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Using Radar Data for Grain Crops Yield Forecasting in the Novosibirsk Region

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Abstract—The possibility is considered of using data of the Sentinel-1B radar satellite in agriculture, in particular, for the crop monitoring and grain crop yield forecasting. For this purpose, based on satellite data, the Radar Vegetation Index RVI was calculated. The values of RVI obviously indicate the dynamics of the development of such crops as spring wheat, oat, and barley. The correlation and regression analysis of the relationship between the normalized difference vegetation index NDVI and RVI revealed the presence of a significant dependence between the indices. The normalized radar vegetation index NRVI was calculated to use radar data in predicting the expected yield. As a part of the experiment, yield forecasts at the farm in the Kochenevo district (the Novosibirsk region) for the 2018 and 2019 growing seasons were calculated. The calculation results showed the yield forecast accuracy above 90%, which allowed the use of NRVI in the 2020 operational activities.

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INTRODUCTION

A relevant task of the information support of the agroindustrial sector of the Russian economy is to obtain reliable information about the current state and development of agricultural crops on vast territories, which became possible due to the use of the remote sensing data processing results [8, 9, 12, 15]. The development of space systems and availability of the data allow finding new approaches to the assigned problems.

To provide the objective control of the dynamics of the growth and development of crops and the evaluation of crop reactions to external forcing, the information received from optical and electronic satellite instruments has been widely used. Often, due to the screening by the cloud cover, the time series of satellite data is reduced, which leads to a decrease in the accuracy of yield forecasts. Technical features of radar observations exclude the influence of clouds and allow significant supplement of the satellite information volume.

The present study focuses on investigating a possibility of using the vegetation index based on radar data obtained from the remote monitoring of crops on the territory of agricultural lands in the Novosibirsk region.

The study has the following objectives: to calculate the radar vegetation index from the Sentinel-1B satellite data, to assess the accuracy of the calculated values of the index, and to simulate test yield forecasts.

RADAR INDEX

The vegetation cover can be characterized by such parameters as NDVI (Normalized Difference Vegetation Index) and LAI (Leaf Area Index). These indices take into account the absorption and reflection of electromagnetic radiation by crops in the red and near-infrared spectral regions (NDVI) and the ratio of the plant leaf area to the unit soil surface (LAI). When deriving the variables of crop conditions from radar data, it is necessary to take into account the features of measurements of radar backscattering polarizations characterizing the reflection of plant elements. The peculiarity of radar observations is the sensitivity of the result to soil moisture. In view of this, the impact of environmental factors should be minimized for calculations.

Several studies were considered to find an approach to obtaining the radar vegetation index. The authors of [19] proposed to use RVI (Radar Vegetation Index), which is poorly sensitive to environmental forcing. The values of the index are close to zero in the absence of vegetation and gradually increase as shoots emerge and the biomass is accumulated by plants [18]. To calculate RVI, three polarizations with the vertical and horizontal signal emission are used (HH, VV, HV):

$$\mathrm{RVI} = \frac{8\sigma_{\mathrm{HV}}}{\sigma_{\mathrm{HH}} + \sigma_{\mathrm{VV}} + 2\sigma_{\mathrm{HV}}} \tag{1}$$

where σ_{HV}, σ_{HH}, and σ_{VV} are calibrated radar signals with the polarizations HV (emission on the horizontal polarization, reception on the vertical polarization), HH (emission and reception on the horizontal polarization), and VV (emission and reception on the vertical polarization).

The results of the study described in [20] showed that the use of polarizations only with horizontal emission in the original formula is sufficient for observing the development of crops. Paper [20] proposed the formula that uses two polarizations HH and HV by substituting VV by HH in the original formula (1). Data from the RADARSAT-2 satellite operating in C band (the wavelength is 5.5 cm) were used for calculations.

The authors of [3, 4, 11] proved the efficiency of using the polarizations VV and VH with respect to HH and HV for monitoring the vegetation cover, in particular, from the data of Sentinel-1B operating in C band (the wavelength is 6 cm).

The close values of the characteristics of penetrating power of RADARSAT-2 and Sentinel-1B radar waves, as well as the positive result of the experiment using two polarizations, allowed assuming a possibility of calculating the vegetation index based on the data of two polarizations: VV and VH (provided that in the original formula, HV is replaced by VH and HH is substituted by VV). As a result, the formula for calculating RVI (1) took the following form:

$$\mathrm{RVI}_{\mathrm{VV}} = \frac{4\sigma_{\mathrm{VH}}}{\sigma_{\mathrm{VV}} + \sigma_{\mathrm{VH}}} \tag{2}$$

where σ_{VH}, σ_{VV} are the calibrated radar signals with the polarizations VH (emission on the vertical polarization, reception on the horizontal one) and VV (emission and reception on the vertical polarization). The proposed approach allows calculating the vegetation indices using the Sentinel-1B satellite data.

DESCRIPTION OF THE STUDY AREA AND INITIAL DATA

The Novosibirsk region located in the southeast of Western Siberia occupies the area of 178000 km^2. The administrative-territorial division is represented by 30 municipal districts. The study territory is characterized by continental climate with four strongly pronounced seasons. Average temperature of the warmest month (July) is 18–20°C. In terms of moisture availability, most of the territory belongs to the zone of sufficient moisture. Southern districts are in the arid zone, with possible dry winds and droughts. Average annual precipitation in the region is 414 mm. The longest growing season is observed in the southern areas (up to 163 days), while the growing season in the northern areas is shorter (up to 148 days) [1].

The farm enterprises in the region are characterized by different yield indicators, soil and climatic parameters, as well as by the features of agrotechnical activities. Most of the study was performed at the farms of the Kochenevo district located in the eastern part of the region. Monthly mean temperature of the warmest month is 18.7°C there. According to agroclimatic conditions, the district belongs to the moderately cool zone with insufficient moisture. Average annual precipitation is ~420 mm, the growing season length is up to 160 days. The district occupies a leading position in agricultural production, more than 60% of the territory is used as agricultural land. The spring grain crops prevail: wheat (54%), barley (8%), and oat (6%) [2].

The technologies for grain crops yield forecasting and crop monitoring in the southern regions of Western Siberia were implemented in the Siberian Center of Planeta State Research Center on Space Hydrometeorology. The forecast operations have been carried out in the Novosibirsk region since 2005 so that database was formed of the datasets of vegetation indices, observed yield, meteorological parameters, crops placement, etc. [13, 14]. The study used archival data for the 2018 and 2019 growing seasons, which include information about 36 farms containing 473 test fields: 377 fields sown with spring wheat, 59 fields sown with oat, and 37 fields sown with barley.

The Sentinel-1B data were obtained from the open web resource ASF Data Search (NASA Earthdata) [17]. The survey was conducted in the interferometric mode with a spatial resolution of 5 × 20 m and a swath of 250 km. The preliminary processing of the images included radiometric calibration, speckle noise filtering, and terrain effect correction.

RESULTS OF CALCULATIONS AND ASSESSMENT OF THE RADAR INDEX ACCURACY

At Chistopol'e farm (the Kochenevo district), the values of RVI over the growing season were calculated for spring wheat, oat, and barley. The results of calculations demonstrated the steady dynamics of the index growth until the beginning of the ripening stage for all three crops. The comparison of the obtained values of RVI and the information provided by the agricultural administration of the Kochenevo district about the dates of sowing and harvesting operations led to the conclusion that the proposed method is suitable for monitoring the development of the crops (Fig. 1). As well as NDVI, a change in the radar vegetation index reflects the main stages of crop development: the accumulation of biomass, ripening, and the end of the growing season.

The values of NDVI computed from the Terra/MODIS MOD09 standard satellite-based product were used to estimate the obtained RVI. As a rule, crops in the analyzed region are sown at the end of May, and the peak of the plant biomass accumulation falls on the middle of July. The calculation of NDVI for all farms in the Novosibirsk region was carried out during the period of crops growth from June 1 to July 20, three–four measurements were conducted on cloudless days. The number of observations with the satellite radar instrument during the similar period was from 5 to 8 survey days. The availability of the time series of RVI measurements allowed choosing a sufficient number of dates for the comparative analysis of the values of optical and radar vegetation indices.

For the experimental revelation of the relationship between RVI and NDVI, 830 paired measurements of vegetation indices for the Novosibirsk region were selected for the matching dates, including 668 measurements for wheat, 110 measurements for oat, and 52 measurements for barley. The multiple correlation coefficient was 0.846 ($R^2 = 0.716$) for wheat, 0.848 ($R^2 = 0.719$) for barley, and 0.761 ($R^2 = 0.578$) for oat. The results show high correlation between the vegetation indices for all three crops, which indicates the prospects of using RVI for the yield modeling.

Thus, the next stage of the study was to reduce the values of RVI and NDVI to the single numerical range by using NRVI (Normalized Radar Vegetation Index) that satisfies the relationship

$$\frac{\mathrm{RVI} - \mathrm{RVI}_{\min}}{\mathrm{RVI}_{\max} - \mathrm{RVI}_{\min}} = \frac{\mathrm{NRVI} - \mathrm{NDVI}_{\min}}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}}, \tag{3}$$

where NRVI is the normalized radar vegetation index; RVI is the radar vegetation index for the certain observation date; $\mathrm{RVI}_{\min}$, $\mathrm{RVI}_{\max}$ are the fixed minimum and maximum values of RVI; $\mathrm{NDVI}_{\min}$, $\mathrm{NDVI}_{\max}$ are the fixed minimum and maximum values of NDVI.

The fixed values were found by the analysis of more than 3000 of RVI measurements, which showed that the mean minimum is equal to 0.3, and the mean maximum is 1.3. The measurements were performed during the period of crops growth from June 1 to July 20. At the same time, the minimum and maximum values of NDVI were taken during the vegetation period: 0.2 and 1, respectively. Taking into account the selected minima and maxima of the vegetation indices in (3), NRVI was calculated from the formula

$$\mathrm{NRVI} = 0.8\mathrm{RVI} - 0.04, \tag{4}$$

where RVI is the radar vegetation index for a certain observation date.

One of the key parameters for calculating the yield prospects is the normalized vegetation index. For using NRVI in the yield modeling, the index should be in the same numerical ranges as NDVI at different stages of the crop development. The comparative analysis with the reference values of NDVI was performed to estimate NRVI. The indices calculated at Chistopol'e farm (the Kochenevo district), where the forecast accuracy for spring wheat in 2018 was 99%, were chosen as a reference. The values of NRVI and NDVI were compared for three matching observation dates: two in June and one in early July. The results of the analysis showed the close values of the vegetation indices obtained using different systems. The root-mean-square error did not exceed 0.005, and the multiple correlation coefficient was equal to 0.964.

Taking into account the obtained statistical data, it was supposed that the use of NRVI in the yield prediction can give quite an accurate result. Experimental forecasts at Chistopol'e farm were prepared for the 2018 and 2019 growing seasons for wheat, oat, and barley.

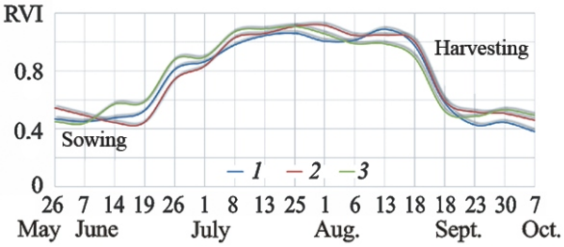

Fig. 1. The dynamics of RVI during the 2018 growing season, Chistopol'e farm. (*1*) Wheat (7 fields); (*2*) oat (2 fields); (*3*) barley (3 fields).

MODELING YIELD PROSPECTS

The EPIC (Erosion Productivity Impact Calculator) modified bioproductivity model implemented in the SDIM (System of Databases and Imitating Modeling) software package was used to forecast the yield of grain crops [16, 21]. The main calculation parameters were the vegetation index and the meteorological parameters: air temperature (maximum and minimum), daily precipitation, relative air humidity, average wind speed, and total solar radiation. The database of the meteorological parameters containing information from 1985 was formed for each district of the Novosibirsk region [13].

Based on meteorological parameters, the modeling of grain crops development was carried out. It included the determination of the values of the leaf area index and biomass. Using the values of the vegetation index, the leaf area index characteristics were refined, based on which the corrections to the simulated biomass parameters were made approximately three–four times per the growing season. The correction of the simulated value of biomass was performed using the formula [5, 16]

$$\mathrm{BIOM} \quad 1.09\mathrm{LAI}_{\mathrm{NDVI}} \quad 0.57 \tag{5}$$

where $\mathrm{LAI}_{\mathrm{NDVI}}$ is the leaf area index obtained using NDVI.

In the SDIM package, the grain crops yield was computed using the corrected values of land biomass and the yield index. The yield index is a unique parameter for each test farm, which depends on the type of crops, weather conditions, and the level of agrotechnical activities. The yield prospects of grain crops were determined for each separate field, with the subsequent averaging of the values over the farm. For the correct comparison of the results of yield forecasting based on the data of different observation systems, the single time range was specified for the determination of the vegetation indices.

Based on the data on the observed grain crop yield obtained from the agricultural administration of the Kochenevo district, the forecast accuracy was calculated and used as a forecast skill score. It was calculated using the formula [7]

$$100\% \quad \left| \frac{u_{\mathrm{p}} \quad u_{\mathrm{o}}}{u_{\mathrm{o}}} \right| \quad 100\% \tag{6}$$

where u_{o}, u_{p} are the observed and predicted yields, respectively.

Test forecasts of the grain crops yield at Chistopol'e farm were prepared separately for each kind of crops, as well as on average for 2018 and 2019. The accuracy (%) of the grain crops yield forecast based on NDVI and NRVI was:

Year	2018		2019	
Index	NDVI	NRVI	NDVI	NRVI
Wheat	99.4	91.4	66.8	95.3
Oat	94.0	94.9	61.2	100.0
Barley	87.2	96.7	99.2	99.2
Mean	93.5	94.3	75.7	98.2

The experimental calculations revealed that in 2018 the yield forecast based on radar data had confident results for all analyzed crops. The mean value of the accuracy of forecasts based on NDVI and NRVI was within the close ranges. It should be noted that measurements from the optical and radar systems were obtained for the identical time period from the beginning of June to the middle of July. The values of the vegetation indices recorded by different observation systems were also close.

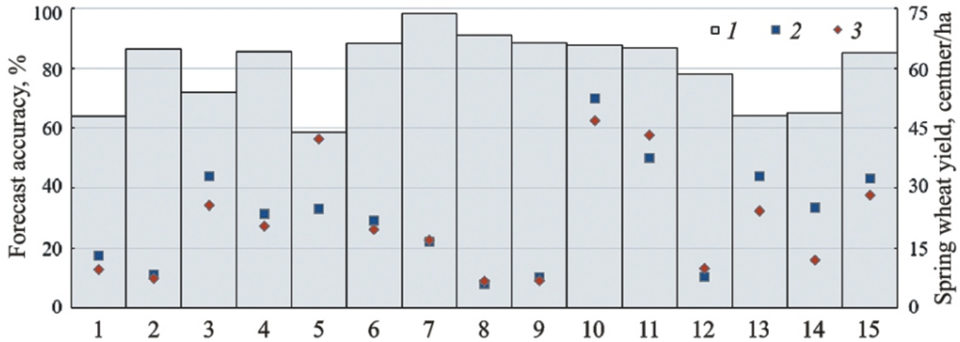

Fig. 2. Modeling spring wheat yield forecasts for the test farms (1–15) in the 2020 operational season. (*1*) Accuracy; (*2*) predicted yield; (*3*) observed yield.

The parameters for 2019 demonstrated a high reliability of forecasts using NRVI in the calculations both for spring wheat and oat. The yield modeling for barley demonstrated an identical high accuracy of calculations using both NRVI and NDVI. Due to the high screening by cloudiness, the values of NDVI were registered only in June, which did not allow indicating the maximum of crops development. The measurements of NRVI were available for a longer period covering the first half of July. The closest maximum values of the vegetation indices calculated from radar and optical data were registered for barley, which was indicated in the comparable values of predicted yield. The mean accuracy for three crops was 98% in case of using the radar indices and 76% in case of using NDVI.

OPERATIONAL APPLICATION OF THE TECHNOLOGY FOR YIELD FORECASTING BASED ON RADAR DATA

The results of modeling yield prospects based on NRVI favored the implementation of this technology in the test mode in the operational practice of the Siberian Center of Planeta State Research Center on Space Hydrometeorology in 2020. During the active growing season, the monitoring was performed on the territory of 18 farms in the Novosibirsk region for 258 fields with spring wheat, oat, and barley.

According to the Roshydromet ground-based observation network, a significant precipitation deficiency in combination with a high temperature background was observed in the study area during the growing season. At some farms in the southwestern districts, the sparseness of seedlings, general suppression and inhomogeneity of crops in height and density, leaf yellowing and drying were registered. Due to adverse meteorological conditions, an emergency mode was introduced in 16 districts of the region, a partial or complete loss of crops caused by the death of plants was observed at several farms [6, 10].

Adverse weather conditions had a negative effect on the development of crops and the formation of the future yield, especially at the farms in the steppe area of the region, where the yield reduction as compared to the multiyear mean characteristics varied from 10 to 40% and reached 60% at some farms, up to the complete loss of crops.

The yield simulation skill assessment was based on the results of grain crops harvesting obtained directly from agricultural organizations and district agricultural administrations. The accuracy of spring wheat yield forecasts of 80% and more was registered in most of the test farms, the mean value over all farms made up 80%. The accuracy of the oat and barley yield forecast was on average equal to 81% for each crop. Figure 2 presents graphs for the observed and predicted yield of spring wheat, as well as the skill score of the forecasts for each farm.

The results of modeling the yield of grain crops based on NRVI in the 2020 operational season demonstrated the efficiency of radar data use.

CONCLUSIONS

The study focused on investigating a possibility of using radar data to solve the problems of agricultural production. It was found that the proposed radar vegetation indices indicate the dynamics of the growth and main stages of development of such crops as spring wheat, oat, and barley. The results of calculations and ground-based data led to the conclusion that RVI is suitable for monitoring agricultural crops. At the same time, it is reasonable to perform additional research to assess a relationship between the values of RVI and the crops characteristics, such as biomass, leaf area, density, etc.

The comparative analysis of the vegetation indices indicates a high correlation between the parameters obtained using optical and radar systems. The highest correlation was found for the farms with the 90% accuracy of NDVI-based yield forecasts. The statistical data led to the conclusion that the normalized radar index can be used for the yield prediction.

The results of the yield forecast verification for 2019 allow the conclusion that an increase in the number of observation days by using radar data makes it possible to obtain quite accurate simulation results. The application of radar data significantly complements the existing methods of grain crops monitoring, extending the informational resources of agrometeorology.

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