Relationship between NDVI index obtained from MODIS and winter wheat yield

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Abstract. Programming a high-quality winter wheat crop cultivated using No-till technology is an urgent task for an agricultural producer. The use of No-till technology in soil cultivation in arid climatic conditions of the Pre-Caucasus allows increasing its moisture accumulation. Obtaining a given crop yield is solved not only by ground monitoring and crop control, but also by a system for controlling the production capacity of plants based on remote sensing data of the Earth. Thus, satellite images of various temporal and spatial resolutions provide information on the current state of crops, and field and laboratory studies - on the structural and functional state of the photosynthetic apparatus of plants, which is reflected in crop yields. This combined method makes it possible to have operational information and timely adjust technological operations included in the No-till system for its wider implementation in agricultural production.

The research was conducted in 2017-2020 in the arid zone of the Pre-Caucasus on the basis of the agricultural enterprise «Agrokhleboprodukt». Temperature conditions and precipitation were not constant. The average annual precipitation in the territory is 506 mm, the average annual air temperature is 10.1 °C, and the average annual precipitation is 30.7 mm. During the period under consideration, satellite data confirmed the fact that the values of the vegetation index NDVI grew by an average of 12% in comparison with the average long-term data. The NDVI index increased from 0.41 to 0.49. At the same time, plant productivity decreased from 4.87 to 3.14 t/ha. The obtained data made it possible to identify a regression relationship between the yield of winter wheat and the vegetation index NDVI (R² = 0.78) and to predict in 2021 a further decrease in crop productivity (provided that previously identified trends remain) and the need for operational remote and ground control over the state of crops.

1. Introduction
The most important crop in arid zone of the Central Pre-Caucasus is winter wheat as it occupies 75% of the total area of arable area. This crop is very important for food security due to the high variability of grain crops from year to year. The forecast of the grain yield season is important and should be prepared as early as possible, as it allows to carry out proper trade planning of grain by agricultural enterprises. Grain yield forecasts are based on various methods, including statistical models where meteorological data is used. Remote sensing data from satellites is more often used as source data in the grain crop productivity models for yield forecasts. The most popular satellite sensor to obtain intra-seasonal information in order to predict yields on a regional scale is MODIS.

A characteristic feature of vegetation and its condition is spectral reflectivity, characterized by large differences in the reflection of radiation of different wavelengths. Knowledge of the relationship
between the structure and state of vegetation and its spectral reflectivity makes it possible to use aerospace imagery for mapping and identifying vegetation types and their stress state [1, 2, 3].

To work with spectral information, the creating «index» images are often resorted to. Based on a combination of the brightness values in certain channels that are informative for the selection of the studied object and the calculation of these values of the object "spectral index", an image corresponding to the index value in each pixel is constructed [4, 5]. The spectral indices used to study and assess the state of vegetation are called vegetation indices. Vegetation index is an indicator calculated as a result of operations with different spectral ranges (channels) of remote sensing data and related to the parameters of vegetation in a given pixel of the image [6, 7]. The effectiveness of the vegetation index is determined by reflection characteristics. Currently, there are about 160 index options. They are selected experimentally, based on vegetation spectral reflectivity characteristics. The NDVI index (Normalized Difference Vegetation Index) reflects the total amount of vegetation and it is used to assess its condition in a wide range of tasks, including crop forecasting [8, 9, 10].

2. Problem Statement
The vegetation index NDVI provides information about the condition of crops, so throughout the entire period of growth and development of winter wheat plants, it is necessary to monitor the structural and functional state of the photosynthetic apparatus of plants not only through laboratory analyzes, but also by using remote sensing data [11, 12, 13]. The simplest approach considers NDVI as a predictor of grain yield, where a simple linear regression is used to predict yield. Through the use of such methods (field and laboratory, satellite studies) it is possible to predict grain yield 2-3 months before harvest.

3. Research Questions
The study was conducted from 2017 to 2020 in the arid climatic zone of the Pre-Caucasus. The soil cover of the «Agrokholeboprodukt» enterprise is represented mainly by dark chestnut soils.

The average annual air temperature is 10.1° C and the average annual precipitation is 30.7 mm. The weather and climatic data for 2017-2020 are given in table 1. Thus, in 2017 the average annual temperature was 11.2° C, in 2018 it dropped by 1.6° C, in 2019 and 2020 it increased by 0.5° C and 8.0° C respectively. The amount of precipitation has been decreasing [14, 15]. In 2020, heavy rainfall in May-July was too late to remedy the situation with the development of winter crops.

Table 1. Dynamics of changes in temperature and precipitation (2017-2020).

| Indicators | Month      | I   | II  | III | IV  | V   | VI  | VII | VIII | IX  | X   | XI  | XII | Average |
|------------|------------|-----|-----|-----|-----|-----|-----|-----|------|-----|-----|-----|-----|---------|
| Temperature, °C | 2017       | 2.2 | 3.4 | 5.5 | 10.4| 16.4| 21.5| 26.5| 22.9| 17.1| 10.6| 4.6 | 3.2 | 11.2   |
| Precipitation, mm | 2017       | 9   | 57  | 78  | 49  | 86  | 67  | 40  | 18   | 34  | 45  | 26  | 0   | 35.1   |
| Temperature, °C | 2018       | 4.4 | 3.6 | 1.4 | 9.1 | 16.3| 20.7| 24  | 22.9 | 17.1| 10.1| 3.2 | 1.9 | 9.6    |
| Precipitation, mm | 2018       | 26  | 21  | 26  | 30  | 47  | 64  | 51  | 43   | 34  | 18  | 30  | 45   | 35.7   |
| Temperature, °C | 2019       | 3.9 | 3.1 | 2.8 | 10.1| 16.1| 20.1| 21  | 22.4 | 18.7| 10.5| 4.9 | 0.8 | 10.1   |
| Precipitation, mm | 2019       | 16  | 9   | 40  | 28  | 51  | 19  | 42  | 0    | 45  | 40  | 24  | 37  | 37.6   |
The dry autumn of 2019 and a warm, snowless winter led to the fact that the reserves of productive moisture were insufficient for the further effective development of plants. Periodic spring frosts had a negative impact.

Winter wheat is cultivated on the farm under the No-till system, which involves the following technological operations: pre-sowing treatment with herbicide (Sprut Extra), the application rate was 2 l/ha; sowing winter wheat - 210 kg/ha; pre-sowing fertilization (ammonium nitrate) - 100 kg/ha; early spring feeding (ammonium nitrate) - 100 kg/ha; foliar application (UAN) - 100 kg/ha; herbicide treatment (Ballerina) - 0.4 l/ha; the first fungicidal treatment (Altosuper) - 0.5 l/ha; the second fungicidal treatment (Kolosal Pro) - 0.4 l/ha; harvesting.

The subject of the study are the elements of the No-till system, which are used to perform the various technological operations presented in table 2.

| Technological operations | Composition of an agricultural unit |
|--------------------------|-------------------------------------|
| Pretreatment with herbicides (Sprout Extra) | Self-propelled sprayer Caffini |
| Winter wheat sowing | Buhler John Deere 1890 |
| Application of pre-sowing fertilizer (ammonium nitrate) | Buhler John Deere 1890 |
| Early-Spring Fertilizer (ammonium nitrate) | MTZ 1221 Amazone |
| Leaf dressing application (urea-ammonia mixture) | MTZ 80+trailed sprayer 2000 |
| Herbicide treatment (Balerina) | MTZ 80+trailed sprayer 2000 |
| First fungicide treatment (Altosuper) | MTZ 80+trailed sprayer 2000 |
| The second fungicide treatment (Kolosal Pro) | MTZ 80+trailed sprayer 2000 |
| Insecticide treatment (Borey) | MTZ 80+trailed sprayer 2000 |
| Harvesting | Combine CLAAS |

The No-till technology becomes a land cultivation system only taking into account the selection of crops and their placement in the crop rotation, preserving and improving the fertility of dark-chestnut soils, their protection from wind and water erosion, moisture accumulation, etc.

4. Purpose of the Study

The purpose of this work is to evaluate the accuracy of grain yield forecasts for the arid zone of the Central Pre-Caucasus based on the average MODIS obtained by NDVI from different dates for 2018-2020.

5. Research Methods

The Vega satellite service (http://pro-vega.ru/) based on MODIS spectora diometer data from the Terra satellite, which measures reflected radiation in the red and near infrared wavelength ranges with a spatial resolution of 250 m, was used to assess crop conditions in 2017-2020. In this case, the time series of weekly vegetation index (NDVI) data, cleared from the influence of clouds and other interfering factors,
were used. NDVI (Normalized Differential Vegetation Index) is determined by the following formula [11]:

\[
NDVI = \frac{NIR - \text{red}}{NIR + \text{red}}
\]

(1)

where NIR and red are the reflection coefficients of electromagnetic radiation in the infrared and red regions of the spectrum, which are determined from satellite images of the reference area.

The typical sowing dates and the dates of main phenological stages of winter wheat are presented in table 3.

Table 3. Indicators of phenological records of winter wheat, days (2017–2020).

| Year | Sprouts | Tillering | Tube output | Earing |
|------|---------|-----------|-------------|--------|
|      |         | Fall      | Spring      |        |
| 2017 | 21      | 20        | 12          | 26     |
| 2018 | 23      | 21        | 12          | 27     |
| 2019 | 20      | 19        | 10          | 25     |
| 2020 | 18      | 18        | 10          | 24     |

In the early spring the difference in the values for winter crops is small, because the typical growth stage for winter wheat in this period of time is the tillering stage. Large differences occur in the later stages of growth.

6. Findings

The analysis of the results showed that the high NDVI values in 2019-2020 do not characterize better crop condition and development. In the spring of 2020, they are associated with an earlier season due to the prevailing weather and climatic conditions. At the same time, despite the higher NDVI values, winter crops developed close to the multi-year average, but worse due to the lack of precipitation.

From 2019 to 2020 the winter period was marked by special weather conditions in the study area, which came after a dry autumn. The winter was warm and snowless, which caused winter crops to vegetate throughout the season. By spring, the supply of productive moisture in the soil was insufficient for plant growth and development (figure 1).

Figure 1. Winter wheat crop on the 22nd of June 2020, test day.

At the beginning of February 2020, the indicators reached higher values than the average in recent years. The period of resumption of active crop development (due to the earlier accumulation of active temperatures) began several weeks earlier. NDVI values in 2020 from January to April are higher and
from May to July lower than for the period from 2017 to 2019. Crops were affected by spring drought and June heat waves (Table 4).

**Table 4. Dynamics of the vegetation index NDVI of winter wheat cultivated by No-till technology (2017-2020).**

| Year | I    | II   | III  | IV   | V    | VI   | VII  | VIII | IX   | X    | XI   | XII  |
|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 2017 | -    | -    | -    | 0.53 | 0.80 | 0.74 | 0.32 | 0.26 | 0.25 | 0.34 | 0.41 | 0.40 |
| 2018 | -    | -    | -    | 0.63 | 0.81 | 0.57 | 0.24 | 0.22 | 0.25 | 0.34 | 0.58 | -    |
| 2019 | -    | -    | -    | 0.69 | 0.73 | 0.59 | 0.24 | 0.23 | 0.28 | 0.41 | 0.61 | -    |
| 2020 | -    | -    | -    | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | -    |

The influence of the early development of winter wheat on the NDVI index values can also be observed as of the end of March: the deviation from the long-term average in the fields in 2018 compared to 2017 was 5-15%, in 2019 compared to 2018 - less than 25%. In 2018, the vegetation index in April exceeded the value of the long-term norm by 15-25% compared to 2017, in 2019 compared to 2018 - also by 15-25%. In May, the deviation in 2018 exceeded 2017 by 5-15%, in 2019 in relation to 2018 - also 5-15%.

To predict plant productivity, it is advisable to use the comparison method in order to obtain information on the deviation of the current values of the vegetation index NDVI from the average long-term normal values, from which the features of a particular growing season (its lagging or leading) are excluded. This makes it possible to analyze information about deviations from the norms at comparable stages of plant development and more adequately represents information about the state of crops.

According to our research in 2019 and 2020 the structural and functional state of the photosynthetic apparatus of plants, caused primarily by weather and climatic conditions, had a negative impact on winter wheat productivity (Table 5).

**Table 5. Dynamics of the NDVI vegetation index and productivity of winter wheat cultivated using No-till technology (2017-2020).**

| Indicators     | 2017    | 2018    | 2019    | 2020    | 2017/2020 |
|----------------|---------|---------|---------|---------|-----------|
| Yield, t/ha    | 4.87    | 4.59    | 4.21    | 3.14    | 1.55      |
| (average)      |         |         |         |         |           |
| NDVI (average) | 0.410   | 0.456   | 0.463   | 0.490   | 0.84      |

The productivity of winter wheat in 2017 by 2020 fell by an average of 1.55 times, the NDVI increased by 0.84 times.

For evaluation the relationship between NDVI and winter wheat yield, correlation coefficient was calculated. The calculations were based on the data for 2017-2020 (N = 4). The regression equation reflecting the dependence of the crop yield on the NDVI value has the following general form: \( Y = -\)
20.146x + 13.363. There is a very high positive correlation (reverse correlation coefficients about 0.78). This means that winter wheat grain yields in general can be predicted in these arid zones.

In this study, one of the most promising results is a significant positive correlation between NDVI obtained from MODIS satellite data and winter wheat grain yield in the arid zone of the Central Pre-Caucasus. Winter wheat grain yield depends on the late fall and early spring growing conditions. The climate of 2019 and 2020 is generally unfavorable for winter wheat (e.g., high temperatures during grain sowing, drought during stem lengthening, and lack of soil moisture).

7. Conclusions
The relationship between index NDVI and winter wheat grain yield was very high. This means that winter wheat yield for the arid zone of the Central Pre-Caucasus can be obtained before harvesting. The research has shown that the cultivation of winter wheat without tillage (no-till) on dark chestnut soils in the arid zone from 2017 to 2020 largely depends on the prevailing dynamics of weather and climatic conditions. Higher NDVI values do not indicate better crop condition and development. In the spring 2020 they are associated with a shift in the season to earlier dates. Thus:

- considering the shift of the growing season to an earlier date in 2020, the development of winter crops was worse than in 2019, 2018 and 2017, despite the higher values of the growing season index;
- in 2020 the unfavorable development of winter wheat was affected by a lack of soil moisture, which was the main cause of plant stress or death;
- in 2021 the yield will be lower than the average long-term values (provided that the dynamics of weather and climatic factors persists).

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