Bulgarian Journal of Agricultural Science, 26 (No 6) 2020, 1129–1142

Qualitative evaluation and within-field mapping of winter wheat crop condition using multispectral remote sensing data

Eugenia Roumenina[1*], Georgi Jelev[1], Petar Dimitrov[1], Lachezar Filchev[1], Ilina Kamenova[1], Alexander Gikov[1], Martin Banov[2], Veneta Krasteva[2], Milena Kercheva[2] and Viktor Kolchakov[2]

[1]*Bulgarian Academy of Sciences, Space Research and Technology Institute, Department of Remote Sensing and GIS, 1113 Sofia, Bulgaria*
[2]*Agricultural Academy, Institute of Soil Science, Agrotechnologies and Plant Protection "Nikola Poushkarov", 1331 Sofia, Bulgaria*
[*]*Corresponding author:* roumenina@space.bas.bg

Abstract

Roumenina, E., Jelev, G., Dimitrov, P., Filchev, L., Kamenova, I., Gikov, A., Banov, M., Krasteva, V., Kercheva, M. & Kolchakov, V. (2020). Qualitative evaluation and within-field mapping of winter wheat crop condition using multispectral remote sensing data. *Bulg. J. Agric. Sci., 26 (6)*, 1129–1142

This study presents a method for evaluation and mapping of winter wheat crop condition using a set of crop variables, e.g. leaf area index (LAI), fraction of absorbed photosynthetically active radiation (fAPAR), fraction of vegetation cover (fCover), fresh above ground biomass (AGBf), and Nitrogen uptake derived from multispectral imagery. First, the crop condition is assessed with respect to each variable using a qualitative, three-grade scale. In a second step, these individual assessments are combined to produce assessment map of the crop's general condition, discriminating between three possible conditions – Good, Fair, or Poor. The method was tested on winter wheat fields in Bulgaria in two agricultural years – 2016/2017 at phenological growth stage (FGS) Z31 to Z34 and 2017/2018 at FGS Z30. The results presented were based on Sentinel-2 satellite imagery (at 20 m spatial resolution) and imagery from Specialized Unmanned Aerial Vehicle (SUAV) sense FlyeBee Ag, equipped with Parrot Sequoia camera (resampled to 10 m spatial resolution). The remotely sensed crop condition was validated against independent ground-based assessments in a number of elementary sampling units (ESUs). The proposed approach proved to be effective and the crop condition was accurately determined in 87% – 94% of the ESUs depending on the FGS/agricultural year and the imagery type. We observed only minor differences in the areas of the three crop conditions when mapped with Sentinel-2 and Parrot Sequoia data.

Keywords: winter wheat; crop condition; assessment map; Sentinel-2; Parrot Sequoia camera

Introduction

The development of precision agriculture technology requires an operational production of highly accurate crop condition maps at field level (Whelan & McBratney, 2000; Shanmugapriya et al., 2019). Such type of maps may be composed by transforming spectral data obtained from multi-spectral remote observation into quantitative information determining the condition of crops during their phenological development. The handling of spectral data for these purposes relies on vegetation index (VI) images. These are based on a combination of the brightness values in two or more different spectral bands. The relationship between vegetation indexes and crop condition is derived empirically. The crop condition is determined by the individual characteristics of the crop under observation (Ji-hua & Bing-fang, 2008). Currently, in precision agriculture, maps composed only on the basis of a given vegetation index are used. The crop variables which are most often estimated using VI are discussed in the next few paragraphs.

The *leaf area index* (LAI) is a dimensionless quantity which characterizes plant canopies. It is defined as the one-sided green leaf area per unit ground surface area. LAI is often used in ecological studies to predict primary photosynthetic production and evapotranspiration. In agriculture, LAI is an important indicator of plant growth and biomass accumulation; it also serves as a basis for variable-rate fertilization. LAI can provide an insight into the function and structure of the canopy (Wilhelm et al., 2000). The interaction between vegetation surface and the atmosphere, e.g. radiation uptake, precipitation interception, energy conversion and gas exchange, is substantially determined by vegetation surface (Monteith & Unsworth, 1990). The timely obtaining of data about the crop's LAI change is helpful for the preparation of agricultural production strategies related with the work on the fields.

The *fraction of absorbed photosynthetically active radiation* (fAPAR) is the fraction of the incoming solar radiation in the photosynthetically active region of the spectrum (400-700 nm) which is absorbed by plant canopy. This biophysical variable is directly related to the primary production of photosynthesis. It is an important variable in both plant biomass production and plant growth modelling.

The *fraction of vegetation cover* (fCover), or the percentage of soil surface covered by plant foliage, is an important measure of crop establishment and early vigour. This variable can be related with the interception of solar radiation from crop canopies and thus, with their production potential. fCover quantifies spatial vegetation spread, and could be indicative of plant stress, pests, droughts and other problems in particular areas.

The measurement of *dry above ground biomass* (AGBd) and *fresh above ground biomass* (AGBf) during the growing season provides an opportunity to improve grain yields and quality by site-specific application of fertilizers and pesticides. The leaf area and the total aboveground biomass are key variables because they are a clear indicator of vegetation development and health (Erdle et al., 2011; Jamieson et al., 1998; Pimstein et al., 2009; Serrano et al., 2000; Yue et al., 2017). The maps of these variables are of particular interest to assist in the decision-making process in the context of agriculture. Biomass is one of the most important biophysical surface variables attracting interest in wider researches concerning earth observation data. Remote sensing techniques could provide repeated measures from a field without destructive sampling of the crop, which constitute valuable information for agricultural activities (Hatfield & Prueger, 2010).

Nitrogen (N) is of particular interest in ecological and agricultural studies because its availability can affect the rate of key ecosystem processes, including primary production (Vitousek & Howarth, 1991; Zhao et al., 2019). Nitrogen has traditionally been considered as one of the most important nutrients. It is an essential component of the proteins which build cell material and plant tissues. Nitrogen is often the most important determinant of plant growth and crop yield. It can be expressed either as concentration in the plant tissue in % (N %) or as the quantity within a certain ground area in g m^{-2} (N uptake).

Canopy Chlorophyll content (CCC) is the product of LAI and the chlorophyll concentration in leaves and can directly determine photosynthetic potential and primary production. Chlorophylls can give an indirect estimation of the nutrient status, because part of the leaf nitrogen is incorporated in the chlorophyll. Furthermore, leaf chlorophyll content is indicative of health status and is closely related to plant stress (Merzlyak et al., 1999).

Maps of these crop variables are often derived from remote sensing data and used in precision agriculture. The drawback of these maps lies in the fact that the relationship between the values of the variables and the crop condition is not always straightforward. Moreover, it is not common practice to made assessment maps based on several crop variables that have been quantified and thus reflecting the general crop condition. This renders the use of these maps difficult by the agricultural producers.

Accounting for this, the objective of this study is to examine the possibilities for composing a map containing qualitative evaluation of the condition of winter wheat *(Triticum aestivum* L.) during the active vegetation period using multispectral data from satellite sensor and Unmanned Aerial Vehicle (UAV) camera, as well as to evaluate the precision of the composed assessment mapping products.

Study Area and Materials

Study area

This study has been carried out on farmer fields (or Units) located on the territory of the Zlatia test site, Bulgaria (Figure 1). This area is one of the main agricultural regions in Bulgaria and is situated in the lower Danube plain. This region is part of the moderate continental climatic sub-zone of the European moderate continental climatic zone (Stanev et al., 1991). The continental features of the climate are well pronounced and the area is characterized by high annual amplitude of air temperatures – cold winter (t_{Jan}= -1.5°C) and hot summer (t_{Jul}= 23.3°C), as well as by minimal precipitation in winter (P_{Feb}= 21 mm) and maximum in May–June (P_{May}= 62 mm).

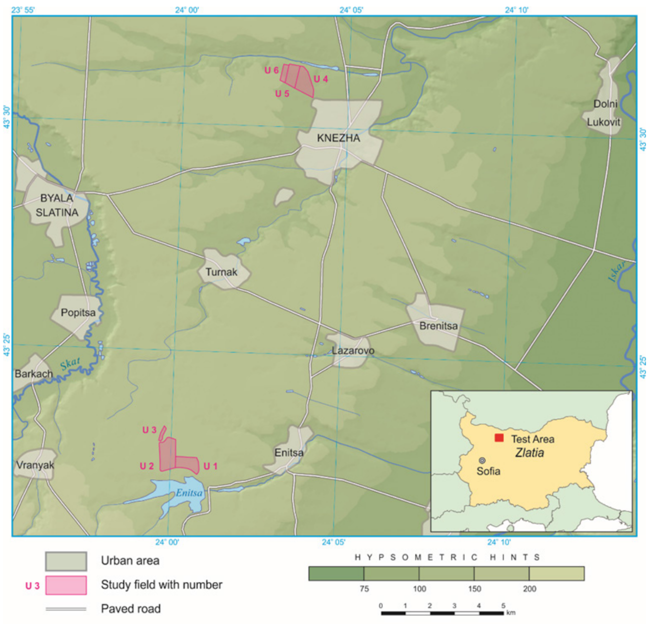

Fig. 1. Location of the Units on which the study has been carried out in *Zlatiya* test site, Bulgaria

Three of the Units are located on the land of the village of Enitsa and the other three are located on the land of the town of Knezha. The altitude varies between 130 – 150 m a.s.l. for Units 1, 2 and 3, and 180 – 191 m a.s.l. for Units 4, 5 and 6. According to the soil mapping data collected by the *Institute of Soil Science, Agrotechnologies and Plant Protection "Nikola Poushkarov"*, soils in the test Units are *Haplic Cambisol Eutric Siltic, Endocalcic Chernozem Siltic and Haplic Regosol Calcaric Siltic* (Figure 2). The soil name is determined according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2014).

Enola variety of winter wheat (*Triticum aestivum* L.) were grown on the Units 1, 2, 3 in 2016/2017 agricultural year and Units 3, 4, 5 in 2017/2018 agricultural year. Winter wheat is the most frequent crop encountered in Bulgaria occupying 34.5% and 35.7% of the arable land in 2017 and 2018 respectively. *Enola* variety has been created at the Agricultural Institute of Dobrudzha, Bulgaria (Kostov et al., 2014) and is the second most frequently used wheat variety in the country, as evidenced by data from the Agrostatistics Department of the Ministry of Agriculture, Food, and Forestry.

During sowing, the Units 1, 2 and 3 have been fertilized with diammonium phosphate 260 kg/ha. In Units 1 and 2, the sowing has been carried out within the optimal time intervals, and in Unit 3 – outside them (Table 1). Within the recommended time intervals, upon resuming of the crops vegetation, spring feeding has been carried out (Table 1). The

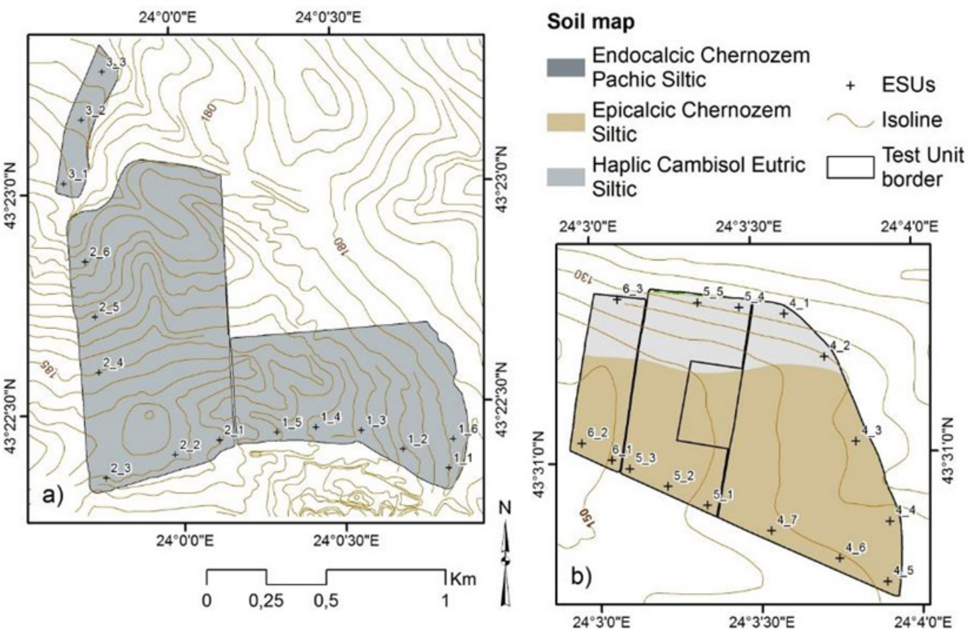

Fig. 2. Soil maps of the Units for field campaign a) April 2017 and b) April 2018

Table 1. Base data for the Test Units

Agricultural year	2016/2017			2017/2018		
Unit Code (U)	U1	U2	U3	U4	U5	U6
ESU Code	1_1; 1_2; 1_3; 1_4; 1_5; 1_6	2_1; 2_2; 2_3; 2_4; 2_5; 2_6	3_1; 3_2; 3_3	4_1; 4_2; 4_3; 4_4; 4_5; 4_6; 4_7	5_1; 5_2; 5_3; 5_4; 5_5	6_1; 6_2; 6_3
Area (ha)	48	79	7	57	37	16
Pre-sowing preparation (type, date)	Disking: three times in the period 08–09.10.2016	Disking: three times in the period 08–09.10.2016	Tillage: 25.10.2016; Disking: 25.10.2016	Disking: 25.09.2017 (at depth of 10-12 cm)	Disking: 4 times in the period 20.07.2017 to 20.09.2017 (at depth of 10-12 cm; for weed control)	
Herbicide treatment (reasons, date, type, amount)	None	None	None	None	25.08.2017: Half of the Unit 5 – ESU 5_4 5_5) was treated with Roundup for weed control. There had been a lot of weeds with the precursor.	None
Fertilization (date, type, amount)	09.10.2016, diammonium phosphate 260 kg ha^{-1} 26.02.2017, *Urea* – 250 kg ha^{-1}		25.10.2016, diammonium phosphate 260 kg ha^{-1} 26.02.2017, *Urea* – 250 kg ha^{-1}	20.09.2017: N10P24S20 – 230-250 kg ha^{-1} 14.03.2018 – 200 kg ha^{-1}; Ammonium nitrate		
Plant protection measures (reasons, date, type, quantity)	25.03.2017, fungicides: *Duet ultra* – 0.60 l ha^{-1} 25.03.2017, herbicides: *Palace* – 0.25 kg ha^{-1} 25.03.2017, fungicides: *Lambada* – 125 ml ha^{-1} 25.03.2017, foliar feeding of wheat: *Betaine* – 0.20 l ha^{-1}			30.03.2018 fungicides: *Capalo* – 1000 ml ha^{-1}; herbicides: Sekator – 100 ml ha^{-1}; foliar feeding of wheat		
Sowing (date, norm)	09.10.2016: 550 seeds per m^2 09.10.2016: 550 seeds per m^2		25.10.2016: 580 seeds per m^2	03.10.2017: 600 seeds per m^2	04.10.2017: 600 seeds per m^2	
Field Campaign date/ Phenological Growth Stage	27.04.2017/ Z31 to Z34 26.06.2017/Z91	26.04.2017/ Z31 to Z34 27.06.2017/ Z91	26.04.2017/ Z31 to Z34 27.06.2017/Z87	02.04.2018/Z30	03.04.2018/Z30	03.04.2018/ Z30
Yields (kg ha^{-1})	6 850	6 860	5 530	6 370	6 700	6 700

total quantity N of the active substance introduced through mineral fertilizing is about 190 kg N ha^{-1}. The mineral nitrogen introduced in the soil is within the optimal norms with respect to the planned maximal production.

In the Units 4, 5 and 6 the sowing has been carried out within the optimal terms. The same agrotechnical measures have been undertaken on all three Units, with only one small area making an exception, which have been treated with *Roundup* on account of the recorded great amount of weeds with the predecessor (Table 1).

Data acquisition and processing

In this study, two different types of data have been used: 1) ground based data obtained from the conducted field campaigns complemented with information provided by the farmers and 2) multispectral images from *Sentinel-2A* and *2B* satellite sensors and *Parrot Sequoia* UAV camera. All collected data have been integrated into a geodatabase.

Field data

Three field campaigns (FCs) were carried out on the test Units to collect data for validation of the maps to be composed based on remotely sensed data. Two of them were carried out in April 2017 and 2018 when the crops are in the phenological growth stage (FGS) *Stem elongation* Z30 and Z31 to Z34 in *Zadoks* decimal code (Zadoks et al., 1974) respectively. One field campaign was carried out before harvesting in 2017, to determine the biological yield on the test Units 1, 2, and 3 (Table 1). The agrotechnical measures carried out by the farmers on the test Units, which are in accordance with the common practices, are presented on Table 1.

On the six Units (Figure 2, Table 1), the location of 30 Elementary Sampling Units (ESUs) sized 20x20 m^2 was determined. During the FCs, on each of the ESUs, three crop-specific Elementary Sub-Sampling Units (ESSUs) were selected – one of them sized 1 m^2 and two sized 0.25 m^2 (the data collected for them were recalculated for 1 m^2). The measurements from all three ESSUs were averaged on ESU level.

During the field campaigns in April 2017 and 2018, on each ESU the following activities were carried out: taking images by a photo camera, GPS measurements of the location of each ESU, recording of the basic variables characterizing crop condition based on expert evaluation, biometrical, biophysical and laboratory measurements of the collected plant and soil samples. The basic variables characterizing crop condition are:

- *soil moisture* content (W, % per mass) – from each ESU, in three repetitions, samples from the surface soil layer and at depth of 30 cm were taken;
- *phenological growth stages* of winter wheat in Zadoks decimal code (Zadoks et al., 1974);
- *number of productive tillers per m^2*. In FGS Z31 to Z34, the number of the tillers having formed 1st, 2nd, 3rd and 4th node detectable which have potential to form class, was recorded. In FGS Z30, the number of the tillers formed on plants and the main shoot only were recorded;
- *crop height (cm)*;
- *AGBf (g m^{-2})* of the winter wheat plant samples (leaf and stem) collected from each ESSU was measured in laboratory conditions;
- *AGBd (g m^{-2})* was determined in laboratory conditions by oven drying the plant samples at 60°C until a constant weight was achieved;
- *total N content (N)* of the collected winter wheat plant samples was determined by the Kjeldahl method and expressed as percent of AGBd. *N uptake (g N m^{-2})* was determined as the product of N content and AGBd for each ESSU.
- *phytosanitary condition of the crop* – the level of weediness was recorded as well as any observed damages from diseases, pests, drought, excessive moisture, frost, freezing or other factors. On most of the ESSUs, weeds and other crops (self-planted) were identified. Apart from winter wheat, these were also measured and samples for laboratory analyses were taken, providing the following variables: phenological growth stages, height (cm) and number of weeds per m^2.
- *Biophysical crop variables*: LAI, fAPAR, and fCover were determined using the AccuPAR PAR/LAI Ceptometer LP-80 in 3 ESSUs within each ESU. In each ESSU, two variables were measured: t, which is the fraction of incident radiation transmitted by the canopy, and r, which is the fraction of incident radiation reflected to a sensor above the canopy. An external sensor was used to take the above canopy readings. A total of 10 below canopy readings were taken and averaged per ESSU. LAI was derived from these measurements internally and stored in the instrument's memory while fAPAR and fCover were calculated during the post-processing of the raw data. fAPAR was calculated using the formula:

$$\text{fAPAR} = 1 - t - r + t{*}rs,$$

where *rs* is the reflectance of soil surface (default value of 0.15 was used). The fCover was calculated using the procedure proposed in the AccuPAR manual (Decagon Devices, 2014).

The descriptive statistics of the crop variables in FGS Z30 and Z31 to 34 is presented on Table 2.

Immediately preceding harvest, a field campaign was carried out (Table 1) to collect samples to determine the biological yield (BY) at ESU level for agricultural year 2016/2017. The BY was determined after harvesting of plants from 1 m^2, measuring the weight of above ground biomass, while separating the ears and threshing with a thresher. The moisture content of the grains was evaluated by drying a sample of the obtained yield at 60°C.

Table 2. Summary of the ground measured biophysical crop variables, AGBf and N uptake during the field campaigns carried out in April 2017 (FGS – Z31 to Z34) and April 2018 (FGS – Z30)

FGS	Number of ESU	Variables	Mean	Min	Max	Standard Deviation
Z31 to Z34	15	LAI (m^2 m^{-2})	5.4	2.2	7.9	1.9
		fAPAR	0.86	0.68	0.95	0.10
		fCover	0.85	0.59	0.97	0.14
		AGBf (g m^{-2})	3014	1673	4394	859
		N uptake (g N m^{-2})	8.2	4.0	13.7	3.0
Z30	15	LAI (m^2 m^{-2})	1.46	0.60	2.33	0.52
		fAPAR	0.57	0.33	0.72	0.12
		fCover	0.46	0.21	0.63	0.13
		AGBf (g m^{-2})	1078	464	1717	444
		N uptake (g N m^{-2})	2.41	0.70	4.09	1.06

Multispectral images

Unmanned Aerial Vehicle images

During the FCs (Table 1), multispectral images were acquired using the Specialized Unmanned Aerial Vehicle (SUAV) sense Flye Bee Ag including drone, cameraplus a sunshine (light) sensor, navigation and image processing software. Before carrying out the field measurements and observations, images of the Units were taken using the *Parrot Sequoia* multispectral camera (Parrot SA, Paris, France). The basic characteristics of its spectral bands are shown on Table 3. Flight planning, including determination of the area coverage, flight height, pixel size, duration, etc. was carried out in advance. In addition to that, the geographic coordinates of 13 Ground Control Points (GCPs) were measured using GNSS Leica GS08+. The GCPs were marked permanently on the ground. The images acquired by the SUAV during the field campaigns were processed and used to generate georeferenced multispectral image mosaics covering the test Units. These images featured spatial resolution of 0.20 m. They were aggregated up to 10 m, so as to be comparable to the data obtained by *Sentinel-2*. These mosaics were used to calculate several spectral vegetation indexes.

Satellite images

Two images without cloud cover from the *Sentinel-2A* and *2B* satellites were available in the Copernicus Open Access Hub (https://scihub.copernicus.eu/) for 19 April 2017 and 30 March 2018 The *Sentinel-2* data were downloaded as Level 1C products and converted to Level 2A using the Sen-2Cor plugin of SNAP software. The plugin performs atmospheric correction and produces top-of-canopy reflectance values with resolution of 10 m (bands 2, 3, 4, and 8) and 20 m (bands 5 to 7, 8A, 11, and 12). Only part of the bands was used in this study (Table 3). Band 4 was resampled to 20 m in order to be comparable to the data obtained from the other three Sentinel-2 bands used in this study – bands 5 to 7 (Table 3). These corrected data were then used to calculate several spectral vegetation indexes.

Database

A geodatabase for the Units included a reference data set about their boundaries, soil varieties, digital elevation model, historical field data (the crops which have been sown), crop calendar, implemented agrotechnical measures, data from field measurements and observations. The database contained also the evaluation criteria for the variables characterizing the crop's condition and validated empirical models to calculate the selected winter wheat crop variables. During the working process, the geodatabase was also supplied with input multispectral images from the selected sensors and derivative data from the processing and analysis of input data. In it, all obtained mapping products were also stored.

Methodology for composing of assessment maps

The methodology for composing of assessment maps for each Unit involves two working stages (Roumenina et al., 2019).

First stage: Composing assessment raster layer (ARL) and assessment map of the condition of each crop variable using remote sensing data.

First, a set of variables related to the economic productivity of the plants has been identified, which are used as indicators to assess winter wheat crop condition. These variables are Fresh Above Ground Biomass (AGBf) (g m^{-2}), Nitrogen uptake (N uptake) by plants (g N m^{-2}), Leaf Area Index (m^2 m^{-2}), fraction of Absorbed Photosynthetically Active Radiation (fAPAR), and Fraction of Vegetation Cover (fCover).

Regression models were used to compose assessment maps of the selected crop variables (Table 4). Each model represents an empirical relationship between the corresponding crop variable and a specific VI. The VIs which were used as predictors are presented in Table 5 along with the bands used for their calculation using Sentinel-2 and Parrot Sequoia data. The accuracy of the regression models used for

Table 3. Characteristics of the spectral bands of *Sentinel-2* and the *Parrot Sequoia* UAV camera used in this study

Name of Bands		Green (Bg)	Red (Br)	Red edge (Bre)			Near IR (Bnir)
				(Bre1)	(Bre2)	(Bre3)	
Central wavelength (nm)	Sentinel 2	–	665	705	740	783	–
	Sequoia	550	660	–	735	–	790
Bandwidth (nm)	Sentinel 2	–	30	15	15	20	–
	Sequoia	40	40	–	10	–	40
Spatial Resolution (m)	Sentinel 2	–	10**	20	20	20	–
	Sequoia	0.20*	0.20*	–	0.20*	–	0.20*

**The size of the pixel was aggregated up to 10 m*

**The size of the pixel was aggregated up to 20 m

Sentinel-2 has been reported in a previous publication (Dimitrov et al., 2019). The regression models used for Parrot Sequoia UAV camera were derived by the authors and are not published elsewhere. For both image types the models were calibrated with ground data collected between tillering (Z20) and anthesis (Z69) in the same study area. The root mean square errors (RMSE) reported in Table 4 were derived by leave-one-out cross validation.

In this stage, VI images are calculated based on the multispectral data from *Sentinel-2* and *Parrot Sequoia*. Based on these VI images and the regression models, a new set of raster layers (RL) is calculated representing the quantitative estimation of the crop variables. The histogram of each RL is analysed. If there are single extreme pixel values, they are replaced by "No data" value and are excluded from further analysis. In most cases, such extreme values are recorded along the boundaries of the Unit or are due to single trees therein. The RL is reclassified into three classes using the Equal Interval method. Each class is assigned a rank of 3, 2 or 1, corresponding to *Good*, *Fair* or *Poor* condition with respect to that crop variable. As a result, an assessment raster layer (ARL) for the variable is obtained. Based on the obtained raster layer, assessment map for the variable is composed, whereas in the legend, both the qualitative evaluation and the boundary quantitative values are indicated (Table 5).

Second stage. Composing of an assessment raster layer (ARLww), and assessment map of the crop's general condition

In the beginning of this stage, an assessment raster layer (ARLww) is calculated, characterizing the general crop condition for the respective date and for each Unit by the arithmetic mean of the evaluation grades of the assessment raster layers for the individual variables obtained during the first working stage (Equation 1):

$$\text{ARLww} = \Sigma(\text{ARL}_v) / \text{N}_v, \tag{1}$$

where ARL_v is the value of the ARL for particular crop variable, v, and N_v is the number of crop variables used. The values of ARLww are separated into three equal intervals: 1.00 – 1.67, 1.68 – 2.33 and 2.34 – 3.00, after which they are reclassified into three conditions: *Good*, *Fair*, or *Poor* and their area is calculated in percentage. The *Good* condition indicates that all selected variables feature optimal values for the respective phenophase. No additional agrotechnical activities are required, apart from the previously scheduled ones. These crops are expected to produce maximal yield. The *Fair* condition indicates that one third of the variables are below the optimal value for a given phenophase. This may cause additional costs and yield reduction. The *Poor* condition indicates that the values of three or more variables are within the scope of the minimal ones for a given phenophase, e.g. they are assessed with grade 1. Significant additional costs for the preservation of these crops are required and they are not expected to produce good yield. When more than 50% of the crop's area features this grade, the option for resowing these areas should be considered, especially in the initial phenophases of the crop's development.

It is assumed that only one or two conditions may be recorded, depending on the factual condition of the agricultural crop.

Table 4. Regression models used to compose assessment maps of the crop variables by data from *Sentinel-2* and *Parrot Sequoia* UAV camera. RMSE – root mean square error

Sentinel-2 satellite sensor		*Parrot Sequoia*UAV*camera*	
Model	RMSE	Model	RMSE
AGBf = 8276.1*SR3-8955.0	526.90 g m^{-2}	AGBf = 3076,9*SR3-3595,5	655.51 g m^{-2}
N uptake = 0.003*exp(CCCI*9.607)	2.35 g N m^{-2}	N uptake = 28.21* reNDVI -2.52	2.42 g N m^{-2}
LAI = 11.244*SR3-12.056	1.29 m^2 m^{-2}	LAI = 4.11*Clre – 0.55	1.39 m^2 m^{-2}
fAPAR = 0.098*exp(NDRE1*2.825)	0.09	fAPAR = 0.05485*exp(OSAVI*3.321)	0.07
fCover = 0.034*exp(NDRE1*4.152)	0.13	fCover = 0.07013* CI green – 0.0603	0.16

Table 5. Spectral vegetation indexes used in the regression models to compose assessment maps of the crop variables by data from *Sentinel-2* satellite sensor and *Parrot Sequoia* UAV multispectral camera

*Sentinel-2*satellite sensor	*Parrot Sequoia UAV camera*
SR 3 = Bre3 / Bre2 (Gitelson&Merzlyak, 1994)	OSAVI = (1+0.16)*(Bnir – Br)/(Bnir + Br + 0.16) (Rondeaux et al., 1996)
CCCI = ((Bre3 – Bre1) / (Bre3 + Bre1)) / ((Bre3 – Br) / (Bre3 + Br)) (Barnes et al., 2000)	reNDVI = (Bnir– Bre2) / (Bnir + Bre2) (Gitelson&Merzlyak, 1994)
NDRE 1 = (Bre3 – Bre1) / (Bre3 + Bre1) (Barnes et al., 2000)	CI re = (Bnir/ Bre2) – 1 (Gitelson et al., 2003, 2006)
	CI green = (Bnir/ Bg) – 1 (Gitelson et al., 2003, 2006)

Based on the obtained raster layer ARLww, assessment map of the general condition of the crop for each Unit is composed. The recorded condition of the crop – *Good*, *Fair* or *Poor* is indicated in the legend.

Methodology for validation of assessment maps

The methodology for validation of assessment maps for each Unit involves the three working stages.

First stage: Validation of the assessment maps of the winter wheat crop variables

For the purpose of the validation it is needed to determine the grade of each ESU with respect to the particular crop variable based on ground measurements. The ground-measured values of the selected crop variable at ESU level are assessed using the three-grade scale obtained during the generation of the respective assessment map. Two grades are thus obtained and compared for each ESU, the one based on the ground-measured value of the crop variable and the other based on the corresponding assessment map. In both cases the border values which define the three grades are obtained from the Equal Interval method as applied to reclassify the RL and to produce the assessment map. The assessment map is considered accurate and can be used for production of assessment map of the crop's general condition if the two grades corresponded to each other for at least 70% of the ESUs.

Second stage. Evaluation of the crop's general condition in the test Units by ground-based data

During the evaluation of the crop's general condition in the test Units by ground-based data, the variables and criteria about phenological growth stages Z31 to Z34 proposed by Kolchakov et al. (Kolchakov et al., 2019) were used. Additionally, criteria to assess the crops condition for phenological growth stages Z30 were introduced (Tables 6 and 7). The variables used in this study include:

- land evaluation of winter wheat growth according to the FAO land evaluation principles (Sys et al., 1991).
- soil moisture content (W, % per mass) in the root soil layer.
- crop height (cm);
- Nitrogen content (N %) in plant samples of winter wheat;
- crop weediness (number of weeds and self-planted cultural plants per m^2);
- phytosanitary condition of the crop damages caused by diseases and pests, damages from drought, excessive moisture, frost, freezing. It was determined based on the percent of damages;
- number of productive tillers per m^2.
- biological yield obtained for agricultural year 2016/2017. This ESU-level variable was used ex-

Table 6. Crop condition evaluation criteria for the soil variables in the ESUs (Kolchakov et al., 2019)

Variable	Evaluation of the variable's condition		
	Poor	Fair	Good
Rank Land/FAO classification	0-40/N2; N1	40-85/S3; S2	85-100/S1
Soil moisture content (W, % per mass)	Epicalcic and Endocalcic Chernozems	Epicalcic and Endocalcic Chernozems	Epicalcic and Endocalcic Chernozems
	<20	>27	20-27
	Haplic CambisolEutricSiltic	Haplic CambisolEutricSiltic	Haplic CambisolEutricSiltic
	<20	>28	20-28

Table 7. Crop condition evaluation criteria for the crop canopy variables measured during the field campaigns carried out in April 2017 (FGS – Z31 to 34) and 2018 (FGS – Z30)

Variable	Phenological growth stage	Condition evaluation		
		Poor	Fair	Good
Height, cm	Z 31 to Z34	≤40	41 – 60	>60
	Z30	≤19	20-24	>24
Nitrogen content (N %)	Z 31 to Z34	<1.0	1 – 3	>3
	Z30	<1.0	1 – 3	>3
Crop weediness(number per m^2)	Z 31 to Z34	>20	2-20	0 – 1
	Z30	>20	2-20	0 – 1
Phytosanitary condition	Z 31 to Z34	50	10 – 50	- <10
	Z30	50	10 – 50	- <10
Productive tillers (number per m^2)	Z 31 to Z34	<450	450 – 600	>600
	Z30	<450	450 – 600	>600

perimentally during the determination of the correspondence between it and the obtained qualitative evaluation of the crop condition based on the composed maps.

Third stage. Validation of the composed assessment maps of the general winter wheat crop condition.

Initially, complex qualitative evaluation at ESU level is made. It is obtained as the arithmetic mean of the grades of each individual variable (Tables 6 and 7) for the phenological growth stages Z30 and Z31 to Z34. The ESUs having a grade ≤ 2.0 are classified as Poor–condition ones, those graded between 2.1–2.5 are classified as Fair–condition ones, and those graded between 2.6–3.0 are classified as Good–condition ones (Kolchakov et al., 2019). The grade for the variable *Productive tillers* per m^2 is doubled to reflect its weight in yield formation. The obtained qualitative grades at ESU level are compared with those recorded on the composed map of the general winter wheat crop condition for the same phenological phase. To establish the precision of the composed map, the ratio of the number of correctly calculated ESUs to their total number is calculated in percent. The validation test is deemed to have been completed successfully where the two grades are identical in 80% of the cases.

Results and Discussion

Evaluation of the condition of winter wheat crops in the test Units by data obtained from the conducted field campaigns

The condition of each variable at ESU level was assessed using a three-grade scale: 3 – *Good*, 2 – *Fair*, and 1 – *Poor* according to the quantitative criteria presented on Tables 6 and 7. The results from the evaluation (Table 8) were required to validate the assessment maps.

The general characteristics of the crop condition in the six Units was made based on the evaluations of its variables measured during the carried out field campaign (Table 8).

The soil in Units 1, 2 and 3 is the same – *Haplic Cambisol Eutric Siltic* (Figure 2a). The Munsell colour (Munsell Soil Color Charts, 1975) of the surface soil horizon in the ESUs is Very dark greyish brown /10YR3/2/ in Unit 1, and ESU 2_1, 2_2, 2_3. In the other ESUs, it is Brown /10YR4/3/. The soil moisture content in soil depth of 0–5 cm varies between 21–25 % per mass.

Two soil varieties have been mapped in each of Units 4, 5 and 6 (Figure 2b). The Munsell colour of the surface soil horizon in the ESUs for *Endocalcic Chernozem Siltic* is Very dark brown /10YR2/2/ and for *Haplic Regosol Cal-*

Table 8. Evaluation of the condition of the measured variables of winter wheat crops in the ESUs recorded during the field campaigns carried out in April 2017 (FGS – Z31 to Z34) and 2018 (FGS – Z30)

Variable	Phenological growth stages	Evaluation of the variable's condition for each ESU		
		Poor	Fair	Good
Rank Land for growing of winter wheat	Z31 to Z34			All ESUs
	Z30		All ESUs	
Soil moisture content (W, % per mass)	Z31 to Z34	3_1; 3_2; 3_3		1_1; 1_2; 1_3; 1_4; 1_5; 1_6; 2_1; 2_2; 2_3; 2_4; 2_5; 2_6
	Z30			All ESUs
Crop height, cm	Z31 to Z34		2_2; 3_1; 3_2; 3_3	1_1; 1_2;1_3; 1_4; 1_5; 1_6; 2_1; 2_3; 2_4; 2_5; 2_6
	Z30	4_1; 4_2; 4_3	4_4; 4_5; 4_6; 4_7; 5_3; 5_4; 5_5; 6_2; 6_3	5_1; 5_2; 6_1
Nitrogen content (N %) in winter wheat plant samples	Z31 to Z34	1_3; 1_4; 1_5; 2_2	1_1; 1_2; 1_6; 2_1; 2_3; 2_4; 2_5; 2_6; 3_1; 3_2; 3_3	
	Z30		All ESUs	
Crop weediness	Z31 to Z34	1_4; 1_5; 2_2	2_1	1_1; 1_2; 1_3; 1_6; 2_3; 2_4; 2_5; 2_6; 3_1; 3_2; 3_3
	Z30	5_2; 5_4; 5_5	4_2; 5_1; 5_3	4_1; 4_3; 4_4; 4_5; 4_6; 4_7; 6_1; 6_2; 6_3
Phytosanitary condition	Z31 to Z34	1_5	1_3; 1_4	1_1; 1_2; 1_6; 2_1; 2_2; 2_3; 2_4; 2_5; 2_6; 3_1; 3_2; 3_3
	Z30			All ESUs
Number of productive tillers per m^2	Z31 to Z34		1_2; 1_3; 1_4; 1_6; 2_2; 3_1; 3_2; 3_3	1_1; 1_5; 2_1; 2_3; 2_4; 2_5; 2_6
	Z30	4_1; 4_2; 4_3	4_4; 4_5; 4_6; 4_7; 5_2; 5_4; 5_5; 6_3	5_1; 5_3; 6_1; 6_2;

caric Siltic it is Brown /10YR4/3/. The soil moisture content in soil depth of 0–5 cm varies between 23–29 % per mass.

The differences of these two variables in the individual ESUs are minimal and do not affect materially VI. Therefore, we assume that the major differences in the values of VI are due to the condition of the studied winter wheat crops.

Phenological growth stages Z31 to Z34

The basic soil characteristics are appropriate for growing of winter wheat. The general land evaluation for all ESUs is *Good* (Table 8).

In Unit 1, the water content stored in the root soil layer was assessed as *Good*. Over 50 % of the crop is in FSG Z33 to Z34. The Nitrogen content (N %) in the crop is *Poor* in ESU 1_3; 1_4 and 1_5, and in the other ESUs it was *Fair*. The Plant height was assessed as *Good*. In ESU 1_3; 1_4 and 1_5, a fungal disease was recorded, which had developed to different degrees. In the last two ESUs, weeds were also recorded – wild camomile, mustard, catch weed, wild violet (*Matricaria inodor*a L., *Sinapis arvensis* L., *Galium aparine* L., *Viola tricolcor* L.), where a noticeable herbicide effect was observed. In the other ESUs, the phytosanitary condition of the crop was *Good*. The grade of the variable Number of productive tillers per m^2 was *Fair*, whereas for ESUs 1_1 and 1_5, it was *Good*. The general grade of the crop's condition (Fig. 3a.) for Unit 1 was *Good* in ESUs 1_1, 1_2 and 1_6, the obtained biological yield exceeding 800 g.m^{-2}. In the other three ESUs, the grade was *Fair* because of their deteriorated phytosanitary condition. The obtained biological yield in them varied between 650–750 g m^{-2}.

In Unit 2, the water content stored in the root soil layer was within the optimal limits. Above 60 % of the crops were in FSG Z33 to Z34. The Nitrogen content (N %) of winter wheat was *Poor* in ESU 2_2, and in the other ones it was *Fair*. The variables Plant height, Phytosanitary condition and Number of productive tillers per m^2 were graded as *Good*, with only ESU 2_2 making an exception, where 268 pieces of weeds were recorded, part of them representing wild chamomile (*Matricaria inodora* L.). No herbicidal effect was observed. ESU 2_1 was weeded to a lesser degree. The grade of the general crop condition (Fig. 3a) was *Good*, and only in ESU 2_2 it was *Fair*. In ESU 2_2, the biological yield was 605 g m^{-2}, and in the other ones it varied between 730–860 g m^{-2}.

In Unit 3, winter wheat lagged behind in its development, whereas more than 81 % of the crop was in FSG Z31 to Z32. The water content stored in the root soil layer was graded as *Poor*, and the phytosanitary state as *Good*. The other variables characterizing the crop were graded as *Fair*. All this affects also the general crop grade (Figure 3a) of Unit 3, which was *Fair*, too. The delayed development of the crop results from delayed sowing. The biological yield varied between 630–760 g m^{-2}.

Phenological growth stages Z30

The soil varieties dominating in the Units 4, 5 and 6 are *Endocalcic Chernozem Siltic* and *Haplic Regosol Calcaric, Siltic* (Figure 2b).They feature mean land evaluation of 71 and their grade with respect to growing of winter wheat is *Fair* for all ESUs (Table 8).

Moisture in the soil root layer of all three Units was optimal. No damages from diseases or pests were recorded. Nitrogen content (N %) in winter wheat plant samples was evaluated as *Fair*.

In Unit 4, crop height was evaluated as *Fair*, but for ESUs 4_1; 4_2; 4_3 where it was lower (Table 8). Weeds were recorded only in ESU 4_2 – wild mustard (*Sinapis arvensis* L.). In four ESUs, the number of productive tillers per m^2 was evaluated as *Fair* (Table 8). The bad grade for this variable in ESUs 4_1, 4_2 and 4_3 is due to the fact that, in them, 63–83 % of the number of developed plants per m^{2}features only one productive tiller. On account of the weaker development of the winter wheat crop, its condition was graded as *Poor* in ESUs 4_1, 4_2 and 4_3, and *Fair* in the rest (Figure 3b).

In Unit 5, crop height was *Fair*, whereas in ESU 5_1 and 5_2, is was *Good*. In all ESUs, different degree of weediness was recorded – wild mustard (*Sinapis arvensis* L.) and field poppy (*Papaverrhoeas* L.). The number of productive tillers per m^2 was *Fair*. This variable was evaluated as *Good* only in ESUs 5_1 and 5_3 where more than 1 000 tillers per m^{2}were recorded. The general grade of winter wheat crop condition in Unit 5 was *Fair*, but for ESU 5_1 where it was *Good* (Figure 3b).

In Unit 6, crop height was *Fair*, whereas in ESU 6_1 it was *Good*. No weeds were recorded. The crop's development with respect to the number of productive tillers per m^2 was *Good*, whereas only in ESU 6_3 it was *Fair*. The general grade of the winter wheat crop condition in Unit 6 was *Fair*, but for ESU 6_1 where it was *Good* (Figure 3b).

Validation of the grade of winter wheat crop condition in the test Units obtained from the composed assessment maps

For each observed phenological growth stage, initially, an ARL layer of all five variables was composed and validated according to the methodology. The AGR layers of the crop variables for FGS Z31 to Z34 and Z30 thus obtained were used to compose an assessment map of the winter wheat crop condition in the six Units.

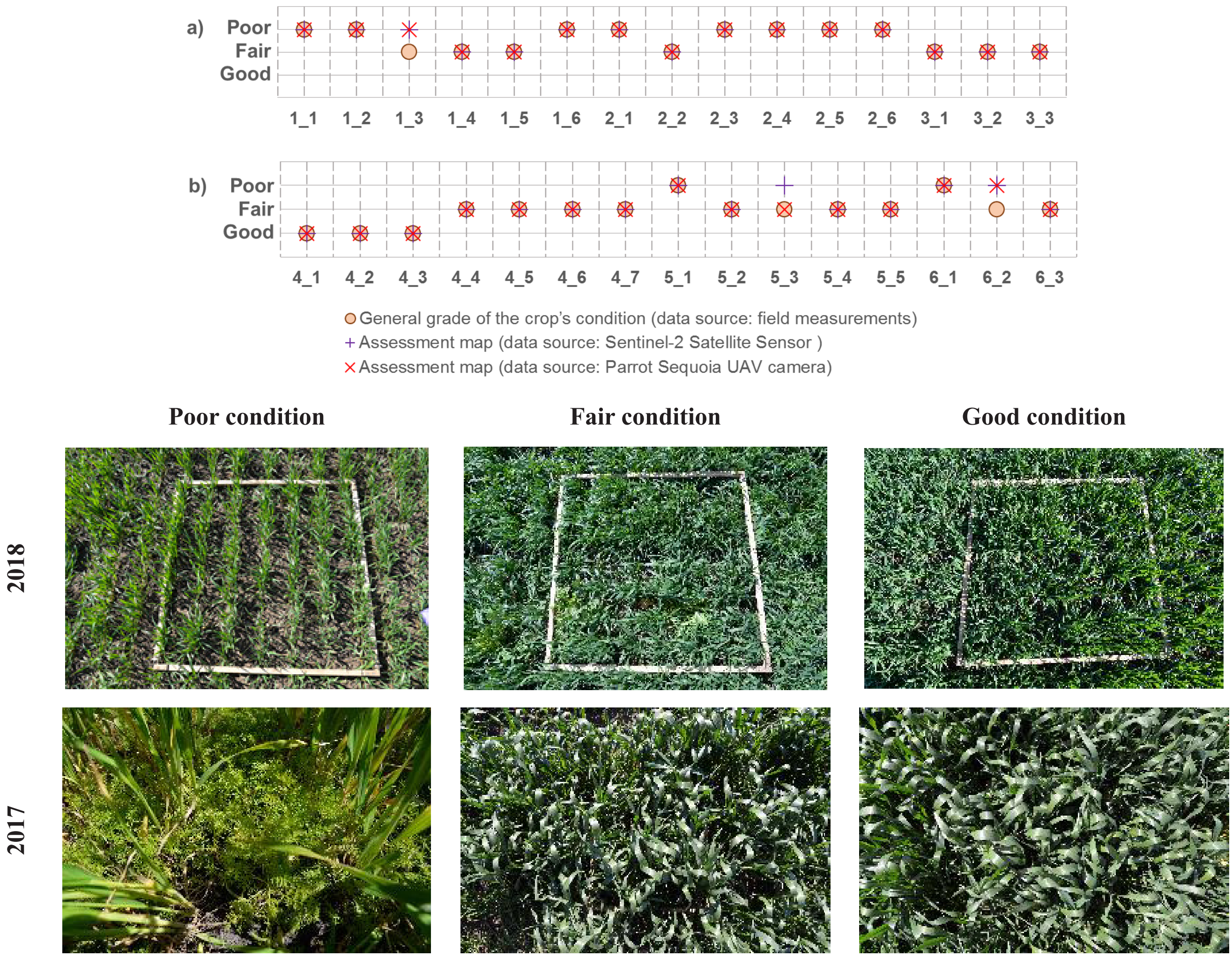

Fig. 3. Correspondence at ESU level between the qualitative assessments the of winter wheat crop condition from the assessment maps and those established by field data for phenological growth stages a) Z31 to Z34 and b) Z30

For FGS Z31 to Z34 the correspondence at ESU level between the qualitative evaluations recorded from the AGR layer and those established by field measurements features accuracy between 94 %–100 % (Table 9). The only exception is the variable *N uptake* by plants (g m^{-2}). With it, the established correspondence varies between74 %–80 % depending on the data source used to compose the ARL layer (Table 9), but it lies within the limits of the allowed accuracy.

The results obtained during the validation of the AGR layers of the selected five crop variables for FGS Z30 are *Fair*.The correspondence between their qualitative evaluations recorded at ESU level and those established by field measurements varies between 80 %–100 % (Table 9). Two variables make an exception which feature accuracy of 73 % which lies within the allowed limits. These are *Leaf area index* and, as well as with FGS Z31 to Z34, *N uptake* by *plants* (g m^{-2}).

The accuracy of all ARL layers of the used crop variables is above 70 % and they may be used to compose assessment maps.

As a result of the conducted study, two assessment maps of the crop condition in each of the six Units were composed. One of them used as a data source images obtained from *Sentinel-2A* Satellite Sensor, and the other – from *Parrot Sequoia UAV* camera (Figure 4). The results from the performed validation of these maps for FGS Z31 to Z34 (Figure 3a) are good. The accuracy of the comparison of the grades of winter wheat crop condition recorded based

Table 9. Correspondence (%) at ESU level between the qualitative assessments recorded from the ARL layers of a set of crop variables, assessment maps and those established by field measurements

Phenological growth stages	Data source	LAI	fAPAR	fCover	AGBf	N uptake	Assessment maps
Z31 to Z34	Sentinel 2	94	100	100	94	74	94
	Sequoia	94	94	94	94	80	94
Z30	Sentinel 2	73	80	80	87	73	87
	Sequoia	73	94	100	87	73	94

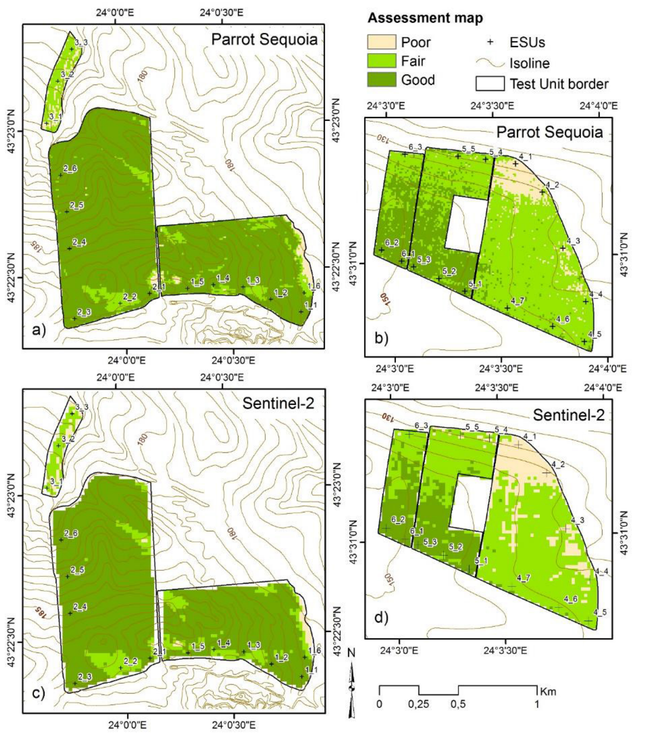

Fig. 4. Assessment maps of winter wheat crop condition in the test Units composed using data from *Sentinel-2* satellites ensor and *Parrot Sequoia UAV* camera for phenological growth stages a) Z31 to Z34 and b) Z30

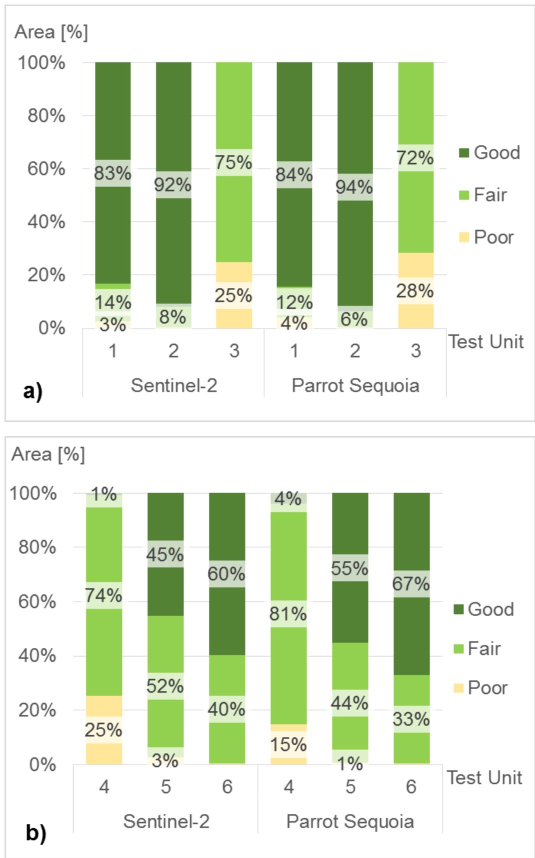

Fig. 5. Diagram of the area distribution (%) of winter wheat crop condition in the test Units obtained from the composed assessment maps using data from *Sentinel-2* satellite and *Parrot Sequoia UAV* camera for phenological growth stages a) Z31 to Z34 and b) Z30

on assessment maps and those obtained from the complex ground-based qualitative evaluation is 94%. The obtained grades differ only for ESU 1_3 (Figure 3a). Based on the map, the crop's condition was graded as *Good*, and based on ground-based data – as *Fair*, with grade of 2.4. There were not major differences in the area distribution of the qualitative evaluations on the two maps (Figure 4a). It was established that over 83% of the crops in Unit 1 and 2 featured *Good* conditions (Figure 5a). In Unit 3, nearly 75% of the crops have overcome partially the unfavorable consequences of the late sowing. This is also confirmed by the yield obtained by the farmers. In Units 1and 2, it is highest compared to the other Units, and in Unit 3, it is lowest (Table 1).

The results from the validation of the assessment maps for FGS Z30 are also promising. The correspondence between the crop's condition in the 15 elementary sampling units assessed by the maps and the crop's condition established through the complex ground-based qualitative evaluation is equal to 94% for the map based on data from *Parrot Sequoia UAV* camera and 87% for the map based on *Sentinel-2A* satellite data (Figure 3b). With both maps, the crop in ESU 6_2 was classified as *Good*, and based on ground-based data – as *Fair,* with a value of 2.5, which is the boundary value between the two conditions.

Between the two assessment maps there are no material differences in the area distribution of the crop's condition qualitative grades for all three Units (Figures 4b and 5b). Over 35% of the crops in Units 5 and 6 are in the *Fair* condition, whereas by data from the farmers, the obtained yield is lower by 150–160 kg ha^{-1} than the yield in Units 1 and 2. Over 90% of the crops in Unit 4 are in *Fair* or *Poor* condition (Figures 4b and 5b) which was proved 490 kgha^{-1} lower yield compared to the yield obtained from Units 1 and 2 (Table 1).

Conclusions

The proposed approach to compose an assessment map using a set of crop variables (AGBf, N uptake, LAI, fAPAR, FCOVER) obtained by data from *Sentinel 2* satellite and *Parrot Sequoia* UAV camera proves to be effective for identification of *Good*, *Fair* and *Poor* condition of winter wheat crops. High correspondence (87% – 94%) has been established between the recorded qualitative condition of the crops based on the composed assessment maps and the condition determined by conventional methods. If necessary, when a considerable area of crop in a field is classified in a *Fair* or *Poor* condition, the farmer may use the assessment maps for the condition and quantitative values for each of the crop variables.

The difference in the areas (Figures 4 and 5) of the recorded conditions of winter wheat crops in the six Units is minor (up to 3% for FGS Z31 to Z34 and 7-11% for FGS Z31) when using data from *Sentinel-2* satellite sensors compared to those obtained from *Parrot Sequoia* UAV multispectral camera. Both information sources can be used in operative monitoring and where data from one of them are lacking, the other one may be used.

Assessment maps enable the farmers, during the active vegetation period, to perform qualitative crop control and, where necessary, to undertake measures to improve crop condition.

To determine the relationship between the recorded condition of the crops based on the composed assessment maps and the biological yield, it is necessary to conduct field campaigns in order to collect data during a minimum of two more agricultural years.

Acknowledgments

This study was conducted as part of the "Testing Sentinel-2 vegetation indices for the assessment of the state of winter crops in Bulgaria (TS2AgroBg)" project funded by the Government of the Republic of Bulgaria through ESA Contract 4000117474/16/NL/NDe under the Plan for European Cooperating States.

We pay our gratitude also to the farmer Mr. Svetlin Ilchovski, the President of the „Zora"Cooperation, Mr. Lyuben Hinkin, and the agronomists Mrs. Polina Marinska and Mr. Yulian Golemanski for the provided data and the carried out useful discussions.

References

Barnes, E., Clarke, T., Richards, S., Colaizzi, P., Haberland, J., Kostrzewski, M., Waller, P., Choi, C., Riley, E., Thompson, T., Lascano, R., Li, H. & Moran, M. (2000). Coincident detection of crop water stress, nitrogen condition and canopy density using ground-based multispectral data. In: *Proceedings of the Fifth International Conference on Precision Agriculture, Bloomington,* MN, USA.

Decagon Devices (2014). AccuPAR PAR/LAI Ceptometer, Model LP-80. Operator's Manual Version, June 20 2014, 78.

Dimitrov, P., Kamenova, I., Roumenina, E., Filchev, L., Ilieva, I., Jelev, G., Gikov, A., Banov, M., Krasteva, V., Kolchakov, V., Kercheva, M., Dimitrov, E. & Miteva, N. (2019). Estimation of biophysical and biochemical variables of winter wheat through Sentinel-2 vegetation indices. *Bulgarian Journal of Agricultural Science*, *25 (5),* 819–832.

Erdle, K., Mistele, B. & Schmidhalter, U. (2011). Comparison of active and passive spectral sensors in discriminating biomass variables and nitrogen condition in wheat cultivars. *Field Crops Research*, *124(1),* 74–84.

Gitelson, A. A. & Merzlyak, M. N. (1994). Spectral reflectance changes associated with autumn senescence of *Aesculushippo castanum* L. and *Acer platanoides* L. leaves. Spectral features and relation to chlorophyll estimation. *J. Plant Physiol., 143,* 286–292.

Gitelson, A. A., Gritz, Y. & Merzlyak, M. N. (2003). Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll evaluation in higher plant leaves. *Journal of Plant Physiology, 160,* 271–282.

Gitelson, A. A., Keydan, G. P. & Merzlyak, M. N. (2006). Three-band model for noninvasive estimation of chlorophyll, carotenoids, and anthocyanin contents in higher plant leaves. *Geophysical Research Letters*, *33 (11).*

Hatfield, J. L. & Prueger, J. H. (2010). Value of using different vegetative indices to quantify agricultural crop characteristics at different growth stages under varying management practices. *Remote Sens., (2)*, 562-578. https://doi.org/10.3390/rs2020562

IUSS Working Group WRB (2014). World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. *World Soil Resources Reports, No. 106.* FAO, Rome.

Jamieson, P. D., Semenov, M. A., Brooking, I. R. & Francis, G. S. (1998). Sirius: a mechanistic model of wheat response to environmental variation. *European Journal of Agronomy*, *8(3–4),* 161–179.

Ji-hua, M. & Bing-fang, W. (2008). Study on the crop condition monitoring methods with remote sensing. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVII*. Part B8, Beijing 2008.

Kolchakov, V., Kercheva M., Banov, M., Krasteva V., Roumenina, E., Dimitrov, P., Jelev, G., Filchev, L., Dimitrov, E. & Gikov, A. (2019). Complex evaluation of winter wheat growing conditions in North-Western Bulgaria. *Proceedings of the 10-th International Soil Congress "Successful Transformation toward Land Degradation Neutrality: Future Perspective*" 2019, 17-19 June 2019 Ankara, Turkey, 10, 2019, ISBN: 978-605-63090-4-5, 482-487.

Kostov, K., Palov, I., Sirakov, K., Kuzmanov, E. & Zahariev, S. (2014). Effect of pre-sowing electric treatments of seeds on the yields of wheat varieties Enola and Kristy. *Bulgarian Journal of Agricultural Science*, *20 (6),* 1508-1512.

Merzlyak, M. N., Gitelson, A. A., Chivkunova, O. B. & Rakitin, V. Y. (1999). Non-destructive optical detection of pigment changes during leaf senescence and fruit ripening. *Physiologia Plantarum*, *106(1),* 135–141. https://doi.org/10.1034/j.1399-3054.1999.106119.x

Monteith, J. & Unsworth, M. (1990) Principles of environmental physics. 2nd ed., Butterworth-Heinemann, Elsevier, Oxford.

Munsell Soil Color Charts (1975). Munsell Color Co. Inc. Baltimore 18, Maryland 21218, USA.

Parrot Sequoia (2019). Available online: https://community.parrot.com/t5/Sequoia/bd-p/Sequoia (accessed on 18.12.2019).

Pimstein, A., Eitel, J., Long, D., Mufradi, I., Karnieli, A. & Bonfil, D. (2009). A spectral index to monitor the head-emergence of wheat in semi-arid conditions. *Field Crops Research*, *111(3),* 218–225. https://doi.org/10.1016/j.fcr.2008.12.009

Rondeaux, G., Steven, M. & Baret, F. (1996). Optimization of soil-adjusted vegetation indices. *Remote Sensing of Environment, 55(2),* 95-107.

Roumenina, E. K., Jelev, G. N., Dimitrov, P. K., Filchev, L. H., Kamenova, I. B., Gikov, A. G., Banov, M. D., Krasteva, V. N., Kercheva, M. S. & Kolchakov, V. I. (2019). Integrated system for remote sensing determination of agricultural crop condition. BG 3283 U1 Certificate for registration of utility model. *Official Bulletin of the Patent Office of the Republic of Bulgaria.* 10.1 on 15.10.2019, 6379 – 6417(Bg).

Serrano, L., Filella, I. & Peñuelas, J. (2000). Remote sensing of biomass and yield of winter wheat under different nitrogen supplies. *Crop Science, 40(3),* 723. doi:10.2135/cropsci2000.403723x

Shanmugapriya, P., Rathika, S., Ramesh T. & Janaki, P. (2019). Applications of remote sensing in agriculture – A review. *Int. J. Curr. Microbiol. App. Sci., 8(1),* 2270-2283. DOI: https://doi.org/10.20546/ijcmas.2019.801.238

Stanev, S., Kyuchukova, M. & Lingova, S. eds. (1991). The climate of Bulgaria, Publishing House of Bulgarian Academy of Sciences, Sofia (Bg).

Sys, C., Van Ranst, E. & Debaveye, J. (1991). Land evaluation. Part I. Principles in land evaluation and crop production calculations. Agricultural Publication N7, General Administration for Development Cooperation, Brussels, Belgium, 274.

Vitousek, P. & Howarth, R. (1991). Nitrogen limitation on land and in the sea: How can it occur? *Biogeochemistry*, *13(2).* 87-115.

Whelan, B.M. & McBratney, A. B. (2000) The "Null Hypothesis" of precision agriculture management. *Precision Agriculture*, *2(3),* 265-279.

Wilhelm, W., Ruwe, K. & Schlemmer, M. (2000). Comparison of three leaf area index meters in a corn canopy. *Crop Sci*., *40*, 1179–1183. doi:10.2135/cropsci2000.4041179x

Yue, J., Yang, G., Li, C., Li, Z., Wang, Y., Feng, H. & Xu B. (2017). Estimation of winter wheat above-ground biomass using unmanned Aerial Vehicle-Based Snapshot Hyperspectral Sensor and crop height improved models. *Remote Sens.*, *9,* 708. doi:10.3390/rs9070708

Zadoks, J. C., Chang, T. T. & Konzak, C. F. (1974). A decimal code for the growth stages of cereals. *Weed Research*, *14,* 415-421.

Zhao, H., Song, X., Yang, G., i Li, Z., Zhang, D. & Feng, H. (2019). Monitoring of nitrogen and grain protein content in winter wheat based on Sentinel-2A Data. *Remote Sens., 11,* 1724; doi:10.3390/rs11141724.

Received: December, 12, 2019; *Accepted:* January, 15, 2020; *Published:* December, 31, 2020