Remote spectral analysis of varieties and lines of winter wheat during the flowering period

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Purpose. Conduct a spectral assessment of winter wheat varieties ('MIP Assol', 'Balada Myronivska', 'Hratsiia Myronivska', 'MIP Yuvileina', 'MIP Lada', 'MIP Dniprianka', and standard 'Podolianka') and perspective breeding lines ('Erythrospermum 55023', 'Lutescens 22198', 'Lutescens 37519', 'Lutescens 60049', 'Lutescens 60107') of Myronivka Institute breeding during the flowering period and to evaluate the dependence of the obtained NDVI indicator on their productivity. **Methods.** The research was conducted during the 2018/19–2020/21 growing seasons in the breeding crop rotation of the winter wheat breeding laboratory of the V. M. Remeslo Myronivka Wheat Institute of the National Academy of Sciences of Ukraine. The main method of research is field, supplemented by analytical studies, measurements, calculations and observations. Obtaining values of vegetation indices of varieties and breeding lines of winter wheat was carried out using the Mavic zoom 2 UAV (unmanned aerial vehicle) using the Parrot Sequoia multispectral camera. Pix4Dcapture and Pix4Dmapper programs were used to create an orthophoto map. Photographing was carried out with a multispectral camera at a height of 30 m above the level of the object under study in order to improve the quality of the orthophoto map with an overlap of 80% of the images and a time interval of 2 seconds. The NDVI index (normalized difference vegetation index) was calculated according to the appropriate formula. **Results.** According to the research results, regardless of the conditions of the year, in the first, optimal sowing period (25.09–05.10), the NDVI indicator in the flowering-ripening phase of wheat had higher values than in the second, late period (05–15.10) (average value over three years for the first semester was 0.69, the second – 0.62). In the course of the research, we established the dependence of the vegetation index NDVI on the level of productivity of wheat genotypes. The best varieties and promising lines among those studied were 'MIP Lada', 'Lutescens 55198' and 'Lutescens 60049', as well as 'MIP Assol' and 'Hratsiia Myronivska', which were less sensitive to sowing dates and had a higher index and control of yield indicators even with late sowing dates. **Conclusions.** Although existing today phenotyping methods need to be improved and localized, in the near future they will become an indispensable tool for the breeder, which will increase the volume of studied varieties and improve the quality of the results of morpho-biological analysis.

Keywords: winter wheat; variety; breeding lines; flowering; NDVI index; spectral evaluation.

Introduction

To feed the several billion people who live on this planet, the production of high-quality food must increase at a lower cost, but this will be especially difficult to achieve in the face of the challenges of global environmental change. Breeders should focus on traits with great potential for higher yields. Therefore, new technologies need to be developed to accelerate breeding by improving genotyping and phenotyping methods and increasing the existing genetic diversity in germplasm used for breeding. The best results will be obtained from the introduction of these technologies in developing countries, but the technologies must be economically available and easily distributed [1].

Plant breeding brings the value of indicators closer to their theoretical maximums,

leaving the indicator of light conversion efficiency, which is mainly determined by photosynthesis, as the only significant prospect for its improvement [2].

Winter wheat is the main agricultural crop in Ukraine. It continues to rank first in terms of sown area (within 6.4–6.8 million hectares) not only among cereals, but also among the entire list of agricultural crops in Ukraine. According to the review of the world wheat market, which the US Department of Agriculture published in October 2021 [3], wheat yields in Ukraine grew at an explosive pace – over 20 years (1996–2016), the average value of the indicator increased by 44%. To a large extent, this was influenced by breeding activities. The creation of modern varieties of winter wheat was the impetus for the intensification of cultivation technologies, which was aimed at increasing the level of crop yield.

Currently, the global trend in agricultural production is the use of spectral images obtained using satellites and UAVs. The introduction and use of modern screening technologies

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in breeding practice, along with existing biometric evaluation methods, opens up the possibility of improving the quality of selection of source and breeding material and enables the breeder to obtain a more objective assessment, as well as to increase the volume of samples under study by several times.

It was proved that the photosynthetic activity and nitrogen status of the plant affect the accumulation of dry matter and nitrogen in the ear before and during flowering, both parameters being correlated with the number of ovaries [4].

According to the international classification of the BBCH (Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie, Bayer, BASF, Ciba-Geigy, and Hoechst), the wheat flowering phase is determined by macrostage 6, which in turn is divided into microstages: 61 – the beginning of flowering (appearance of the first anthers), 65 is the middle of flowering (50% of mature anthers), 67 is full flowering (75% of mature anthers), and 69 is the end of flowering (all spikelets have completed flowering, but some dehydrated anthers may remain) [5]. Winter wheat phenotyping methods are a promising direction in the crop breeding. The most common vegetation index in the spectral assessment is the NDVI index [6]. Recent studies demonstrate close correlations between the NDVI index obtained during the flowering of winter wheat and the yield level [7]. It should be noted that, according to the results of studies, the best period for spectral evaluation during the flowering of winter wheat is the period between 67–69 BBCH microstages.

Creation of multispectral orthophoto maps in the wavelength range of 550–790 nm using unmanned aerial vehicles (UAVs), make it possible to quickly and with high accuracy evaluate different traits at different phases of crop growth [8].

Bearing in mind that UAV imaging is less laborious and, due to its higher accuracy, compared to the non-imaging proximal probing previously used with handheld instruments like GreenSeeker, UAV airborne multispectral probing is expected to increase sample evaluation volumes and accuracy of the obtained vegetation indices [9].

The purpose of the research is to conduct a spectral assessment of modern varieties and promising breeding lines of winter wheat of Myronivka Institute breeding during flowering and compare the value of the obtained NDVI index with the yield.

Materials and methods

The research was carried out during the 2018/19 – 2020/21 growing seasons in the breeding crop rotation of the winter wheat breeding laboratory of the V. M. Remeslo Myronivka Wheat Institute of the National Academy of Sciences of Ukraine (MIP). Sowing was carried out in two periods: 2018 – September 25 and October 5; 2019 and 2020 – October 5 and 15, with soybean as a predecessor. The placement of plots was systematic, with four-fold repetition, the accounting area was 10 m². The sowing rate was 5 million similar seeds per hectare. The 'Podolianka' variety was used as the standard. The research was carried out in accordance with the "Methods of field experience" [10], phenological observations and records – in accordance with the "Methods of examination of plant varieties of the leguminous and grain groups for distinctness, uniformity and stability" [11]. New varieties: 'MIP Assol', 'Balada Myronivska', 'Hratsiia Myronivska', 'MIP Yuvileina', 'MIP Lada', 'MIP Dniprianka' and the standard variety 'Podolianka' and breeding lines: 'Erythrospermum 55023', 'Lutescens 22198', 'Lutescens 37519', 'Lutescens 60049', 'Lutescens 60107' were used in the experiments.

Spectral assessment of varieties and breeding lines of winter wheat was carried out using the Mavic zoom 2 UAV using a multispectral camera Parrot Sequoia with its ability to capture an image in the range of 550–810 nm. Pix4Dcapture and Pix4Dmapper were used to make the orthophoto map. Photographing was carried out with a multispectral camera at a height of 30 m above the level of the object under study in order to improve the quality of the orthophoto map, with an overlap of 80% of images and with a time interval of two seconds. NDVI index (Normalized Difference Vegetation Index) was calculated using the formula [12]:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

where: NIR – display in the near infrared spectral region;
RED – display in the red spectral region.

The years of the study were contrasting in terms of the hydrothermal regime with an uneven distribution of precipitation by months, which made it possible to obtain objective data. Meteorological conditions were analyzed according to the data of a private, stationary

weather station located within a radius of 6 km from the fields where the studies were carried out and connected to the global Meteoblue system (Basel, Switzerland).

Results and discussion

According to the research results, regardless of the conditions of the year, it was established that the NDVI indicator in the flowering-ripening phase had higher values for the first sowing term (the three-year average value for the first term was 0.69, for the second – 0.62). In the 2019/2020 vegetation season, with abnormally dry weather conditions in autumn and spring, the minimum values of the index were noted. The 2020/2021 vegetation season turned out to be the best for the research period: the NDVI value varied from 0.84 (line 'Lutescens 55198', second sowing period) to 0.92 (varieties 'MIP Assol', 'Hratsiia Myronivska', MIP Yuvileina' and lines 'Erythrospermum 55023', 'Lutescens 37519', first sowing period). The main factor that contributed to such a high index indicator was favorable weather conditions during the autumn vegetation period, which made it possible to obtain uniform shoots and form two or three lateral shoots, and moist and warm conditions in the spring.

The weather conditions of the 2018/2019 growing season were satisfactory. In the pre-sowing period, 75 mm of precipitation fell, which made it possible to carry out sowing in well-prepared moist soil (Fig. 1).

In total, 45.3 mm of precipitation was recorded from the sowing of the first term to the end of the autumn vegetation period, which contributed to the good development of winter wheat plants in the autumn period.

Time of spring vegetation resumption (TSVR) was characterized by a gradual increase in the average daily air temperature without significant drops. The amount of precipitation from TSVR to the beginning of flowering was 172.9 mm (one shower of heavy rain, 49 mm), and from the beginning of flowering to the end of maturation – 21.5 mm. In general, the spring-summer vegetation period can be characterized as satisfactory and favorable for the formation of a high yield of winter wheat grain. The average daily air temperature in summer was 21.3 °C without significant air and soil drought.

During the study period, the weather conditions of the 2019/2020 growing season were the most unfavorable for the growth and development of winter wheat plants (Fig. 2).

From the beginning of September 2019 until the first wheat sowing term, 1.1 mm of precipitation fell in the form of unproductive rains, which in turn did not make it possible to conduct high-quality soil preparation and obtain uniform, friendly shoots. During the sowing-seedling period and before the end of the autumn vegetation, 28.9 mm of precipitation was recorded (with only one productive rain – 7.8 mm), other precipitation, due to extreme drought, could not penetrate to the depth of seeding. The result of the autumn soil drought was a significant thinning of crops and an unsatisfactory state of development of winter wheat plants (within 10–13 phases on the BBCH scale). Winter period of the 2019/2020 growing season was abnormally warm and snowless. The average daily air temperature fluctuated within 0 °C with a slight decrease to minus 5 °C. At the time of spring vegetation resumption, there was a significant decrease in the density of winter wheat standing, caused by the freezing of underdeveloped and unhardened plants.

From TSVR (time of spring vegetation resumption) to the onset of flowering of winter wheat, the total amount of precipitation was 186.1 mm, five of which were productive: 11 mm – 04.14.2020, 31 mm – 04.26.2020, 12 mm – 05.25.2020, 16 mm – 05.30.2020 and 14 mm – 06.15.2020. From the beginning of the flowering phase to the end of winter wheat ripening, another 51.3 mm of precipitation were recorded, which was represented by three productive rains, namely: 14 mm – 06.22.2020, 11 mm – 06.28.2020 and 9.3 mm – 07.08.2020. The spring-summer period of 2020 can be characterized as abnormally hot. During June, the daytime temperature was kept at 32–35 °C. Wheat flowering took place in dry, hot weather with a significant deficit of soil moisture. These weather conditions had a significant impact on the growth and development of the culture, which was reflected in the yield indicators, they were the lowest during the last research period (average = 2.23 t/ha).

The weather conditions of the 2020/2021 growing season, especially in spring, were the best for the three-year study period (Fig. 3). In general, 68.3 mm of precipitation fell from the first sowing period to cessation of the autumn vegetation. Also, it should be emphasized that the autumn period of that year was also the warmest among the studied ones, the sum of active temperatures from sowing to the end of the autumn vegetation was 584.8 °C, while in 2019 it was 581.9 °C, and for autumn 2018 – 427.3 °C. Warm and humid weather in the first half of the growing season contributed to the good development of winter wheat plants. The
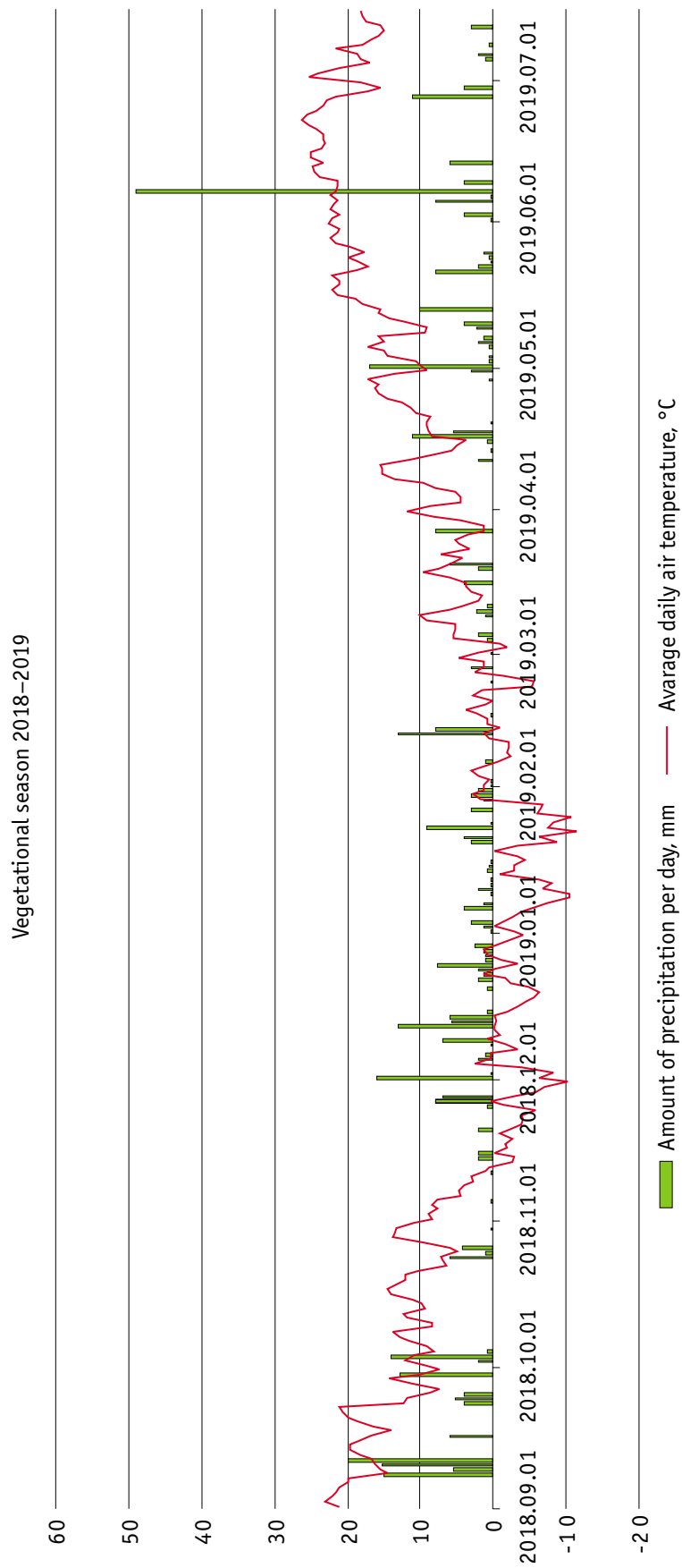
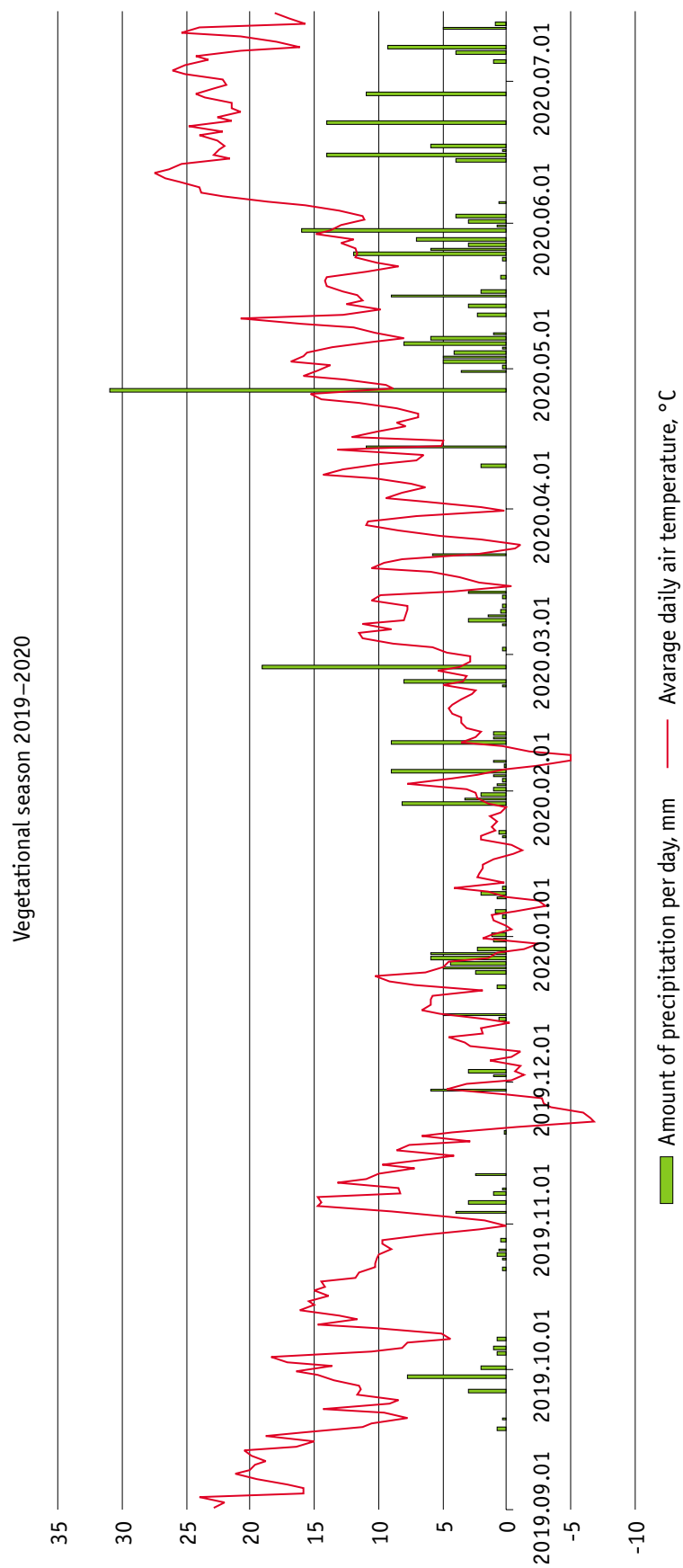**Fig. 1. Hydrothermal conditions of the 2018/2019 growing season**

Vegetational season 2018–2019

Amount of precipitation per day, mm ——— Avarage daily air temperature, °C

Fig. 2. Hydrothermal conditions of the 2019/2020 growing season

Vegetational season 2020–2021

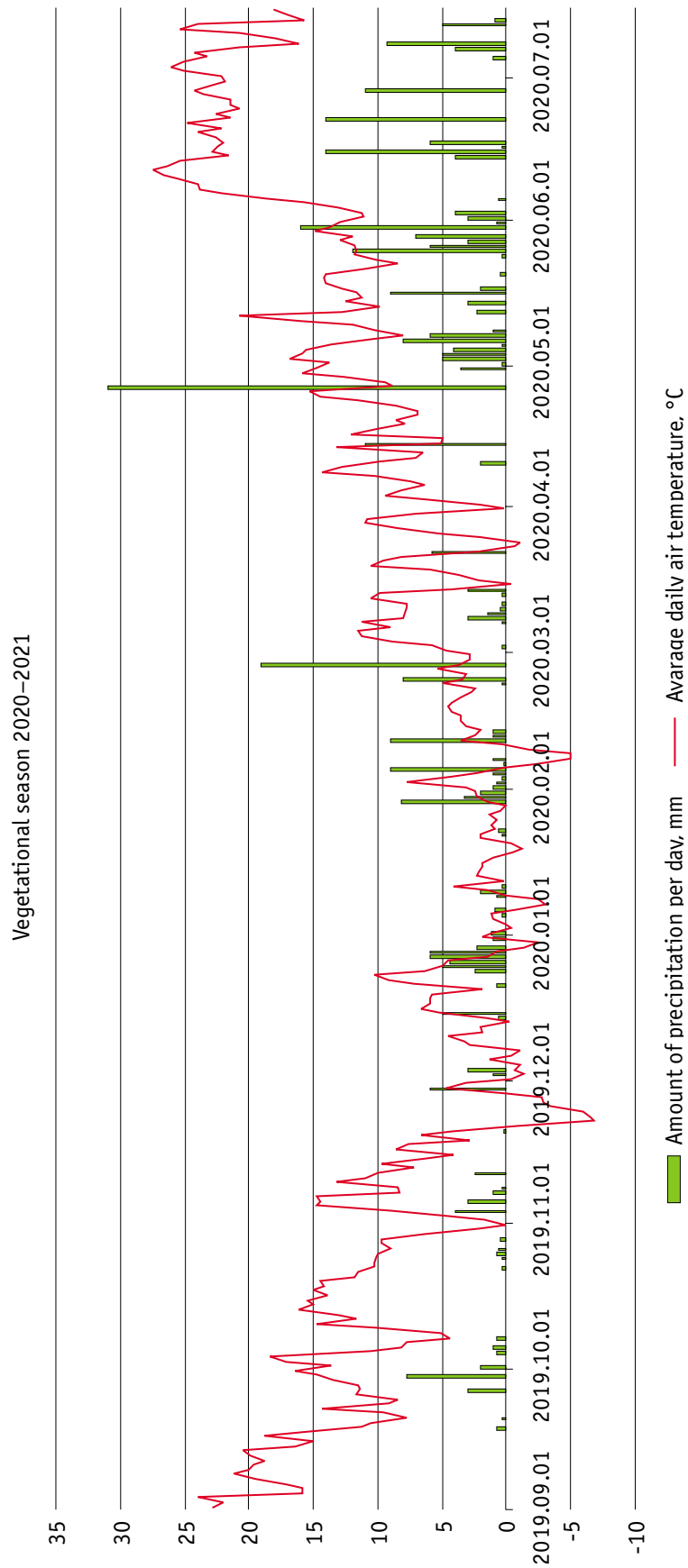Amount of precipitation per dav, mm — Avaraqe dailv air temperature. °C

Fig. 3. Hydrothermal conditions of the 2020/2021 growing season

phase of cultural development at the time of transition to winter stillness was 21–23 on the international BBCH scale.

Winter stillness in the 2020/2021 growing season occured normally. During the observed period, anomalous short-term increases in average daily temperatures above 5 °C were recorded several times, but these weather phenomena did not have negative consequences for cultivated plants.

From the moment of the resumption of the spring vegetation and before the onset of flowering, 221.9 mm of precipitation fell. The temperature regime of that period was gradually increasing, without spring frosts. Spring-summer weather conditions in 2021 were moderate. The sum of active flowering-ripening temperatures was 1333.4 °C, and the time of spring vegetation resumption was the latest (03/26/2021). Plants of winter wheat varieties and breeding lines had good biomass development and high values of the NDVI index at the time of flowering.

Various weather conditions developed during three years of the research had different effects on both the performance results of the studied samples and the results of their phenotyping.

Existing methods of plant phenotyping are considered slow, expensive, sometimes destructive, and can cause discrepancies between observations due to human operator instability. This led to the development of automated phenotyping technologies that overcome these shortcomings [13].

Collection, recording and analysis of information about the studied objects of the environment at a distance is called remote sensing. Methods and techniques for remote sensing of vegetation indices are based on the registration of absorbed, reflected or radiated energy [14]. The use of unmanned aerial vehicles (UAVs) in agriculture for spectral evaluation has great prospects and will continue to develop as an affordable alternative to space sensing [15]. The main advantages of the latter are mobility in use, as well as the best quality of spectral images, which in turn depends directly on the resolution of the spectral camera.

Figure 1 below (from left to right) shows a fragment of experimental plots of wheat of the first and second sowing periods, captured by a DJI Mavic Zoom 2 drone from a height of 30 m above the research object in the NIR (790 nm) spectrum (2020/2021 vegetation season.)
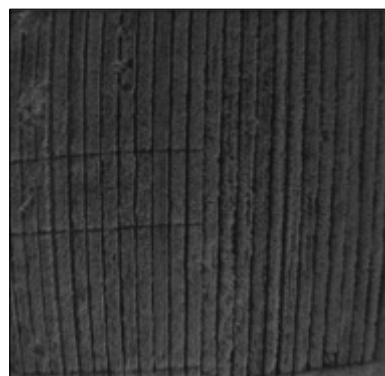
The advantage of using a UAV with a mounted multispectral camera, compared to manual field spectrometers, is a short period of spectral information collection. In the course of

The time of autumn growth cessation
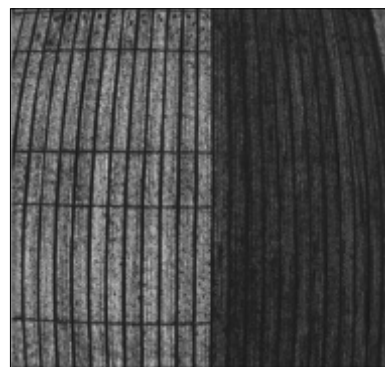
The time of spring vegetation resumption

Flowering-ripening period

Fig. 4. The fragment of the experiment depicted in the NIR (790 nm) spectrum, was made in the three investigated periods of winter wheat plant vegetation

measuring the vegetation index with manual devices, the intensity and the angle of inclination of the lighting may change, which may cause an error with a large number of studied samples. Most multispectral cameras used in scientific research including ours, the Parrot Sequoia, have an insolation sensor eliminating the error that can occur under the influence of this factor, and the period of information collection using a UAV is approximately 10 minutes for the experiment with an area of 960 m².

Of all the main characteristics of the photosynthetic productivity of plants, the content

of chlorophyll more accurately reflects the productional process [16]. Therefore, the data of remote sensing of crops can be used to monitor the progress of winter wheat yield formation. A number of studies have proven that spectral vegetation indices are good predictors of leaf surface index, biomass and agricultural land productivity [17, 18].

As is known, nitrogen is one of the main elements forming the chlorophyll molecule [19]. The ability of the variety or line to absorb nitrogen better makes it possible to form a larger amount of chlorophyll in the leaves. Since the reflectance in the NIR (790 nm) spectrum characterizes the nitrogen content, and the RED (550 nm) is sensitive to the amount of dry matter, an increase in the value in the NIR reflectance region will increase the value of the NDVI index and, accordingly, demonstrate the variety as having the ability to better absorb and distribute nitrogen in the plant body.

The ability to accumulate a high concentration of chlorophyll and photosynthesis products in the flag and sub-flag leaves, as well as in the upper part of the stem and elements of the ear, has a positive effect on the yield characteristics of the variety. Table 1 shows the average data for four-fold repetitions of the assessment of the NDVI index and yield for the first and second sowing periods.

Thinning of crops due to abnormally dry conditions that occurred in the autumn and early spring of the 2019/2020 vegetation season did not provide an opportunity to obtain reliable data. According to the results of research in the 2018/2019 and 2020/2021 vege-

Table 1

Yield and spectral indicators of winter wheat plants during the first sowing period at the time of flowering (2019–2021)

Name of variety/line	NDVI values 2019	Yield, t/ha 2019	NDVI values 2020	Yield, t/ha 2020	NDVI values 2021	Yield, t/ha 2021
'MIP Assol'	0.66	7.64	0.47	3.45	0.80	6.99
'Balada Myronivska'	0.56	7.79	0.53	2.59	0.79	6.13
'Hratsiia Myronivska'	0.66	7.90	0.58	2.04	0.67	4.38
'MIP Yuvileina'	0.61	7.52	0.55	2.43	0.79	6.64
'MIP Lada'	0.89	7.91	0.45	2.00	0.82	7.07
'MIP Dniprianka'	0.79	8.44	0.54	3.58	0.80	6.94
'Erythrospermum 55023'	0.64	6.83	0.64	1.28	0.79	6.40
'Lutescens 55198'	0.69	7.92	0.85	2.05	0.85	7.37
'Lutescens 37519'	0.92	9.05	0.55	0.93	0.80	6.75
'Lutescens 60049'	0.77	8.30	0.62	1.65	0.82	7.24
'Lutescens 60107'	0.77	8.39	0.47	2.52	0.81	7.16
'Podolianka' St	0.59	7.54	0.70	2.54	0.69	5.04
$LCD_{0.05}$	–	1.68	–	0.86	–	1.21

tation season, the best varieties for the first sowing season were: 'MIP Lada', 'MIP Dniprianka' and breeding lines: 'Lutescens 55198', 'Lutescens 37519', 'Lutescens 60049' and 'Lutescens 60107'. They exceeded the 'Podolianka' standard variety according to the NDVI index

Table 2

Yield and spectral indicators of winter wheat plants of the second sowing period at the time of flowering (2019–2021)

Name of variety/line	NDVI values 2019	Yield, t/ha 2019	NDVI values 2020	Yield, t/ha 2020	NDVI values 2021	Yield, t/ha 2021
'MIP Assol'	0.69	7.57	0.44	3.14	0.73	6.82
'Balada Myronivska'	0.54	7.51	0.41	2.51	0.72	6.11
'Hratsiia Myronivska'	0.54	7.80	0.44	2.21	0.71	7.07
'MIP Yuvileina'	0.56	7.33	0.33	2.85	0.72	5.87
'MIP Lada'	0.79	7.39	0.31	2.49	0.80	6.96
'MIP Dniprianka'	0.66	8.14	0.47	2.77	0.74	6.39
'Erythrospermum 55023'	0.56	5.59	0.42	1.04	0.69	5.64
'Lutescens 55198'	0.64	7.93	0.59	2.23	0.82	7.41
'Lutescens 37519'	0.92	7.56	0.48	1.37	0.70	5.81
'Lutescens 60049'	0.77	7.98	0.54	1.31	0.75	7.21
'Lutescens 60107'	0.71	8.19	0.39	2.30	0.78	6.43
'Podolianka'St	0.51	6.66	0.66	3.59	0.72	6.88
$LCD_{0.05}$	–	1.54	–	0.92	–	1.18

from 0.1 to 0.33 and yield results from 0.37 to 2.33 t/ha, respectively.

According to the results of the second sowing period, the variety 'MIP Lada' and the breeding lines 'Lutescens 55198' and 'Lutescens 60049' were the best. 'MIP Dniprianka', 'Lutescens 37519' and 'Lutescens 60107' exceeded the standard variety 'Podolianka' in terms of NDVI index value and yield level only in the 2018/2019 vegetation season. The varieties that also dominated the standard variety in both favorable years of research include 'MIP Assol' and 'Hratsiia Myronivska' (Table 2). Based on the obtained results, it can be concluded that these varieties are less responsive to the conditions of the sowing period and are able to provide high yield indicators in late periods.

Conclusions

As a result of our research, we established the dependence of the vegetation index NDVI on the productivity of wheat varieties. The best varieties and promising lines among studied, regardless of sowing dates, were: 'MIP Lada', 'Lutescens 55198' and 'Lutescens 60049', as well as 'MIP Assol' and 'Hratsiia Myronivska', which were less sensitive to sowing dates and had the index and yield values higher than those of the control variant at late sowing dates.

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Мета. Провести спектральну оцінку сортів ('МІП Ассоль', 'Балада Миронівська', 'Грація Миронівська', 'МІП Ювілейна', 'МІП Лада', 'МІП Дніпрянка' та сорт-стандарт 'Подолянка') і перспективних селекційних ліній ('Еритроспермум 55023', 'Лютесценс 22198', 'Лютесценс 37519', 'Лютесценс 60049', 'Лютесценс 60107') пшениці озимої миронівської селекції під час цвітіння та оцінити залежність отриманого індексу NDVI від їхньої врожайності. **Методи.** Дослідження виконували впродовж 2019–2021 рр. у селекційній сівозміні лабораторії селекції озимої пшениці Миронівського інституту пшениці імені В. М. Ремесла НААН України. Основний метод досліджень – польовий, доповнений аналітичними дослідженнями, вимірами, підрахунками та спостереженнями. Значення вегетаційних індексів сортів і селекційних ліній пшениці озимої отримували за допомогою БПЛА (безпілотний літальний апарат) Mavic zoom 2 з використанням мультиспектральної камери Parrot Sequoia. Для формування ортофотоплану використовували програмне забезпечення Pix4Dcapture та Pix4Dmapper. Фотофіксацію проводили мультиспектральною камерою на висоті 30 м над рівнем досліджуваного об'єкта для підвищення якості ортофотоплану, з перекриттям знімків 80% і з проміжком часу у дві секунди. NDVI індекс (нормалізований відносний індекс рослинності) розраховували за відповідною формулою. **Результати.** За результатами досліджень, незалежно від умов року, за перших, оптимальних строків сівби (25.09–05.10), показник NDVI у фазі цвітіння–достигання пшениці мав більші значення, ніж для другого, пізнього строку (05–15.10) (середнє значення за три роки для першого строку становить 0,69, для другого – 0,62). У процесі досліджень установлено залежність вегетаційного індексу NDVI від рівня продуктивності генотипів пшениці. Найкращими сортами та найбільш перспективними лініями серед досліджуваних, виявились 'МІП Лада', 'Лютесценс 55198' та 'Лютесценс 60049', а також 'МІП Ассоль' та 'Грація Миронівська', які були менш чутливими до строків сівби та мали значення індексу та врожайності вище контролю навіть за пізніх строків сівби. **Висновки.** Попри те, що наявні сьогодні методи фенотипування ще потребують доопрацювання та локалізації, найближчим часом вони стануть невід'ємним інструментом селекціонера, що дасть змогу збільшити обсяги досліджуваних сортозразків та поліпшити якість отриманих результатів морфо-біологічного аналізу.

Ключові слова: пшениця озима; сорт; селекційні лінії; цвітіння; індекс NDVI; спектральна оцінка.