [20, 21], as well as NDVI dynamics for the growing season for each field [22-24]. Curves of NDVI dynamics by analysis time were smoothed in the dispersion mode. The data were presented graphically [21]. The software for precision farming FieldRoverII (Site-Specific Technology Development Group, Inc., USA) and SMS Advanced (Ag Leader Technology, Inc., USA), as well as own developments of Agro-Network Technologies (Kazakhstan) and API GIS (Russia), were used.

Results. A distinctive feature of the conducted studies is their precision nature, which for the first time made it possible to move from the assessment of the observed phenomena to the operational use of crop correction means.

The use of ERS in Kazakhstan is far from new. Earlier, the National Center for Space Research and Technologies introduced the AgroGIS information and analytical system, adapted to solve the problems of space monitoring of grain production in Kazakhstan [27]. Based on data from EOS MODIS (Moderate Resolution Imaging Spectroradiometer), Terekhov presented empirical relationships between productivity and various spectral characteristics of fields for non-cereal [28] and grain crops [29] over a number of seasons. Results have been obtained that confirm the close relationship between the vegetation indices and the yield of cultivated crops [27-29]. However, these and other monitoring studies in the conditions of Kazakhstan were carried out over large territories, therefore, they were rather statistically generalizing and predictive in nature and did not detail the data for each field separately in terms of their mosaicity in fertility and agricultural landscape features. At the same time, the intra-field diversity (heterogeneity) of each field has not yet been taken into account, which can be realized only with the help of precision farming technology.

Methods based mainly on geostatistics have been developed to identify intra-field heterogeneity; however, there are not many approaches for decoding ERS in an inhomogeneous field space. Based on many years of research by the Agrophysical Research Institute (API) on the introduction of precision farming technology, the authors have developed an algorithm for the transition from typical monitoring studies to new management techniques for wheat cultivation in the unfavorable arid conditions of Kazakhstan. So, to identify the boundaries of intra-field inhomogeneity, a new precision approach was proposed based on the conjugate processing of remote sensing and ground-based precision information

[4, 15], which was first implemented in the conditions of Northern Kazakhstan [30].

At the precision farming landfill, a detailed assessment of the heterogeneity of the state of the soil cover was carried out according to the main agrochemical indicators. A network of 159 elementary plots with an area of 1 hectare was formed, as well as a network of landfills of 5 and 25 hectares. According to the main agrochemical characteristics, the comparative heterogeneity of the massifs was revealed. So, in a 1-ha grid with an average $N\text{-}NO_3$ content of 15.2 mg/kg, the coefficient of variation (*Cv*) was 65%, for P_2O_5 (27.2 mg/kg) 27%, and for K_2O (733 mg/kg) 21%. An increase in the size of an elementary plot in determining the most variable indicator (the content of nitrate nitrogen in the soil) led to a decrease in the coefficient of variation. And with a decrease in the size of the elementary section, the inhomogeneity index for mobile phosphorus decreased.

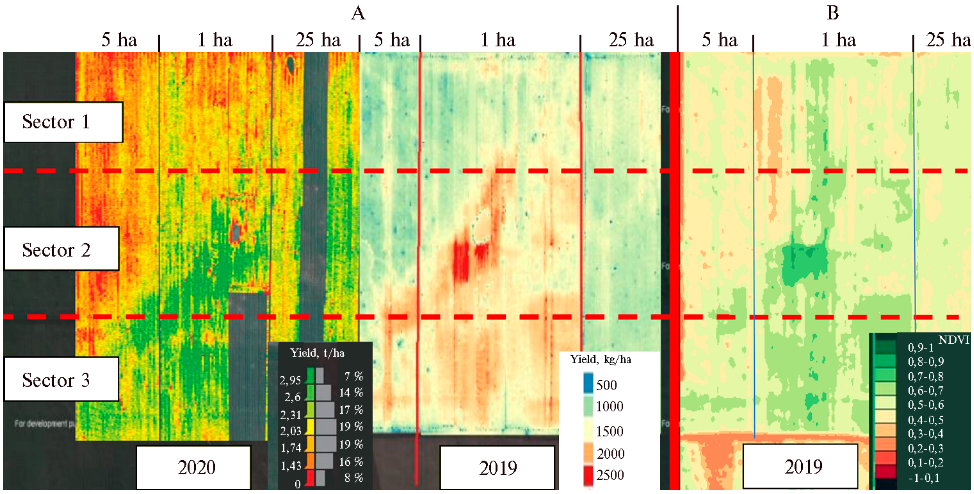

Fig. 1. Integration of terrestrial (yield maps of spring wheat *Triticum vulgare* L.) (A) **and satellite remote sensing data (normalized vegetation index, NDVI)** (B) **with differentiation by assessment grids of 5, 1, and 25 hectares and clusters** (sectors 1-3) **in different years** (LLP Baraev Production Center of Grain Farming, Kazakhstan).

Of particular practical interest were the data that serve as an information basis for subsequent calculations and analysis — an electronic yield map with a grid of 1, 5, and 25 hectares (Fig. 1). Each field had zones (designated as sectors, or clusters) with clearly lower and higher yields. These clusters were clearly manifested according to the data of the yield map for the growing season of 2019, as well as independently and unambiguously — in the conditions of 2020. Moreover, the cluster manifested itself as a separate zone of field heterogeneity, identified not only by the yield map, but also in the conjugate assessment with ERS.

The results obtained in the arid conditions of Kazakhstan in 2019 and confirmed in the conditions of the growing season of 2020 made it possible to reveal the dominant influence on the productivity of the crop rather than typical agrochemical parameters of soil fertility, but others related to the stock and distribution of soil moisture (soil-landscape-hydrological). Earlier [30], the authors, like other researchers [4-6], focused on the parameters of the agrochemical heterogeneity of the field and, using the differential application of mineral fertilizers, tried to eliminate nutritional deficiencies. Therefore, as a result of cluster and detailed analysis of the yield for each cell of the landfill for a 1 ha grid, it was not possible to reveal any significant interdependence with the parameters of soil fertility.

However, in the present experiment, a very close relationship was found between yield and NDVI. Along the long run of the field in the direction of the wheat sowing rows, the correlation coefficient between yield and NDVI along the transect was *r* = 0.64-0.99 (sample of 9 rows with a cell of 1 ha), across the field *r* = 0.62-0.98 (sample of 18 rows with a cell of 1 ha). However, based on the results obtained, as well as the data of other researchers [30, 31], the authors were unable to identify a factor that determines the increase in yield across clusters of a field that is heterogeneous in the direction from its northern part (sector 1) to its southern part (sector 3).

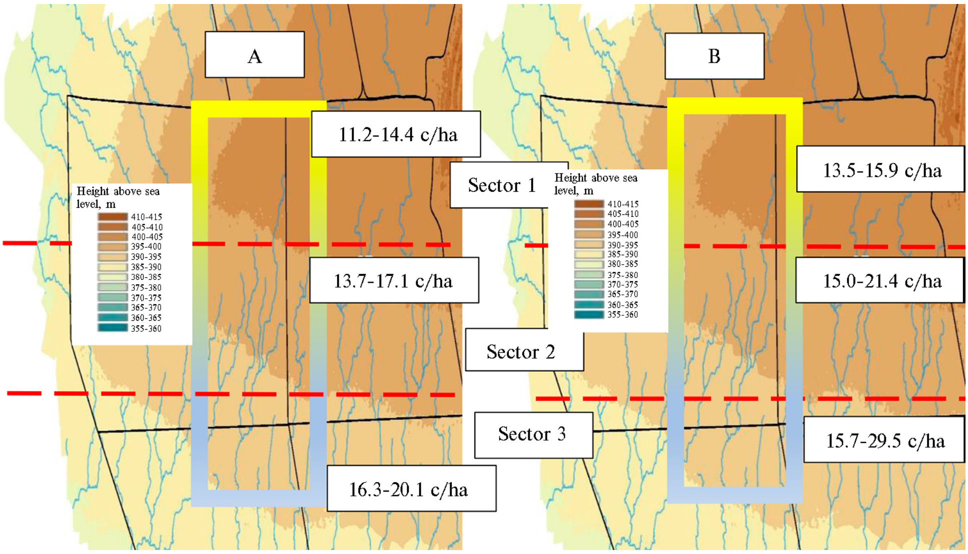

Fig. 2. The distribution of the yield of spring wheat *riticum vulgare* L. on the digital elevation model map in different years: A — 2019, Б — 2020. Sectors are marked with a coordinate reference at a constant longitude of 71°02'30.7″E with heights registration (h): for sector 1 51°33′15.8″N (h = 400-405 m), for sector 2 51°33′54.7″N (h = 390-395 m, for sector 3 51°32′43.7″N (h = 385-390 m) (LLP Baraev Production Center of Grain Farming, Kazakhstan). The rectangles in the center of images A and B illustrate an increase in moisture availability from the top of the figure to the bottom.

It was found that only one agrochemical heterogeneity of the experimental field was partially leveled by the differentiated introduction of nutrients. This heterogeneity was clearly manifested in the detailed accounting of yield data. Dividing the field according to the zones of heterogeneity of the array into three sectors (Fig. 2), it can be noted that the average yield for 2019 in the upper part of the field (sector 1) was 12.8 c/ha, in the center (sector 2) 15.4 c/ha, in the lower part 18.2 c/ha (sector 3). In 2020, this trend continued, but the average yield turned out to be slightly higher. It was found that with an increase in the degree of precision of studies (grids of 25, 5, and 1 ha), both the total yield and the differentiation of the yield along the slope increased. If in 2019, on a grid of 25 hectares, the average yield on an area of 82.9 ha was 14.6 c/ha, then in 2020, on an area of 559 ha, a yield of 18.1 c/ha was recorded; in a 5-ha grid, in 2019 and 2020, this indicator was 16.0 c/ha (area of 68.3 hectares) and 18.9 c/ha (65 hectares), respectively, in a 1 ha grid 17.4 c/ha (174.4 ha) and 22.6 c/ha (418 ha).

On the basis of coupled precision studies, the authors were able to identify the reason for the change in yield in different parts of the field, which was determined by the slope of the field and, accordingly, by different degrees of moisture supply. Here one can single out a factor associated with the stock and distribution of soil moisture, due to the peculiarity of the terrain, the combination of soil and hydrological conditions of the agricultural landscape (that is, soil-landscape-hydrological conditions). This was realized with the help of remote sensing and the creation of a digital elevation model [31], for which mathematical and digital models of the earth's surface were used [32]. The more detailed the data analysis was, the higher the accuracy of estimating the yield increase was. Thus, the increase in yield when detailed on a 5-ha grid was slightly less than 10%, and with a 1 ha grid 2 times more compared to the traditional technology (on a 25-ha grid).

Based on the change in agrolandscape conditions determined by the slope of the terrain, it was possible to estimate the distribution of watercourses characterizing the supply of productive moisture in one or another part of the field (see Fig. 2).

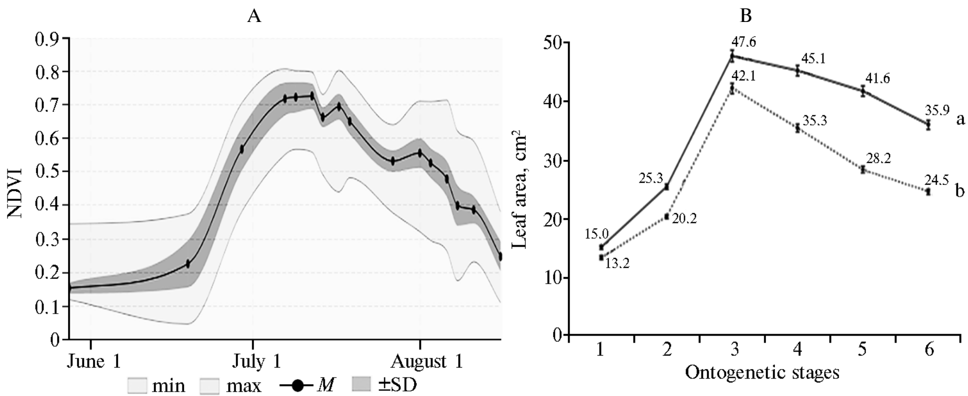

Fig. 3. Correspondence between the dynamics of the vegetation index by dates (A, Earth remote sensing data, LLP Baraev Production Center of Grain Farming, Kazakhstan, 2019) **and change in the wheat leaf surface area** (B) **in ontogenesis under irrigation** (a) **and drought** (b) **[33]:** 1 — tillering, 2 — stem elongation, 3 — earing, 4 — flowering, 5 — milk ripeness, 6 — wax ripeness.

When assessing the dynamics of plant development from May 26 to August 10, 2019, it was noted that the change in NDVI over time was uneven. A gradual increase in the vegetation index from 0.15 to 0.71-0.73 (July 6-9) characterized an increase in the vegetative mass and growth activation (Fig. 3). However, the vegetation index did not reach the expected values of 0.9-1.0, which indicated the insufficient completion of the physiological processes of accumulation of plastic substances in the plant biomass. The latter could be associated with arid conditions, high temperatures, and lack of moisture, which did not allow realizing the potential of cultivated varieties and agrotechnological solutions of precision farming [33].

A correlation (*r*) was found between the yield and ERS data according to the NDVI index: for sector 1 – 0.68, for sector *2* – 0.83, for sector 3 – 0.65. However, here the influence of not an agrochemical factor, but a hydrological factor, which determined the difference in yield across the estimated clusters, was already manifested.

Also in precision field experiments, it was found that when using foliar plant feeding at different phases of ontogenesis, wheat yield increased from 22.1 c/ha (high agricultural background) to 22.7-24.7 c/ha, or by 10-20%. A statistically significant (LSD_{05} = 3.42 c/ha) yield increase of 3.7 c/ha was noted for Vitanoll-NP fertilizer, of 4.1 c/ha for CCF, and 4.6 c/ha for Vitanoll-micro. This data was obtained in 2019, the first year of the research. However, in the conditions of the 2020 season, no statistically significant increases in yield due to the use of foliar feeding were revealed. In the future, it is necessary to clarify the features and reasons for the ambiguity of these results.

Thus, as a result of the performed studies, an algorithm was proposed for the transition from passive monitoring activities using ERS to active control actions aimed at increasing the productivity and quality of spring wheat in the conditions of Northern Kazakhstan. This algorithm is based on the use of remote sensing data and associated ground precision measurements. It allows determining the specifics of differentiated fertilization, taking into account the response of plants to changes in the vegetation index NDVI, and controlling the physiological processes of growth and development of cultivated crops, which ultimately affects an increase in yield. So, with remote sensing using UAVs, it was possible to find out the features of the formation of the spring wheat crop in different zones of field heterogeneity. Such an indicative indicator as the vegetation index NDVI, determined using UAVs, was more informative than satellite images. With the help of remote sensing data, it was possible to assess the specificity of the dynamics of physiological processes during the growth and development of different varieties of wheat, to identify critical phases, and to determine the optimal timing for applying corrective actions. Significant increases were obtained when vegetating wheat plants were treated with Vitanoll-NP (1 l/ha) at germination and tillering (by 18%), CCF (1 l/ha) at tillering (by 19.9%), and Vitanoll-micro (1 l/ha) upon a combined application at tillering, earing, and milk ripeness of grain (by 22.3%). In addition, with the help of remote sensing, it is possible to quickly identify zones of depression in plant development in the heterogeneous space of the field and timely carry out the necessary fertilizing. On the basis of the chosen scheme of plant treatment according to the phases of ontogenesis using means of crop correction (foliar feeding), promising data were obtained. In general, precision control of wheat productivity in the conditions of Northern Kazakhstan is very promising and requires further comprehensive study.

REFERENCES

1. Merchuk-Ovnat L., Fahima T., Ephrath J.E., Krugman T., Saranga Y. Ancestral QTL alleles from wild emmer wheat enhance root development under drought in modern wheat. *Front. Plant Sci.*, 2017, 8: 703-715 (doi: 10.3389/fpls.2017.00703).
2. Araus J.L., Slafer G.A., Royo C., Serret M.D. Breeding for yield potential and stress adaptation in cereals. *Critical Reviews in Plant Sci*ences, 2008, 27(6): 377-412 (doi: 10.1080/07352680802467736).
3. Guo Y., Du Z., Chen J., Zhang Z. QTL mapping of wheat plant architectural characteristics and their genetic relationship with seven QTLs conferring resistance to sheath blight. *PLoS ONE*, 2017, 12(4): e0174939 (doi: 10.1371/journal.pone.0174939).
4. Uskov I.B., Yakushev V.P., Chesnokov Yu.V. Actual physical, agronomic, genetical and breeding aspects in agrobiological management (towards 85 anniversary of Agrophysical Research Institute, Russia**).** *Sel'skokhozyaistvennaya biologiya* [*Agricultural Biology*], 2017, 52(3): 429-436 (doi: 10.15389/agrobiology.2017.3.429eng).
5. Panayi E., Peters G.W., Kyriakides G. Statistical modelling for precision agriculture: a case study in optimal environmental schedules for Agaricus Bisporus production via variable domain functional regression. *PLoS ONE*, 2017, 12(9): e0181921 (doi: 10.1371/journal.pone.0181921).
6. Banu S. Precision agriculture: tomorrow's technology for today's farmer. *J. Food Process Technol.*, 2015, 6(8): 1000468 (doi: 10.4172/2157-7110.1000468).
7. Busse M., Doernberg A., Siebert R., Kuntosch A., Schwerdtner W., König B., Bokelmann W. Innovation mechanisms in German precision farming. *Precision Agric.*, 2014, 15(4): 403-426 (doi: 10.1007/s11119-013-9337-2).
8. Spivak L.F., Terekhov A.G., Vitkovskaya I.S., Batyrbaeva M.ZH. *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa*, 2009, 6(2): 450-458 (in Russ.).
9. Gopp N.V., Savenkov O.A., Smirnov A.V. *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa*, 2019, 16(3): 125-139 (doi: 10.21046/2070-7401-2019-16-3-125-139) (in Russ.).
10. Roy D.P., Wulder M.A., Loveland T.R., Woodcock C.E., Allen R.G., Anderson M.C., Hel-

der D., Irons J.R., Johnson D.M., Kennedy R., Scambos T.A., Schaaf C.B., Schott J.R., Sheng Y., Vermote E.F., Belward A.S., Bindschadler R., Cohen W.B., Gao F., Hipple J.D., Hostert P., Huntington J., Justice C.O., Kilic A., Kovalskyy V., Lee Z.P., Lymburner L., Masek J.G. McCorkel J. Shuai Y., Trezza R., Vogelmann J., Wynne R.H., Zhu Z. Landsat8: Science and product vision for terrestrial global change research. *Remote Sensing of Environment*, 2014, 145: 154-172 (doi: 10.1016/j.rse.2014.02.001).

11. Bastiaanssen W.G.M., Noordman E.J.M., Pelgrum H., Davids G., Thoreson B.P., Allen R.G. SEBAL model with remotely sensed data to improve water resources management under actual field conditions. *Journal of Irrigation and Drainage Engineering*, 2005, 131(1): 85-93 (doi: 10.1061/(ASCE)0733-9437(2005)131:1(85)).
12. Menges R.M., Nixon P.R., Richardson A.J. Light reflectance and remote sensing of weeds in agro-nomic and horticultural crops. *Weed Science*, 1985, 33(4): 569-581 (doi: 10.1017/S0043174500082862).
13. Thorp K., Tian L.F. A review on remote sensing of weeds in agriculture. *Precision Agriculture*, 2004, 5(5): 477-508 (doi: 10.1007/s11119-004-5321-1).
14. Diker K., Heermann D. F., Bordahl M. K. Frequency analysis of yield for delineating yield response zones. *Precision Agriculture*, 2004, 5: 435-444 (doi: 10.1007/s11119-004-5318-9).
15. Komarov A.A., Muntyan A.N., Sukhanov P.A. *Izvestiya SPbGAU*, 2018, 3(52): 64-70 (in Russ.).
16. Tahar K.N. Multi rotor UAV at different altitudes for slope mapping studies. *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences*, 2015, XL-1/W4: 9-16 (doi: 10.5194/isprsarchives-XL-1-W4-9-2015).
17. Dospekhov B.A. *Metodika polevogo opyta.* M., 1985.
18. Aggarwal C., Reddy C. *Data clustering: algorithms and applications.* CRC Press, Boca Raton, London, New York, 2013: 652.
19. Ghassempour S., Girosi F., Maeder A. Clustering multivariate time series using hidden Markov models. *International Journal of Environmental Research and Public Health*. 2014, 11(3): 2741-2763 (doi: 10.3390/ijerph110302741).
20. Kelley D.R., Salzberg S.L. Clustering metagenomic sequences with interpolated Markov models. *BMC Bioinformatics* 2010, 2(11): 544 (doi: 10.1186/1471-2105-11-544).
21. Kataev M.Yu., Bekerov A.A., Shalda P.V. *Doklady Tomskogo GUSUR*, 2017, 20(1): 81-84 (doi: 10.21293/1818-0442-2017-20-1-81-84) (in Russ.).
22. Bradley B.A. A curve fitting procedure to derive inter- annual phenologies from time series of noisy satellite NDVI data. *Remote Sensing of Environment*, 2007, 106(2): 137-145 (doi: 10.1016/j.rse.2006.08.002).
23. Hird J.N. Noise reduction of NDVI time series: An empirical comparison of selected techniques. *Remote Sensing of Environment*, 2009, 113: 248-258 (doi: 10.1016/j.rse.2008.09.003).
24. Jönsson P., Eklundh L. TIMESAT — A program for analyzing time-series of satellite sensor data. *Computers & Geosciences*, 2004, 30(8): 833-845 (doi: 10.1016/j.cageo.2004.05.006).
25. Komarov A.A., Komarov A.A. *Agrokhimicheskii vestnik*, 2018, 6: 34-38 (doi: 10.24411/0235-2516-2018-10057) (in Russ.).
26. Kurtener D.A., Komarov A.A., Krueger E.D., Lavrukov M.Yu, Nayda N.M. Fuzzy multi-attributive analyzes of organic-mineral fertilizer “Stimulayf” and “Humate Sodium” application for cultivation *of Dracocephalum L. European Agrophysical Journal*, 2014, 1(1): 14-24 (doi: 10.17830/j.eaj.2014.01.014).
27. Bekmukhamedov N.E., Ayupov K.A., Karabkina N.N., Degtyareva O.V., Vorotyntseva V.V. *Materialy chetyrnadtsatoi Vserossiiskoi konferentsii «Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa»* [Proc. 14th Russian Conf. «Current problems of the Earth remote sensing from space»]. Moscow, 2016: 328 (in Russ.).
28. Terekhov A.G. *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa*, 2008, 5(2): 371-375 (in Russ.).
29. Terekhov A.G. *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa,* 2010, 7(3): 305-314 (in Russ.).
30. Abdullaev K., Irmulatov B., Komarov A., Nugis E. Precision agriculture in the North of Kazakhstan. *Journal of Agricultural Science*, 2020, 31(2): 115-121 (doi: 10.15159/jas.20.25).
31. Wang L., Liu H. An efficient method for identifying and filling surface depressions in digital elevation models for hydrologic analysis and modelling. *International Journal of Geographical Information Science*, 2006, 20(2): 193-213 (doi: 10.1080/13658810500433453).
32. Hengl T., Evans I.S. Mathematical and digital models of the land surface. *Developments in Soil Science*, 2009, 33: 31-63 (doi: 10.1016/s0166-2481(08)00002-0).
33. Lushnikova T.A. *Vestnik KGU*, 2012, 3: 70-76 (in Russ.).