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Assessment of drought impact on phenological development of selected sunflower hybrids based on vegetation indices and orthogonalization of multispectral satellite data

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Abstract

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Agriculture is one of the leading sectors, directly affected by the negative impacts of climate change and in particular of drought. Water stress is amongst the key growth limiting factors in crop production. It is expected that in the next decades Bulgaria will be affected by warming of air temperatures and reduction of precipitation sum that will significantly increase the risk of droughts. Although, sunflower *(Helianthus annuus* L.*)* is known to be a drought tolerant crop, sufficient and optimized agrotechnical activities are needed to achieve yield increase under changing environmental conditions and depletion of natural resources. The proper irrigation scheduling, for example, requires determination of biologically optimal health and water status for different sunflower varieties, at different stages of ontogeny. The research suggests a remote sensing methodology, integrating vegetation indices and orthogonalization of multispectral satellite data for studying phenological development of selected sunflower hybrids under drought conditions. Two indices – Normalized Differential Greenness Index (NDGI), and Normalized Differential Wetness Index (NDWNI), based on Tasseled Cap Transformation are introduced for agricultural assessments. The results show the dynamics of water and health status of the studied agroecosystems in the different growth stages, defined according to BBCH scale. NDGI and NDWNI appear to be especially suitable for determination of timing and duration of growth stages and for monitoring of the status of the studied crops during these stages. The methodology possesses a great potential for better understanding of drought impact on crop dynamics and functioning.

Keywords: agricultural vegetation response; growth stages; health and water status; remote sensing; Sentinel 2; Northwestern Bulgaria

Introduction

In the next decades Bulgaria will be affected by warming of air temperatures and reduction of precipitation sums. The combination of high air temperatures and precipitation deficit will lead to higher transpiration and evapotranspiration during the summer season. This will significantly increase the risk of all types of droughts – meteorological, hydrological, agricultural, and even socioeconomic drought (IWMB, 2008).

Agriculture is one of the leading sectors, directly affected by the negative impacts of climate change and in particular of drought, and water stress is amongst the crucial growth limiting factors in crop production (Wu & Cosgrove, 2000).

Long periods of severe water deficit, particularly at water sensitive growth stages affect the health status and proper functioning of crop plants, causing significant reduction in seed yield (Beyazgul et al., 2000). These negative effects are induced by the different energy levels of plant water status, affecting the plant ability to absorb nutrients. There is a close biophysical relationship between the photosynthetic activity and the changes in moisture energy levels in plants and soils (Christov, 1989). Severe water deficits during the early vegetative growth of sunflower reduce plant height. Proper bud development in late vegetative period is dependent also on the water content, but the most sensitive to water deficits is flowering period, in which the water stress causes considerable yield decrease since fewer inflorescentes come to their full development (Beyazgul et al., 2000; Ali & Shui, 2009). Seed formation is the next most sensitive period to water deficit, causing severe reduction in both yield and oil content (Doorenbos & Kassam, 1979). Substantial yield increases can be achieved by supplementary irrigation, which is one of the most effective strategies to mitigate the effects of dry spells in crop production (Fox & Rockstrom, 2000; Xiao et al., 2007). A proper irrigation scheduling and precise regulation of fertilization rates can be achieved by determination of biologically optimal water status for each sunflower variety, at different stages of its development.

Remote sensing (RS) technology provides cost-effective and objective methods for monitoring and quantitative assessments of impacts of climate changes and water scarcity on the soil-vegetation-atmosphere-transfer processes. In agriculture, RS is used to analyze aspects like crop area (Qinghan et al., 2008), crop phenology (Sakamoto et al., 2005; Pan et al., 2015), growth dynamics (Shang et al., 2014); to determine vegetation indicators (Dimitrov et al., 2019; Roumenina et al., 2020); for current monitoring (Eerens et al., 2014).

In the present research, vegetation indices and orthogonalization of multispectral satellite data are used to study water and health status of certain sunflower hybrids, developing under natural crop water regimes during the growing seasons of 2019 and 2020. Both years are distinguished with strongly expressed drought conditions for agricultural development. The analysis encompasses different growth stages of the crop development, defined as intervals during the growing season. The growth stages include the phenological phases and have the same or close susceptibility to changes in the quantity and quality of crop yield. The changes in the health and water status of the plants and in the dynamics of their functioning directly affect the values of the spectral vegetation indices. Being influenced by a decrease in the energy level of the water status at a certain growth stage, the indices values can serve to assess the crop susceptibility to drought during this stage of ontogeny. Through continuous monitoring of crops health and water status, the methodology allows determination of the optimal ecological conditions for development of the studied sunflower hybrids. Multispectral satellite images, acquired by the Sentinel-2 A & B satellites of the European Space Agency (ESA) were used. Each multispectral band contains specific information and the combination of these bands results in new and more complex information. In addition to traditionally used vegetation indices as Normalized Difference Vegetation Index (NDVI); the narrowband Normalized Difference Vegetation Index (NDVI705); the Modified Soil-Adjusted Vegetation Index (MSAVI2); the Modified Chlorophyll Absorption Ratio Index (MCARI2); the Normalized Difference Water Index (NDWI); and the Moisture Stress Index (MSI), two indices –NDGI, and NDWNI, based on orthogonalization of multispectral satellite data are introduced for agricultural assessments. The obtained results will serve as a basis for development of predictable models for assessment of the sunflower agroecosystems health status in different environmental conditions.

The present research is not a coordinated experiment. It is performed in real conditions, which may occur in any farm. The advantage of this approach is that it allows identification of real problems that satellite remote sensing face when offering services to support management decisions in agriculture.

Study object

Sunflower is the most significant oilseed crop in the countries with moderate climate. Bulgarian export of sunflower-seed oil has increased by 10.7% on an annual basis since 2014. In the last years, Bulgaria is in the first ten countries in the export of sunflower-seed oil (Sunflower Oil Production in Bulgaria, 2021). In the Northwestern Bulgaria, where the studied sunflower fields are located, the harvested sunflower area is about 30% of the areas total for the country (Crop Production Data, 2021).

Sunflower hybrids selected for the study

Sunflower producers seek to use high-yielding hybrids, having the ability to overcome constantly changing stressors such as changes in environmental and meteorological conditions and pest infestation. Hybrids, resistant to herbicides are preferred, because they clear the soil of weeds and reduce plant protection costs. Taking this into consideration, in the focus of the sunflower breeding programs in Bulgaria is the development of high-yielding hybrids, resistant to the economically important diseases (Georgiev et al., 2019).

In the present study, the dynamics in the phenological development and the health status of one Bulgarian sunflower line and three hybrids (Line 3607 A x 12.51R, Enigma, Dara, Sunny IMI), created especially for the Bulgarian ecological conditions and three foreign sunflower hybrids, widely used among the Bulgarian producers (P64LE25,P64LE99,P64LE136) was assessed.

Bulgarian sunflower hybrids

The studied Bulgarian hybrids are developed in the only breeding center of sunflower in Bulgaria – Dobrudzha Agricultural Institute at Bulgarian Agricultural Academy (Georgiev et al., 2019).

Enigma is a sunflower hybrid, in which through selection, genes for resistance against the parasitic plant *Orobanche cumana* (sunflower broomrape) are included. Enigma is a mid-early hybrid, with duration of the vegetative growth 115 – 120 days and plant height 180 – 190 cm. In the fields of the Dobrudzha Agricultural Institute it shows a yield of 3.95 t/ha and 47-48% oil content in seed. It is created using ClearfieldPlus® technology, which beside *Orobanche cumana* controls both annual cereal and broad-leaved weeds during the vegetative growth (Milev et al., 2019).

With similar qualities is the sunflower Line 3607 A x 12.51R. In the growing season 2019, Line 3607 A x 12.51R is still in a process of testing the predefined indicators of resistance (diseases, pests, herbicides, stress and climatic factors, etc.). The collected information, during the test period, allows determining the yield structure under changing environment and developing appropriate technological solutions for growing (Baychev & Mihova, 2014). On the basis of this sunflower line is developed the hybrid Dara, which in 2020 is introduced in the systems of official testing in Bulgaria.

Sunny IMI is the third hybrid, selected to be studied in the present research and developed by the Dobrudzha Agricultural Institute. It is resistant to downy mildew, races 700 and 731, and to *Phoma*, *Phomopsis* and *Sclerotinia* as well. It is resistant also to broomrape, races A to F including. The vegetative growth is 120-125 days and plant height is 160 – 170 cm. Sunny IMI is a competitor of the high-yielding foreign hybrids. Its yield-potential is over 400 kg/da and the achieved yield in northeastern Bulgaria is 431 kg/da in 2016 (Sunflower hybrid Sunny IMI, 2021).

Foreign sunflower hybrids

The most widely used foreign sunflower hybrid amongst the Bulgarian producers is P64LE25. It is a mid-early hybrid, with high oil content and a very good tolerance to *Sclerotinia* diseases and *Phomopsis* stem canker. It is resistant to all races of downy mildew of sunflower (*Plasmopara halstedii*) distributed in Bulgaria. P64LE25 possess a gene for resistance to broomrape. It is tolerant to dry conditions, showing high yield potential under normal and dry conditions (P64LE25, 2021).

The second most cultivated hybrid in Bulgaria is P64LE99. P64LE99 is a late-maturing sunflower hybrid, with very high and stable yield, more suitable for growing in the ecological conditions of Northern Bulgaria, where the study area is situated (P64LE99, 2021). It is resistant to broomrape and possesses a great tolerance to *Phomopsis* and *Sclerotinia*, both on stalk and head. Due to the very well developed root system, it is with a good tolerance to drought and heat (Panaitescu et al., 2015). Similar to P64LE25, P64LE99 is resistant to all races of downy mildew of sunflower distributed in Bulgaria and possesses a gene for resistance to broomrape.

P64LE136 is a mid-early hybrid, with a very high and stable yield potential in both normal and dry climate conditions. It is a new, alternative genetics of the most cultivated herbicide tolerant hybrids to date (P64LE25, P64LE99) in Bulgaria. It has high oil content and possesses a great tolerance to dry conditions (P64LE136, 2021).

The study sites in both years encompassed four sunflower fields, planted with the listed sunflower hybrids (Table 1).

Table 1. Area of the experimental fields, sown with the studied sunflowers hybrids/lines in growing seasons 2019 and 2020

Sunflower hybrid/line	Area in 2019, ha	Area in 2020, ha
Enigma	22.36	–
Line 3607 A x 12.51R	48.28	–
Sunny IMI	8.66	–
P64LE25	7.88	11.11
P64LE99		10.33
P64LE136		9.56
Dara		51.21

Study sites

Agroecological conditions

The studied fields are located in Lom Municipality, Northwestern Bulgaria (Figure 1).

Soil characteristic

The fields are covered by Calcic Chernozems. Due to changes in their texture (silt-loam), microaggregates and structural components, these soils are characterized with a high soil dustiness and “structural deficiency”. The alternating wet and dry periods lead to a high degree of carbonatation

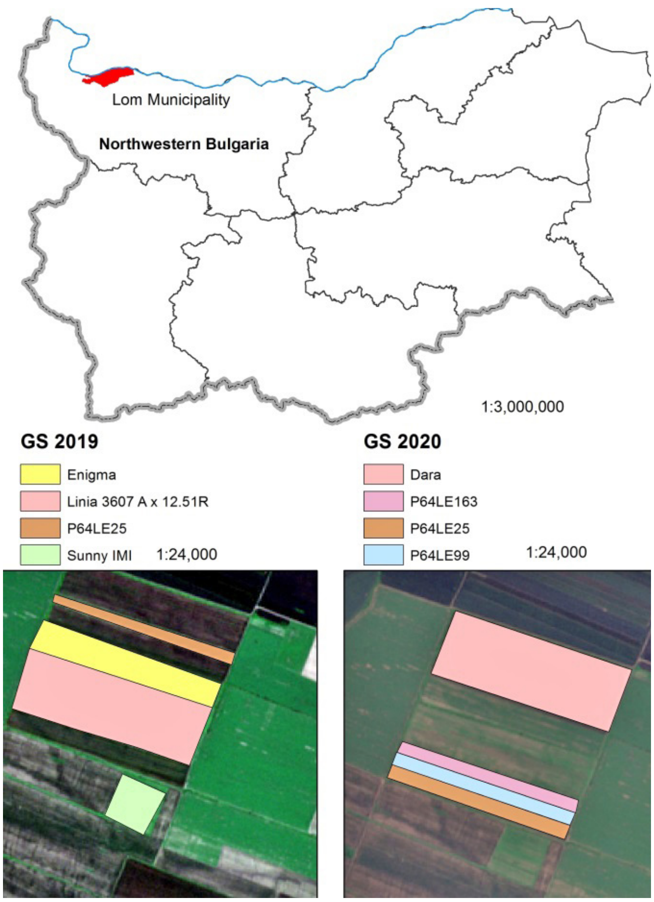


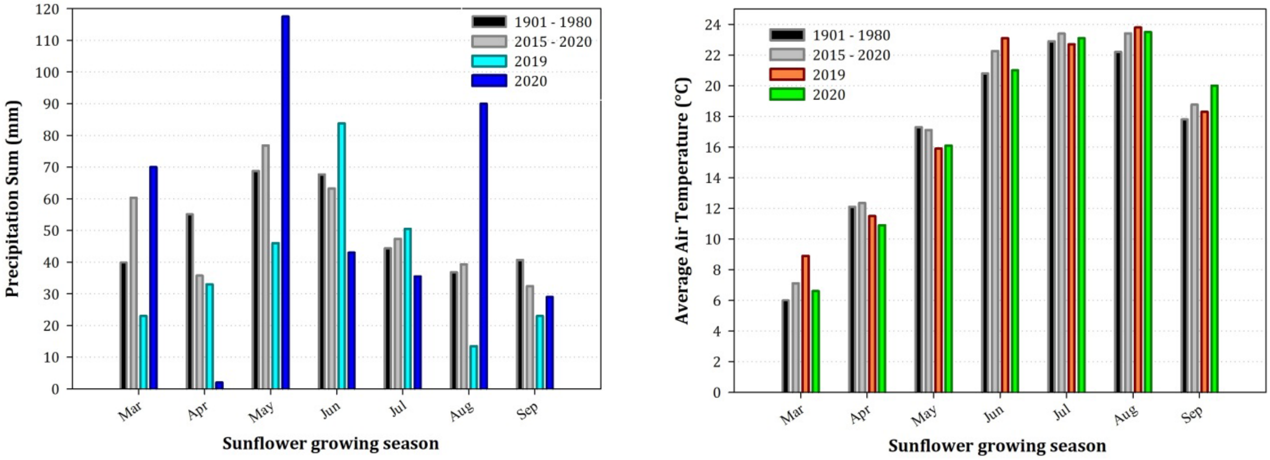
Fig. 1. Location of Lom Municipality and the fields of studied sunflower hybrids in growing seasons (GS) 2019 and 2020

and seasonal migration of carbonates, having as consequences chlorosis or dryness. The Calcic Chernozems in the study area are characterized with reduction of the clay fraction and high dustiness of topsoil, unsatisfactory water regime, low humus content, reduction of the agronomically valuable aggregates, and hence weakened resistance and stability of topsoil. These characteristics contribute to an increase of its density and hardness, limiting aeration, delaying filtration of water, and hence influencing the overall health and water status of the agroecosystems (Shishkov & Kolev, 2014; Teoharov et al., 2014).

Climatic characteristic for a typical sunflower growing season

Agriculture in the region is developing under the conditions of water deficit, frequent droughts in the spring and longer in the summer. The precipitations are insufficient and unevenly distributed within the year. The air temperatures in the sunflower growing season (March to September) are typically high and the relative humidity – low. Field measurements show that the average air temperature over the last years (2015 – 2020) has increased by 0.8°C, reaching 17.8°C in comparison to the period 1901 – 1980 (17°C), while the precipitation sum is almost the same – around 355 mm.

The average air temperature from March to September 2019 (17. 7°C) is close to the averages for the period between 2015 and 2020, and those in 2020 (16.9°C) is similar to the norm for the period between 1901 and 1980. In comparison to the both referent periods, the precipitation sum in 2019 is lower (272.8 mm) and in 2020 is much higher (452 mm) (Figure 2a, 2b). These observations indicate for better environmental conditions in sunflower growing season 2020 and conditions of pronounced drought in 2019.



a) b)

Fig. 2. Precipitation sums: (a) – and average air temperatures; (b) – for a typical sunflower growing season (from March to September) in the referent periods 1901 – 1980 and 2015 – 2020 and in the studied 2019 and 2020 seasons

Table 2. Climatic characteristics of precipitation sum, average daily air temperature, and average air temperature at 2 p.m in the individual growth stages for the studied 2019 and 2020 growing seasons

Climatic elements	Growing season		Germination – Flowering		Flowering		Development of fruit			Ripening		
	2019	2020	2019	2020	2019	2020	2019	2019 P64LE25	2020	2019	2019 64LE25	2020
Precipitation sum, mm	225.8	293	132.8	167.5	35.5	0	44	54	35.5	13.5	3.5	90
Average daily air temperature, °C	21.4	22.05	14.9	17.7	23.9	24.2	23.2	22.9	22.9	23.8	24.4	23.4
Average air temperature at 2 p.m °C	28.6	29.1	20.5	24	31.3	31.7	31	30.3	30	31.6	32.8	30.6

Autumn and winter precipitation sum in the both studied years are also lower (2019 – 101 mm; 2020 – 184 mm) than the reference periods 1901 – 1980 (266.6 mm) and 2015 – 2020 (203.6 mm) (data is not shown). The higher precipitations in the autumn-winter season in 2020 create more favorable conditions, as concerns the accumulated soil moisture before the sunflower sowing, than 2019. However, the sowing in 2020 is conducted with about 2 weeks of delay (10 – 16 April) than in 2019 (28 March – 03 April). April 2020 is a very dry month, with amount of precipitation of only 2 mm and this reduces the advantage in terms of soil moisture store, gained in the autumn-winter season (Figure 2a).

Climatic characteristic in the 2019 and 2020 growing seasons in particular

The period of sunflower crop development in the various growth stages is affected by planting time, environmental conditions (air temperature, humidity, precipitation sum, soil moisture, etc.), time needed for the various hybrids to ripen and can be of different duration. The duration of the growing season in 2019, from crops planting till harvesting, is 146 days. Due to the better environmental conditions and the later sowing, affecting the thermal time / heat sum for developmental phases, the duration of growing season 2020 is shorter – 126 days.

As a result of the different start and duration of growing seasons, the sunflower growing season of 2020 is warmer by 0.65°C than those in 2019. The precipitation sum in 2020 is higher by 67.2 mm than those in 2019 (Table 2).

The individual growth stages in both years are also affected by the different start and duration of the growing seasons. The period from germination to flowering is warmer (by 2.8°C) and wetter (by 34.7 mm) in 2020 (Table 2). The air temperatures in the flowering of season 2020 are also higher (by 0.3°C) than 2019. No precipitation was reported during this stage in 2020, and in 2019, the precipitation sum is 35 mm (Table 2). There are slight differences in the development of the various sunflower hybrids after the flowering in 2019.The development of fruit stage is few days longer for P64LE25 and this influence the conditions, under which it is developed in this stage. P64LE25 receive 10 mm more precipitations than the other hybrids in 2019 and the air temperatures are slightly lower (by 0.3°C). Generally, the development of fruit stage in 2019 is characterized with higher air temperature and precipitation sum in comparison to 2020 (Table 2). The ripening stage in 2019 is warmer and dryer than 2020. The difference is most significant for P64LE25. In the ripening stage of 2019, P64LE25 received only 3.5 mm precipitation, whereas for the other hybrids, the amount of rainfalls is 13.5 mm. In 2020, the precipitation sum for all hybrids is 90 mm. The air temperatures in 2020 are lower than those in 2019 (Table 2).

Agrotechnical methods performed

The agrotechnical methods performed include tillage, plant protection and weed control. The tillage system includes basic, pre-sowing and vegetation tillage. The weed control was performed by compliance with crop rotation and proper cultivation of agricultural lands. Herbicides were used for chemical weed control. The optimal scheme for conducting such control in the arid conditions of Bulgaria is pre-sowing treatment of the field by incorporation of herbicide, active against graminaceous weeds, and after sowing treatment, before germination with an anti-broadleaf herbicide. Mechanical weed control was also applied. During the vegetative development, treatments of the row spacing with cultivators were performed (Figure 3).

Data and methodology

Satellite data

In the present study, multispectral satellite images, acquired by the Sentinel-2 A&B satellites of the European Space Agency (ESA), were used. The satellites carry multispectral optical instruments and collect information in 13 spectral bands (ESA, 2015). Each band contains specific

a)

b)

c)

Fig. 3. Mechanical weed control and treatments of the row spacing of the sunflower fields (05 May 2020)

information and their combination results in new and more complex data. The Sentinel-2 images are acquired between 30 March 2019 and 22 August 2019 for the growing season 2019 and between 23 April 2020 and 31 August 2020 for the growing season 2020. The satellite images encompass the period from the sowing till the full maturity and harvesting of the sunflower hybrids. All available cloudless Sentinel-2 images for those periods are used. The image acquisition date and the relevant growth stage for the sunflower crops are presented in Table 3.

Methodology

Aiming to assess the health and water status of the selected sunflower hybrids, we used methods for spectral data transformation. These methods encompass calculations of spectral vegetation indices; orthogonalization of multispec-

Table 3. Satellite images acquisition dates and relevant crop growth stages (Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie – BBCH scale) (Meier, 2001)

Image acquisition date (2019)	Growth stage of sunflower crops (BBCH scale)	Image acquisition date (2020)	Growth stage of sunflower crops (BBCH scale)
30 March	Germination	23 April	Germination
24 April	End of Leaf development / Beginning of Stem elongation	28 April	Germination
04 May	End of Stem elongation / Beginning of Inflorescence emergence	08 May	Leaf development
08 June	Inflorescence emergence	13 May	Leaf development
13 June	Flowering	23 May	Leaf development
03 July	Flowering	27 June	End of Inflorescence emergence/Beginning of Flowering
08 July	Flowering	02 July	Flowering
18 July	Development of fruit	12 July	Development of fruit
23 July	Development of fruit	17 July	Development of fruit
28 July	Development of fruit	22 July	Development of fruit
02 August	Development of fruit/Ripening	01 August	Ripening
07 August	Ripening	06 August	Ripening
12 August	Ripening	11 August	Ripening
17 August	Ripening	21 August	End of Ripening/ Physiological maturity
22 August	Physiological maturity	26 August	Physiological maturity
–	–	31 August	Harvesting

tral satellite data, including application of the Tasseled- Cap Transformation (TCT); and calculation of indices, based on TCT.

Selection of spectral vegetation indices for assessment of drought impact

The health status of crop plants is directly dependent on the water content in the agroecosystems. The great part (80-90%) of biomass of non woody plants comprises of water. Consumption of less water causes physical limitation in plants (Pirasteh-Anosheh et al., 2013; Nemeskeri et al., 2015). Movement of water, oxygen and carbon dioxide, in and out of a plant, is governed by stomata (Bouranis et al., 2014). In water stress conditions, stomata close down to conserve water and that leads to a decrease of photosynthesis (Taiz & Zeiger, 2002; Mahajan & Tuteja, 2005; Mutava et al., 2015). Chlorophyll and water content of vegetation are used as a major indicator for plant stress (Carter, 1993; Wardlow et al., 2012; Piro et al., 2017; Avetisyan et al, 2019). Decreasing chlorophyll content leads to a complete change in absorption of light by leaf pigments and directly affects the spectral signature of the plant (Zarco-Tejada et al., 2000). The increased reflectance in the visible region and the reduced reflectance in the near-infrared region (NIR) are found to be consistent with chlorophyll reduction and cell structure damage among various species due to stress agents (Carter, 1993). Canopy reflectance in the visible and NIR regions is strongly dependent on biochemistry and structural properties of the canopy as Leaf Area Index (LAI), leaf orientation, canopy structure. This makes the task of revealing the health status of each plant species especially difficult and practically impossible with the application of only one universal spectral index (Wardlow et al., 2012). Taking this into account, we applied several of the most widely used vegetation indices, such as: the Normalized Difference Vegetation Index (NDVI); the narrowband Normalized Difference Vegetation Index (NDVI705); the Modified Soil-Adjusted Vegetation Index (MSAVI2); the Modified Chlorophyll Absorption Ratio Index (MCARI2); the Normalized Difference Water Index (NDWI); and the Moisture Stress Index (MSI). The formulas for calculating each index are shown in Table 4.

NDVI has been the most widely used spectral index for vegetation monitoring and evaluation of the photosynthetic activity of the crops. NDVI corresponds to the differential response of chlorophyll absorption and internal spongy mesophyll layer reflectance from plant leaves in the visible red and NIR regions. It has been found that NDVI fluctuations over time are strongly correlated with climate variations and can serve as an effective measure of climate-related vegetation changes (Rouse et al., 1974).

NDVI705 is a modified version of the broadband NDVI index and, just like it, is related to the chlorophyll content. NDVI705 uses a narrow band at the edge of the chlorophyll absorption maximum (at 705 nm) and normalizes the ratio with a waveband, not affected by chlorophyll content (i.e., 750 nm) (Gitelson & Merzlyak, 1994; Gamon & Surfus, 1999). The narrowband indices are based on specific wavelengths associated with the leaf pigments. Changes in wavelengths values can be related to the physiological state of the plant. The narrowband indices require a more accurate calibration of the measuring instruments and provide more detailed information. NDVI705 decreases when the vegetation is under stress and is particularly advantageous for detection of plant stress caused by drought and water scarcity (Piro et al., 2017).

Table 4. Spectral indices, used for assessment of state and functioning of the sunflower hybrids

Spectral Index	Formula	References
NDVI	$NDVI = \frac{\rho NIR - \rho RED}{\rho NIR + \rho RED}$ (1)	Rouse et al., 1974
NDVI705	$NDVI_{705} = \frac{(R_{750} - R_{705})}{(R_{750} + R_{705})}$ (2)	Gitelson & Merzlyak, 1994
NDWI	$NDWI = \frac{\rho NIR - \rho SWIR}{\rho NIR + \rho SWIR}$ (3)	Gao, 1996
MSAVI2	$MSAVI_2 = \frac{2NIR + 1 - \sqrt{(2NIR+1)^2 - 8(NIR-R)}}{2}$ (4)	Qi et al., 1994
MCARI2	$MCARI_2 = \frac{1.5[2.5(\rho_{800} - \rho_{670}) - 1.3(\rho_{800} - \rho_{550})]}{\sqrt{(2\rho_{800}+1)^2 - (6\rho_{800} - 5\sqrt{\rho_{670}}) - 0.5}}$ (5)	Haboudane et al., 2004
MSI	$MSI = \frac{\text{SWIR}}{\text{NIR}}$ (6)	Hunt & Rock, 1989

The MSAVI2 is an adapted version of the Soil-Adjusted Vegetation Index (SAVI), developed to diminish weaknesses of NDVI connected with its inaccuracies when it is applied to areas with a high degree of exposed soil surface (Huete, 1988), such as agricultural lands in the early stages of crop development. This index is particularly effective in areas, which have different soil brightness coefficients (Qi et al., 1994) and hence, an appropriate for examination of the vegetation in agricultural ecosystems.

MCARI2 is a modified version of the Chlorophyll Absorption Ratio Index (CARI), developed for estimation of chlorophyll variation by measuring the depth of chlorophyll absorption at 670 nm in relation to the green reflectance peak at 550 nm and the reflectance 700 nm (Kim et al., 1994). On the basis of CARI, Daughtry et al. (2000) developed its primary improved version – MCARI, and found that it is suitable not only for estimation of chlorophyll variation, but also has a great potential for LAI predictions although no NIR wavelength was considered in its formulation. Taking into account these advantages of the index, by introducing two main changes in MCARI, Haboudane et al. (2004), developed the MCARI2. The first change is the suppression of the ratio (ρ_{700}/ρ_{670}), aiming to decrease the sensitivity to chlorophyll effects and the second one is the integration of NIR wavelength to increase the sensitivity to LAI changes. In order to reduce the soil contamination effects, they incorporated a soil adjustment factor. In result, the derived MCARI2 index is less sensitive to variations in chlorophyll concentration and has a great linear relationship with NIR canopy reflectance, and therefore, a great linearity with green LAI. LAI is a key variable, used for estimation of biophysical processes of crop canopies and for prediction of crop growth and productivity. The exposed area of living leaves has an important role in different biophysical processes such as plant transpiration and CO_2 exchange (Daughtry et al., 2000; Moran et al., 1997). In the context of precision farming, the determination of LAI is crucial for assessment of plants health status and agriculture management purposes.

Water vegetation indices have been found to be very well correlated with various vegetation variables like LAI, standing biomass, Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), and productivity (Sellers, 1987; Tucker, 1980). Such index is the NDWI (Gao, 1996), which capitalizes on the differential response of the NIR and the shortwave infrared (SWIR) reflectance in healthy vegetation. The SWIR reflectance shows both the changes in the moisture content and changes associated with the spongy mesophyll structure in vegetation canopies. The NIR reflectance, in turn, is influenced by leaf internal structure and leaf dry matter content but not by moisture content. The combined use of the both wavebands (NIR and SWIR) eliminate variations, caused by leaf internal structure and leaf dry matter content, enhancing the precision in assessment of the vegetation moisture content (Ceccato et al., 2001). That is the reason the NDWI to be a very good indicator for plant water stress.

MSI is used for canopy water stress analysis, productivity prediction and biophysical modeling. MSI is developed to detect changes in leaf water content on the basis of NIR and SWIR reflection ratio (Hunt & Rock, 1989). As the leaf water content in vegetation canopies increases, the absorption in SWIR region of the electromagnetic spectrum increases with absorption in NIR remaining nearly unaffected by changing water content. Higher values of the index indicate for greater plant water stress and consequently, for less moisture content. In their study, Welikhe et al. (2017) concluded that MSI is sensitive to soil moisture fluctuations, increasing in value with decreases in soil moisture, with strongest correlation at 20 cm soil depth. Hence, in growing season, MSI can be used indirectly in the estimation of soil moisture variation (Table 4).

Tasseled Cap Transformation (TCT), and indices derived after application of TCT

Tasselled Cap model (Kauth & Thomas, 1976) for orthogonalization of satellite images is a highly effective in assessment of processes related to changes in soil, vegetation, and water (Nedkov, 2017a). In orthogonalization, three differentiable classes (soil brightness, greenness, and wetness axes), strongly sensitive to small changes in vegetation process are obtained. This enables more precise classification and monitoring of current condition of the soil and vegetation components of the land surface. Brightness component is based on the spectral reflectance characteristics (SRC) of non-vegetated areas. Greenness component is defined by the signature of photosynthetically-active vegetation, and wetness – by the signature of moisture content. SRC are determined by the momentary condition of the studied object (cell structure and water/chlorophyll content). Minimal changes in condition of a given component do not significantly affect SRC and their assessment with commonly used vegetation indices is difficult (Nedkov, 2017b). These advantages of TCT are most noticeable in studying restoration processes (processes following stress events such as droughts, wildfire, etc.) and upon initiation of the vegetation process (Nedkov, 2017b).

In present study, two indices, based on the greenness and wetness TCT components are used. The NDGI estimates quantitatively the slight positive and negative values of change in the vegetation green mass for a given time period. NDGI ranges from +1 to −1, as NDGI < 0 indicates a

Table 5. Spectral indices, based on TCT and used for remote determination of phenological timing (Nedkov, 2017a,b)

Formula for calculation of an index	Formula for calculation of an index variable	Description
$NDGI = \frac{GR_n(t_2) - GR_n(t_1)}{\lvert GR_n(t_2)\rvert + \lvert GR_n(t_1)\rvert}$	$GR_n(t) = \frac{GR(t) - E\{GR(t)\}}{St.Dev.[GR(t)]}$	$GR_n(t_1)$ and $GR_n(t_2)$ are the normalized values of the Greenness component at time points t_1 and t_2; $\lvert GR_n(t_1)\rvert$ and $\lvert GR_n(t_2)\rvert$ are the absolute values of the same component; $E\{GR_n(t)\}$ is the mean of $GR(t)$.
$NDWNI = \frac{W_n(t_2) - W_n(t_1)}{\lvert W_n(t_2)\rvert + \lvert W_n(t_1)\rvert}$	$W_n(t) = \frac{W(t) - E\{W(t)\}}{St.Dev.[W(t)]}$,	$W_n(t_1)$ and $W_n(t_2)$ are the normalized values of the Wetness component at time points t_1 and t_2; $\lvert W_n(t_1)\rvert$ and $\lvert W_n(t_2)\rvert$ are the absolute values of the same component; $E\{W_n(t)\}$ is the mean of $W(t)$.

negative change, and NDGI > 0 indicates a positive change (Nedkov, 2017b).

NDWNI is based on the wetness component of TCT and identify the small changes, occurring in the agroecosystems in relation to moisture content. Similar to NDGI, NDWNI ranges from +1 to −1 and indicates the positive and negative changes in moisture content for a given time period. The formulas for calculation of both indices NDGI (Nedkov, 2017b) and NDWNI are shown in Table 5.

Results

The differences between sowing dates (28 March – 03 April 2019 and 10 – 16 April 2020) affect timing of phenophases and create differences between hybrids, which influence their spectral reflectance. This is especially noticeable in the initial growth stages, when the ratio between the spectral reflectance of bare soil and those of recently sprouted crops is still high. In the later growth stages, these differences in spectral reflectance are significantly reduced. Taking this into account, flowering and post-flowering growth stages are with priority in the analysis of the results.

Determination of timing of different growth stages

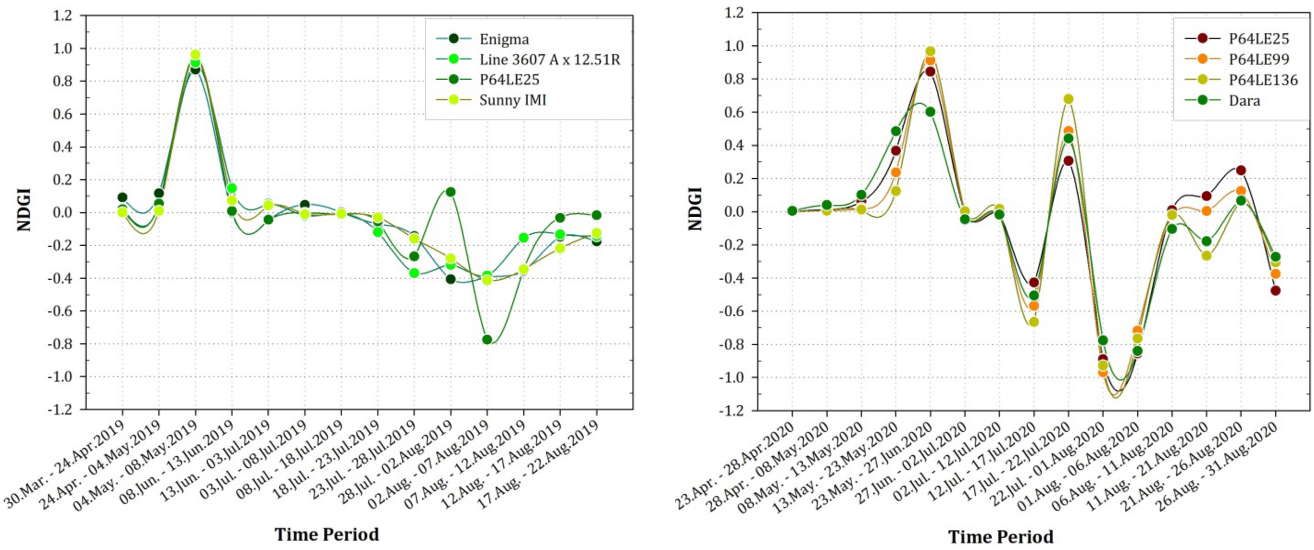
NDGI and NDWNI indices are used for remote determination of timing of critical growth stages (inflorescence emergence, flowering, development of fruit, and ripening stages). The accuracy of remote determination is verified trough field observations. The values of the indices are indicative for the phenological development of the predominant part of the crops, not of individual plants, which could be in more advanced or earlier stage of development. The indices show the dynamics in the greenness and wetness components of TCT and respectively can also be used for tracking the health status and dynamics of moisture content in the crops by certain periods. These periods encompass two consecutive satellite images, called “couples” in the present research. Their duration vary depending on the acquisition date of the satellite images.

Maximum in NDGI marks the end of inflorescence emergence/beginning of flowering stage and corresponds to the peak of intensive growth of the plants. Beginning of development of fruit stage is recorded by a sharp decline in NDGI after the peak in flowering. Maximum in NDWNI corresponds to the higher growth of moisture content early in grain filling, when the maximum grain volume is observed (Rondanini et al., 2009). The beginning of ripening is marked by the minimum in NDWNI and NDGI values, when the sunflower canopy start to senesce faster and the area of the leaf mass decreases sharply (de la Vega et al., 2011), affecting negatively the moisture content in the plants (Figures 4 and5). Undoubtedly, these properties of the two indices facilitate largely determination of timing of listed growth stages and monitoring the development of crops during the course of the stages. However, there are also some limitations related to the variability of the time period between two applicable satellite images, forming a couple. In the optimal scenario, this period lasts several days (5 days) when using Sentinel- 2 images, but there are periods of prolonged cloudiness (spring and early summer for growing season of sunflower in Bulgaria), during which the available images are practically unusable as the TCT involves the all 13 spectral bands of Sentinel 2, including the optical ones. Such situations additionally “dissolves the scissors” when calculating the indices, hindering the accurate determination of timing of the growth stages. The long period of time between two images, forming a couple in calculating the NDGI, for instance, obscures the maximum caused by the intensive growth in inflorescence emergence stage, which merges with the other phases of plant growth until entering the flowering stage. Unfortunately, this circumstances are valid for the both preflowering periods, studied in the present research (Figure 4). The higher the frequency of the applicable for TCT satellite images, the greater the accuracy in determination of timing of the growth stages.

The highest NDGI values, for both years, are observed in the spring and early in the summer (04 May – 08 June 2019 and 23 May – 27 June 2020) in the inflorescence emergence/beginning of flowering stages (Figure 4, Table 3). The inflorescence emergence stage is a period of intensive growth of the constituent parts of the inflorescence and of the vegetative organs – stem, leaves, and root system. Three of the studied hybrids in 2020 (the foreign hybrids) are with NDGI values between 0.84 and 0.97 in the flowering stage. The highest growth in green mass is in P64LE136, followed by P64LE99 and P64LE25. The NDGI average value for the domestic hybrid Dara is 0.6. Similar to the values for the foreign hybrids are the NDGI values in 2019, when all studied hybrids have NDGI average values between 0.87 and 0.96 during the anthesis. The increase of NDGI values is followed by a period of relative stability, lasting to the beginning of development of fruit stage, when the NDGI decrease to negative values. In the early growth stages, the high concentration of chlorophyll in the receptacle tissues is directly associated with the green color (Hernández et al., 2008). As maturity advances, chlorophyll in green organs degrades (Sexton & Woolhouse, 1985) and the predominance of xanthophylls and other carotenoid pigments causes color change from green to yellow (Sinecker et al., 2002). In sunflower crops this color change starts about 30 days after the first anthesis with maturation of the sunflower fruits and is influenced by the moisture content in plant tissues (Hernandez & Larsen, 2013).

However, in the same growth stage, early in grain filling, a sharp increase in NDWNI is observed. This increase is related to the timing of maximum grain volume, occurring about 10–12 days after the end of anthesis (Rondanini et al., 2009), just when the above mentioned rise in the NDWNI for the both years is observed (Figure 5). In 2019, the increase in the NDWNI values, induced by the grain filling is weaker (between 0.14 and 0.29 for the different hybrids) (Figure 5a). In the same growing season, the Sunny IMI enters the development of fruit stage a little later (5-6 days) than the other hybrids, which is marked by NDWNI average value for the field of 0.14 (Figure 5a). In growing season 2020, the increase in moisture content in grains in the beginning development of fruit stage (12 July – 17 July) is more significant than in 2019 and varies between 0.5 and 0.88 for the different sunflower hybrids (Figure 5b). In 2020, higher NDWNI values are observed also in the subsequent period (17 – 22 July 2020). This increase is accompanied by an increase in NDGI too (Figures 5b, 4b). Similar increase in NDGI is observed in the end of development of fruit / beginning of ripening stage in 2019 (28 July – 02 August 2019), but only for P64LE25. The values of the observed increase in NDGI are quite different in both years. The average NDGI value of P64LE25 in 2019 is just 0.12 and the change does not affect the NDWNI values (Figure 4a, 5a), whereas in 2020 the average NDGI value for the same hybrid (P64LE25) is 0.31 (Figure 4b). The NDGI values for the other hybrids are between 0.44 and 0.68.

The highest increase is observed in P64LE136, followed by P64LE99 and Dara (Figure 4b). The observed increase in NDGI in the both years is accompanied by significant precipitations – 30 mm in 2019 and 27 mm in 2020 (the data is not shown) and probably is associated with a genetic trait (e.g. stay green) of the studied hybrids. However, it should be noticed that in 2020, the depicted increase in NDGI occurs earlier in the vegetative growth (17 – 22 July 2020) than in 2019, when the plants have not yet begun to senescence.



a) **b)**

Fig. 4. NDGI values of the studied sunflower hybrids in growing season 2019 (a) and 2020 (b)

In 2019, the fallen precipitation affects the P64LE25 field in the beginning of ripening stage (Figure 4).

A sharp decline in both NDGI and NDWNI follows when crops enter ripening stage (28 July – 02 August 2019 and 22 July – 01 August 2020) (Figures 4, 5; Table 3). In the ripening stage, the manifestation of the indices for both years is different. In 2019, a gradual decline in NDGI, started after the peak in inflorescence emergence stage is observed. The sunflower hybrids reach NDGI minimum around the beginning of ripening stage (NDGI values between -0.38 and -0.77 for different hybrids). The decline of the greenness component of TCT continues till the end of the growing season (Figure 4a). In 2020, when entering ripening stage, the decrease in NDGI reaches values between -0.97 and -0.84 for the different hybrids. In contrast to 2019, a stabilization of the NDGI and a slight increase in the period 21 – 26 August 2020 is observed (Figure 4b). This increase is related to growth of invasive weeds (see Discussion section).

The process of entering the ripening growth stage is also confirmed by the minimum in NDWNI values. In season 2019, the NDWNI minimum vary between -0.08 and -0.27 for the different hybrids. In 2020, the minimum in NDWNI values is more pronounced and vary between -0.95 and -0.66 (Figure 5).

Vegetation indices dynamics and differentiation of the health status of the individual sunflower hybrids

The highest values of vegetation indices are observed in the flowering stage. After entering the development of fruit growth stage, the indices values decrease. Lowest indices values are observed in the beginning of crop development, when the proportion of leaves area, compared to those of bare soil is smaller. The opposite is the tendency only for the MSI, which evaluate the moisture stress in the agroecosystems. Each of the indices reflects specific features in the behavior of the individual sunflower hybrids during the growing season and indicates for their health and water status.

In terms of NDVI, there are no significant differences between the average values of the sunflower hybrids in both years. In the beginning of vegetative growth in season 2019, highest NDVI values have Enigma and P64LE25, followed by Line 3607 A x 12.51R and Sunny IMI (Figure 6a). In 2020, Dara occupies the leading position since the beginning of vegetative growth, followed by P64LE25, P64LE99, and P64LE136 (Figure 6b). The maximum NDVI values are observed in the beginning of flowering stage. An exception is only Sunny IMI in 2019, which records its maximum in the end of the flowering stage (Figures 6a, 6b). Comparing the both seasons, the differences between the NDVI average values are not significant during and after the flowering stage. More considerable differences are observed during the development of fruit stage and between the individual sunflower hybrids (Table 6). Larger differences between the hybrids and also between their states in the individual growth stages are observed in 2020. On the contrary, in 2019, the hybrids steadily follow the dynamics established still in the initial stages of development (Figures 6a, 6b). This ten-

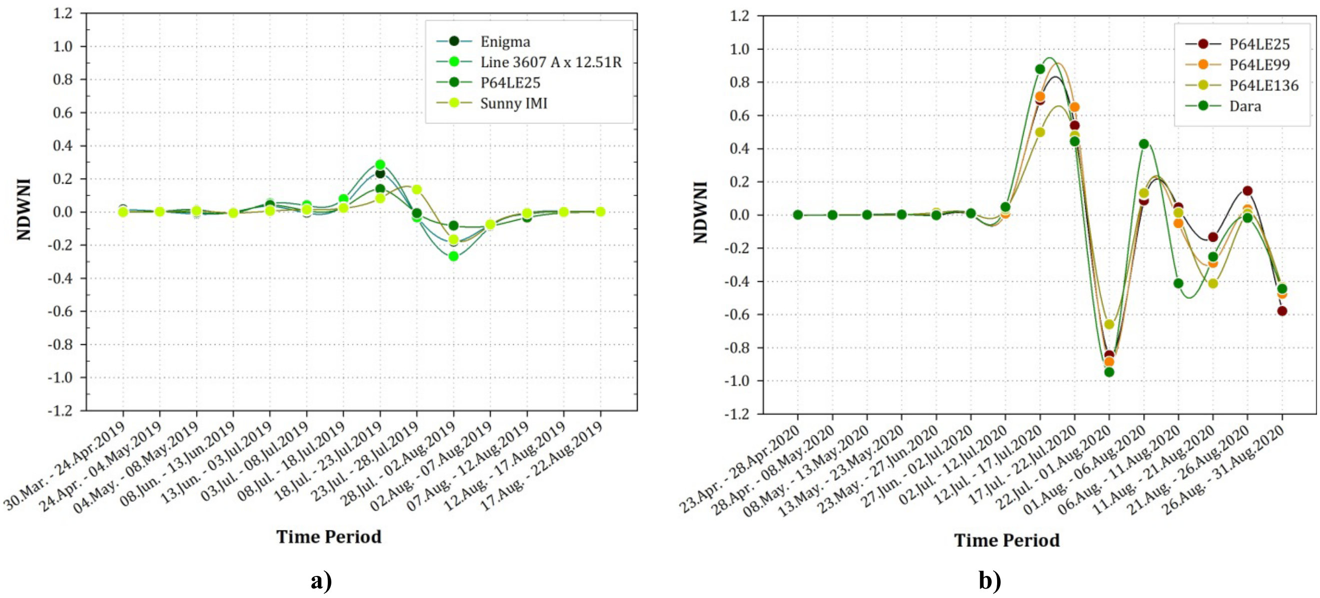
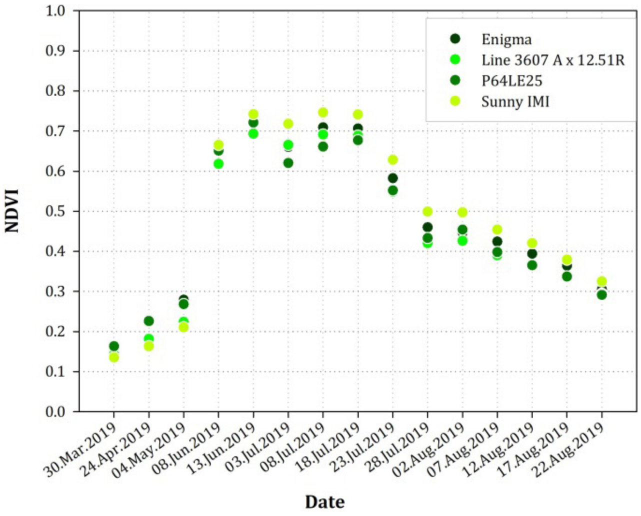


Fig. 5. NDWNI values of the studied sunflower hybrids in growing season 2019 (a) and 2020 (b)

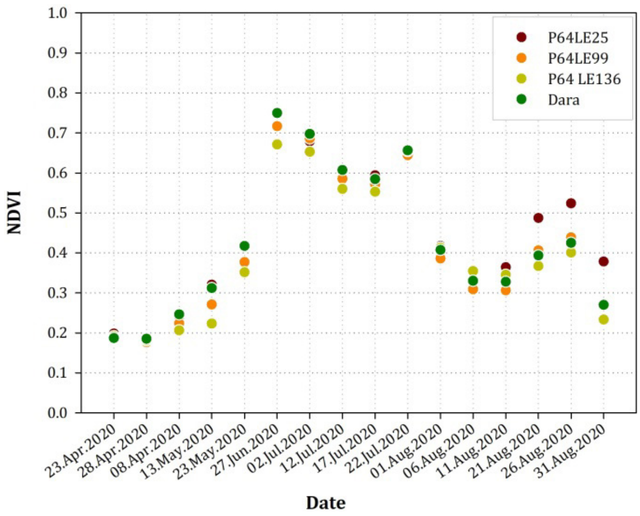
dency can be found in all of the calculated indices (Table 6). In 2019, after entering the development of fruit stage, the NDVI values start to decrease, whereas in 2020, the expected tendency of decrease is interrupted by a slight growth in the end of the stage and re-growth at the end of the season. Similar tendency show also the other vegetation indices (Figures 6 – 9). The first growth in the development of fruit stage is most probably related to the precipitation events described above and the regrowth after that, with the presence of weed vegetation (see Discussion section). The hybrids in development of fruit stage in season 2020 are distinguished with higher NDVI values (Table 6). An exception is Sunny IMI (2019), characterized with the highest NDVI among the studied hybrids in the both seasons. In growing season 2020, the highest NDVI values in flowering and development of fruit stages has Dara, followed by P64LE25. In the ripening stage, due to the presence of weeds that influence the NDVI after the withering of the sunflower, the values reported for the P64LE25 field significantly exceed those of Dara (Figure 6b). Similar NDVI values to those of P64LE25 in flowering and development of fruit stages has P64LE99. In this hybrid, however, a weaker increase in NDVI values during the ripening stage is observed. The lowest NDVI in 2020 have P64LE136 (Figure 6b).

In terms of NDVI705, the average values of sunflower crops are more diverse than those of NDVI, comparing the 2019 and 2020 growing seasons. The differences are clearly noticeable in flowering and development of fruit growth stages. The NDVI705 values between the individual hybrids are closer than the NDVI values (Figure 7a,7b; Table 6). In the beginning of vegetative growth of 2019 season, Enigma and P64LE25 are distinguished with higher values, followed by Line 3607 A x 12.51R and Sunny IMI. In the last two hybrids, there is a slight delay in reaching the maximum of NDVI705 (03 July 2019) in the beginning of flowering, related to the later sowing. In the other two hybrids, the NDVI705 maximum is noted on 13 June 2019 (Figure 7a.). As regards 2019 season, the trend in differences between the individual hybrids in flowering and post-flowering growth stages is steadier and continues till the end of the season (Table 6). In the beginning of vegetative growth of 2020 season, highest NDVI705 has P64LE25, followed by Dara, P64LE99, and P64LE136. Slight differences are observed during the flowering stage, with leading position for Dara, but in the following growth stages, these differences are minimized (Figure 7b, Table 6). Due to the presence of weeds, the higher values of P64LE25 in the ripening stage stand out (Figure 7b, Table 6).

Comparing the two growing seasons, MSAVI2 also shows larger differences in the average values for all sunflower hybrids in favor of 2020 (Table 6). In the beginning of vegetative growth, the dynamics shown by the individual hybrids is similar to those of NDVI705. In general, MSAVI2 is distinguished with more significant differences in development of fruit stage when compare the both studied seasons. The MSAVI2 values in season 2019 are stable in relation to the established trend. In 2020, greater dynamics between the individual hybrids is shown in flowering stage, when Dara



a)



b)

Fig. 6. NDVI values of the studied sunflower hybrids in growing season 2019 (a) and 2020 (b)

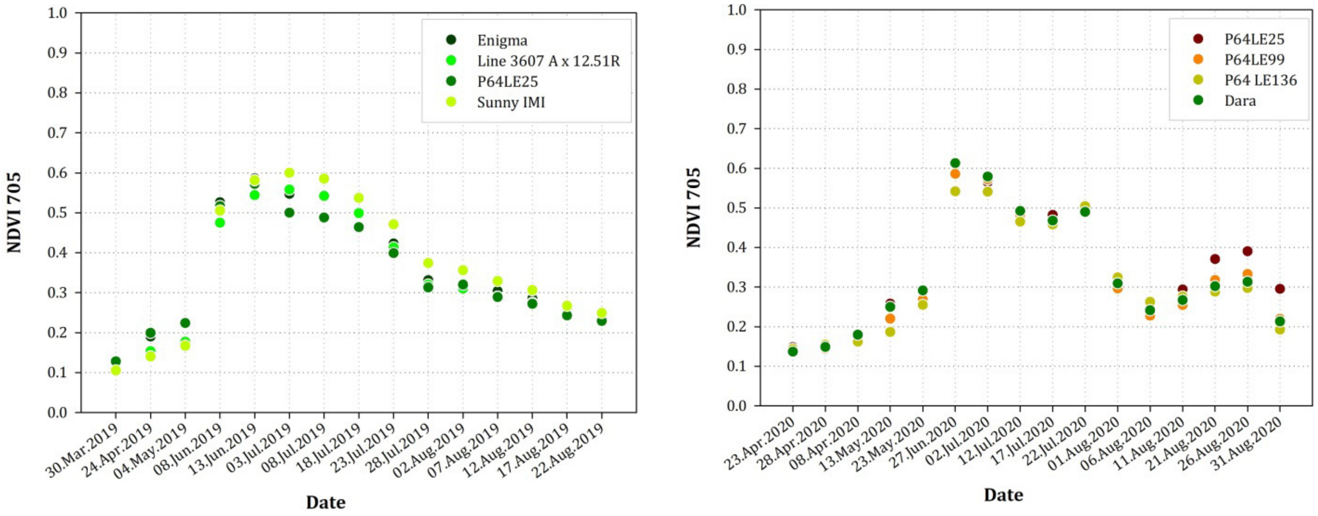
Table 6. Spectral indices values of the studied sunflower hybrids in the individual growth stages of growing seasons 2019 and 2020

Growth season 2019	Flowering	Development of fruit	Ripening	Average
NDVI average	0.70	0.57	0.40	0.56
Enigma	0.70	0.58	0.41	0.56
Line 3607 A x 12.51R	0.68	0.55	0.38	0.54
P64LE25	0.67	0.53	0.37	0.52
Sunny IMI	0.74	0.62	0.44	0.60
NDVI 705 average	0.55	0.42	0.29	0.42
Enigma	0.56	0.42	0.29	0.42
Line 3607 A x 12.51R	0.55	0.41	0.28	0.41
P64LE25	0.52	0.37	0.27	0.39
Sunny IMI	0.59	0.46	0.32	0.46
MSAVI2 average	0.81	0.71	0.56	0.69
Enigma	0.82	0.73	0.57	0.70
Line 3607 A x 12.51R	0.81	0.70	0.54	0.68
P64LE25	0.80	0.68	0.53	0.67
Sunny	0.84	0.75	0.60	0.73
MCARI 2 average	0.81	0.73	0.55	0.70
Enigma	0.81	0.75	0.56	0.71
Linia	0.80	0.71	0.52	0.68
P64LE25	0.80	0.71	0.51	0.67
Sunny IMI	0.84	0.77	0.60	0.74
NDWI average	0.28	0.19	-0.06	0.14
Enigma	0.28	0.19	-0.04	0.14
Line 3607 A x 12.51R	0.26	0.18	-0.07	0.13
P64LE25	0.24	0.13	-0.08	0.10
Sunny IMI	0.33	0.26	-0.03	0.19
MSI average	0.57	0.70	1.13	0.80
Enigma	0.57	0.70	1.11	0.79
Line 3607 A x 12.51R	0.59	0.71	1.17	0.82
P64LE25	0.62	0.78	1.19	0.87
Sunny IMI	0.50	0.60	1.07	0.72

Growth season 2020	Flowering	Development of fruit	Ripening	Average
NDVI average	0.70	0.60	0.39	0.56
P64LE25	0.70	0.61	0.43	0.58
P64LE99	0.70	0.60	0.37	0.56
P64LE136	0.66	0.59	0.38	0.54
Dara	0.72	0.62	0.38	0.57
NDVI 705 average	0.57	0.48	0.30	0.45
P64LE25	0.58	0.49	0.33	0.46
P64LE99	0.58	0.48	0.29	0.45
P64LE136	0.54	0.48	0.29	0.44
Dara	0.60	0.48	0.29	0.46
MSAVI2 average	0.82	0.75	0.55	0.71
P64LE25	0.82	0.76	0.60	0.73
P64LE99	0.81	0.74	0.53	0.70
P64LE136	0.80	0.74	0.54	0.69
Dara	0.84	0.76	0.54	0.71
MCARI2 average	0.81	0.76	0.54	0.70
P64LE25	0.82	0.77	0.60	0.73
P64LE99	0.80	0.75	0.52	0.69
P163	0.79	0.74	0.52	0.68
Dara	0.84	0.78	0.53	0.71
NDWI average	0.26	0.21	-0.05	0.14
P64LE25	0.27	0.21	-0.02	0.15
P64LE99	0.27	0.21	-0.06	0.14
P64LE136	0.22	0.19	-0.06	0.12
Dara	0.30	0.23	-0.05	0.16
MSI average	0.59	0.66	1.11	0.79
P64LE25	0.58	0.66	1.05	0.76
P64LE99	0.57	0.66	1.14	0.79
P64LE136	0.65	0.69	1.14	0.82
Dara	0.54	0.63	1.12	0.76

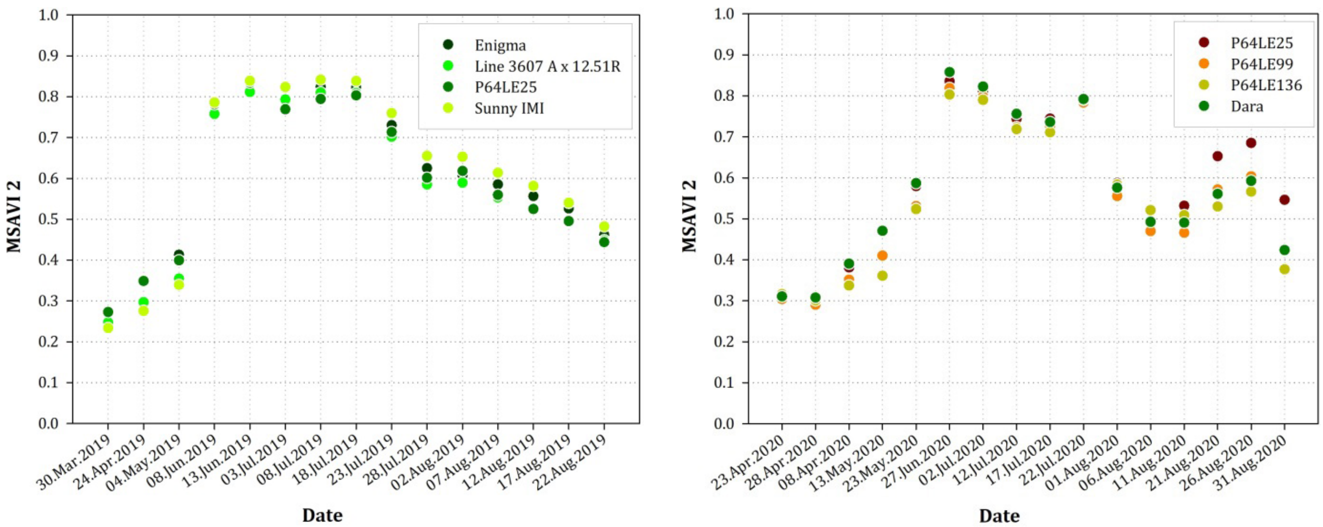
has the highest MSAVI2, followed by P64LE25, P64LE99, and P64LE136 (Table 6). The differences between Dara and P64LE25, as well those between P64LE99 and P64LE136 are minimized during the development of fruit stage (Table 6). Most of the studied hybrids reached the maximum of MSAVI2 in the beginning of flowering (Figure 8a,b). Exception is only Sunny IMI (2019) that reached the maximum in the end of the stage (Figure 8a). However, the maximum MSAVI2 values of Sunny IMI do not differ significantly from those, recorded in the beginning of the flowering. After development of fruit stage, till the end of growing period, the tendency in the functioning of the studied sunflower hybrids remains generally the same (Figure 8a, b).

In relation to MCARI2, the sunflower hybrids show similar to MSAVI2 dynamics. There is a slight difference between the indices, referring the individual hybrids, and



a) **b)**

Fig. 7. NDVI705 values of the studied sunflower hybrids in growing season 2019 (a) and 2020 (b)



a) **b)**

Fig. 8. MSAVI2 values of the studied sunflower hybrids in growing season 2019 (a) and 2020 (b)

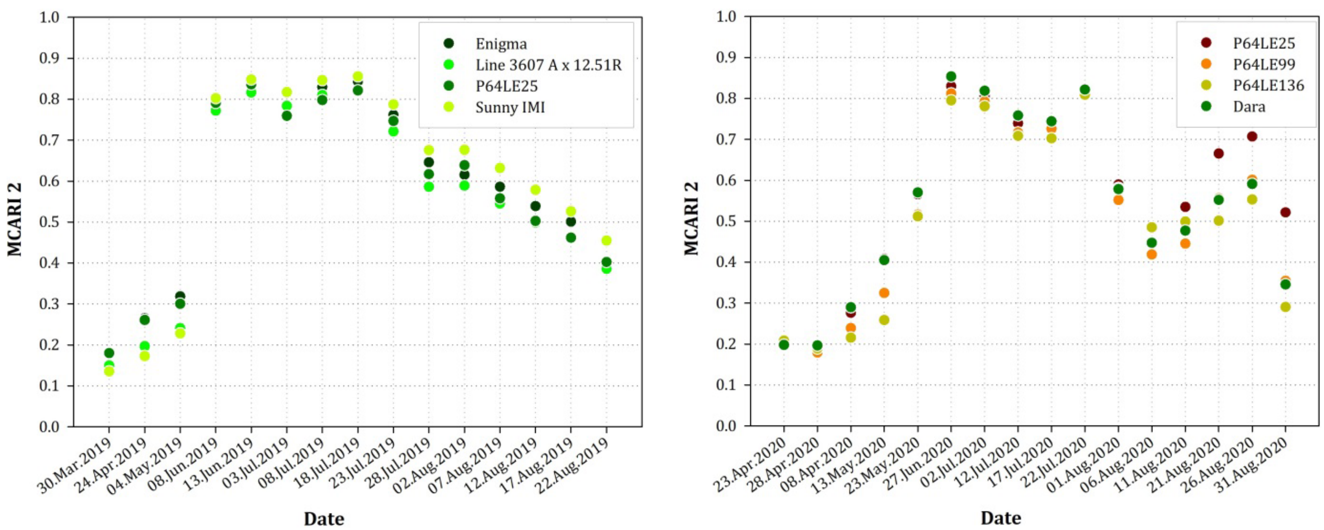
the timing of MCARI2 maximum. In season 2019, Enigma and Sunny IMI record their maximum MCARI2 when entering the development of fruit stage, whereas P64LE25 and Line 3607 A x 12.51R reaches the maximum $MCARI_2$ value in the beginning of the flowering stage (Figure 9a). In season 2020, P64LE25, P64LE99, and Dara reach the maximum in the beginning of flowering stage, whereas P64LE136 – in the end of the development of fruit stage (Figure 9b). Nevertheless, the values in the beginning of flowering and those in the development of fruit stage for both seasons are close (Figure 9a, b). The MCARI2 show clear tendency to minimization of the differences between Line 3607 A x 12.51R and P64LE25 with the progress of season 2019. Similar tendency is observed for all studied indices (Figure 9a, Table 6).

Water indices dynamics and differentiation of the water status of the individual sunflower hybrids

NDWI and MSI are the indices, proposed for monitoring of vegetation liquid water and plant stress, caused by drought and water scarcity.

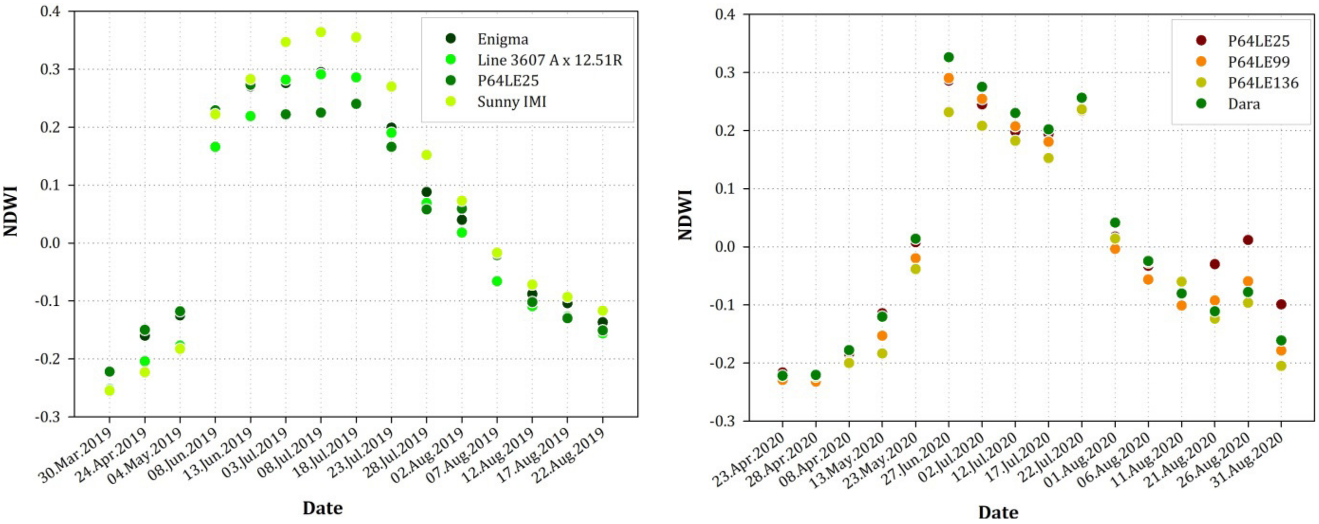
Water content in the agroecosystems, indirectly represented by the NDWI is highest in the flowering stage. Highest NDWI in season 2019 has Sunny IMI, followed by Enigma, Line 3607 A x 12.51R, and P64LE25. The maximum NDWI of P64LE25 is recorded in the beginning of the flowering stage, whereas for the other three hybrids, the maximum is observed in the end of the flowering stage (Figure 10a). In season 2020, the highest NDWI is observed in the beginning of flowering for all of the studied hybrids (Figure 10b). In the early stages of development and in the ripening stages, the NDWI values are negative (Figures 10a, 10b). In the flowering of season 2019, the values are slightly higher and the shown dynamics is similar to those of the vegetation indices (Table 6). In season 2020, Dara is distinguished with the highest NDWI, followed by P64LE25, P64LE99, and P64LE136 (Figure 10b, Table 6).

Similar to NDWI, higher degrees of moisture stress (MSI > 1), are observed in the early stages of development and during the ripening (Figure 11a, b). This is related to the smaller proportion of leaves area, compared to those of bare soil and respectively to lower water retention capacity of the agroecosystems. Comparing both seasons, a slightly higher moisture stress is observed during the flowering in season 2020 (Table 6), reflecting the lack of precipitation and the short-term drought stress in the agroecosystems (Table 2). On the other hand, the stress during the development of fruit stage is lower than in 2019 (Table 6), despite the similarity in the climatic conditions (Table 2). Flowering is the growth stage with the lowest MSI values (Figure 11a, b; Table 6). Unlike to NDWI, MSI shows higher dynamics in the flowering stage of season 2020. Dara is distinguished with the lowest moisture stress, followed by P64LE99, P64LE25, and P64LE136 (Table 6). In the development of fruit stage, the MSI average value of P64LE25 is the same as those of P64LE99 (Table 6, Figure 11b). The lower MSI values of



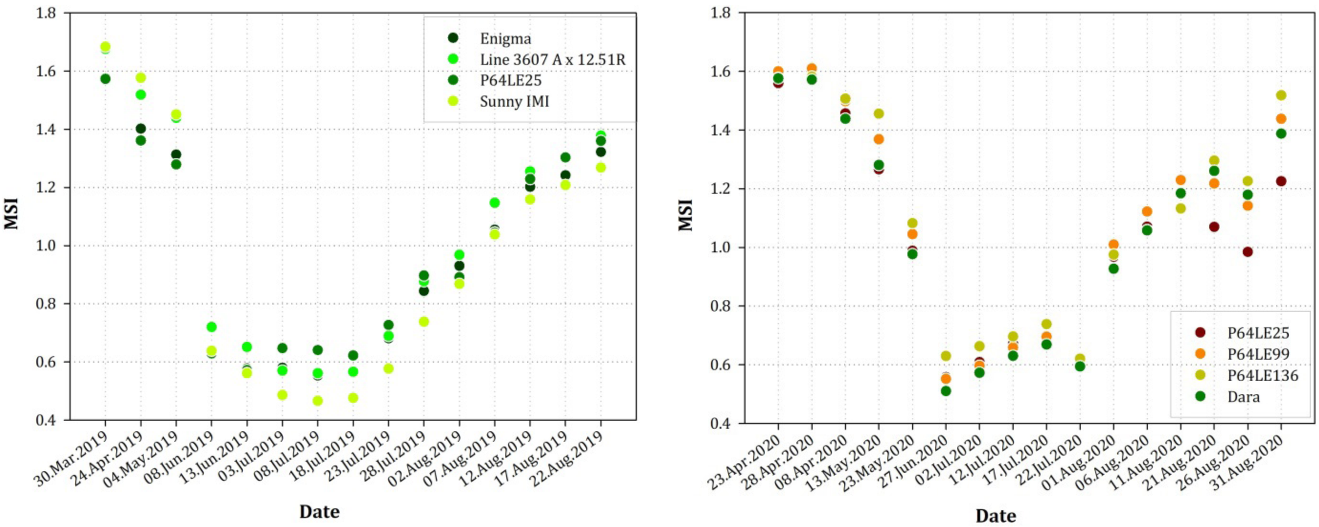
a) b)

Fig. 9. MCARI2 values of the studied sunflower hybrids in growing season 2019 (a) and 2020 (b)



a) **b)**

Fig. 10. NDWI values of the studied sunflower hybrids in growing season 2019 (a) and 2020 (b)



a) **b)**

Fig. 11. MSI values of the studied sunflower hybrids in growing season 2019 (a) and 2020 (b)

P64LE25 in the ripening stage of season 2020 are influenced by the presence of weed vegetation (Table 6, Figure 11b).

Discussion

The spectral reflectance of the individual sunflower hybrids can be affected by various natural and man-made factors such as environment and climate, phenological characteristics, genetic modifications, and agrotechnical activities.

The present research is not a coordinated experiment. It is performed in real conditions, which may occur in any farm. The advantage of this approach is that it allows to identify real problems that remote sensing methods face when offering services to support management decisions in agriculture, but this additionally complicates the interpretation of the results. Different factors affected the spectral reflectance of studied hybrids during both growing seasons and they consistently will be addressed.

The first factor is related to the limited manpower and problems with agricultural machinery at the time of the experiment. This factor slows down the process of cultivation of the land and the sowing of the individual fields, as well as, the subsequent agricultural activities. The individual fields are sowed in the period 28 March – 03 April in season 2019. In 2020, the sowing is delayed about two weeks and is performed in the period between 10 April and 16 April. Later sowing in 2020 predetermines warmer conditions of crop development at the beginning of the vegetative growth. There is a shift in time of the individual growth stages and shortening of their duration. Different time of sowing also has impact on the individual hybrids in entering the individual growth stages. These factors inevitably affect the spectral reflectance characteristics of the studied agricultural fields, which is particularly evident in the leaf development stage, when the ratio between the bare soil and vegetation decreases earlier in time in those hybrids that are sown earlier. The differences of this nature are clearly shown by the dynamics of MSAVI2 and MCARI2 in the beginning of vegetative growth in the both seasons (Figures 8a,8b,9a,9b). With the progress of vegetative growth, the impact of the different sowing dates on the spectral reflectance characteristics of the fields is more clearly visible in growing season 2019 and particularly in the NDVI705 values. The NDVI705 values of two of the sunflower hybrids (Line 3607 A x 12.51R and Sunny IMI) show lower values from the earliest date of satellite observation (Figure 7a). These hybrids are distinguished also with later maximum in flowering stage. Apart from the other factors, and provided that all hybrids are characterized with similar duration of growing period, different time of sowing is expected to lead to a later start of the next stages of development.

All of the studied sunflower hybrids in season 2019 are mid-early hybrids and the length of their growing period is about 120 days. The later entering in the next stages of development, determined by the later sowing should result in gradual increase of indices values and a slight delay in reaching their maximum (as in NDVI705) (Figure 7a) and subsequently to a slower decline of the values. Such slower decline in indices values in 2019 is observed only in Sunny IMI and it continues till the later stages of development, even in the ripening stage (Figures 6a – 9a). Unlike the indices values of Sunny IMI, the values of Line 3607 A x 12.51R aligns with those of the earlier sown hybrids even during the anthesis (Figures 6a – 9a). This indicates that in the manifestation of the indices from flowering onwards, other factors such as climate resilience and genetic modifications (e.g. stay-green trait) already have a more significant role. The stay-green trait provides longer preservation of green mass in plants, increasing their capacity to uptake water from the soil for a longer time, even in grain filling phase, when the root systems senesce. There is a clear evidence of correlation between the live root length density and LAI (Lisanti et al., 2012).

The delayed leaf senescence during the grain filling phase slows down the loss of post-anthesis canopy LAI. Stay-green hybrids distinguish with higher LAI at physiological maturity as percentage of LAI at anthesis (de la Vega et al., 2011). The stay-green trait increase the length of the period with higher indices values, which by themselves reflect higher photosynthetic activity, higher LAI, and better functioning of the crops (Figures 6a – 9a, 6b – 9b). In these hybrids, higher indices values are reported when entering the ripening stage. Especially noticeable is the effect of genetic modifications in the manifestation of MCARI2 that shows a great linear relationship with green LAI. The sunflower hybrids with delayed MCARI2 maximum are characterized with slower decrease of indices values. Such hybrids are Sunny IMI and to lesser extent Enigma in 2019 and P25LE136 in 2020 (Figure 9a, b).

The impact of the different ecological conditions and the specifics of genetic improvements on the state and functioning of the sunflower hybrids in the separate growth stages can be assessed through the differences in the indices values. During the autumn-winter period of 2020, a larger amount of precipitation falls (184.3 mm), which result in a greater moisture store in the soil in pre-sowing period. For comparison, during the same period in 2019, the precipitation sum is 101 mm (data is not shown). This tendency is observed also in the months exactly prior the sowing. In March 2020, the fallen precipitations are 70 mm (Figure 2), whereas the precipitation sum in both months February and March 2019 is 34 mm (data is not shown). The more favorable conditions in pre-sowing and in the sowing period facilitate tillage and sowing process, contributing for germination of a greater number of seeds than those sown in 2019, when the drought leads to soil compaction. Despite the drier conditions and shorter duration of flowering stage in 2020, the greater number of well-developed sunflower plants impact the performance of sunflower crops during the grain filling stage.

The observed increase in NDWNI in 2020 (12 – 17 July), related with the increase in moisture content of seeds in grain filling stage , range between 50% and 88% for the individual fields (Figure 5b), while in 2019 (18 – 28 July), the increase of NDWNI is between 14% and 29% (Figure 5a.).The later period of flowering in 2020 and the lack of precipitation during it result in lower values of NDWN in this stage and slightly more pronounced water stress, affecting the MSI (Figure 11b). During the development of fruit stage, the environmental conditions in both years are similar, even slightly wetter in 2019 (Table 2). Despite that, the sunflower crops show better moisture status in 2020, which is probably related to the increase in grain volume and related moisture content during the grain filling (Figures 5a, 5b, 10a, 10b, 11a, 11b, Table 6).

Due to the higher indices values in development of fruit stage in the wetter 2020 season, the difference, recorded between flowering and development of fruit stages is smaller than those in 2019 season (Table 6). The retention of higher indices values in development of fruit stage indicates for a better health state and functioning of the sunflower hybrids. In season 2020, the smallest difference between the flowering and development of fruit stages in terms of NDVI and NDVI705 is observed in P64LE136 (the hybrid with lowest indices values), whereas in 2019, the smallest difference is observed in Sunny IMI (the hybrid with the highest indices values) (Table 6). Sunny IMI retains this small difference also in the other two vegetation indices (MSAVI2 and MCARI2) (Table 6). The depicted manifestation of the indices indicates for better state and functioning of Sunny IMI, compared to the other hybrids in development of fruit stage and presence of genetic improvements aimed at drought resilience. Despite the more favorable environmental conditions in season 2020, P64LE136 is distinguished with the worst state amongst the studied hybrids from the beginning till the end of vegetative growth. That results in insignificant difference in indices values between the individual growth stages (Table 6).

The differences in MSAVI2 and MCARI2 values between the flowering and fruit development stages for the individual hybrids in 2020 are similar. Exception is only Dara hybrid, characterized with the highest indices values (Table 6). In addition, the differences between flowering stages of both growing seasons are significantly smaller than those between the development of fruit stages (Table 6).

Amongst the water indices, MSI shows larger differences between the development of fruit stages of the both seasons (Table 6). These findings confirm that the more favorable conditions in pre-sowing and sowing periods, as well as in the early stages of development affect to a greater extent the development of fruit stage than the flowering stage. Under similar environmental conditions, during the development of fruit stage, the accumulated soil moisture in the earlier stages of development (2020) predetermines the retention of higher indices values.

As concerns the hybrids, represented in both seasons (P64LE25 and Dara/ Line 3607 A x 12.51R), the observed differences significantly exceed the average values for the sunflower crops in general (Table 6). In P64LE25, the differences in the development of fruit stages between the both seasons are considerably larger than those in the flowering stages. This show also the indices values of Dara, but not to such an extent. In P64LE25, the differences in NDVI705 (0.11) and MSI (0.13) are especially large (Table 6). In the case of hybrid Dara, there is no index, in which the difference between the values to be greater than 0.8 (MSI) (Table 6). Dara is the hybrid with the highest indices values (except MSI) and respectively with optimal health state in 2020 (Table 6). An exception is only ripening stage in 2020, when the weed vegetation incorrectly raises the indices values in the fields. During the same year, P64LE25 is the second hybrid with the highest values (Table 6).

However, in the environmental conditions of growing season 2019, these two hybrids are with the lowest indices

a)

b)

Fig. 12. Weed vegetation (*Cannabis sativa* L.) in the sunflower fields in the inflorescence emergence (22 June 2020) (a) and in the ripening (17 August 2020) (b) growth stages

values among the studied hybrids (Table 6). Hence, these two hybrids show unsatisfactory values of the studied indicies under more pronounced soil drought during sowing and less rainfalls in early stages of development (such as in 2019). The differences for the both hybrids between the flowering and development of fruit stages are larger in 2019. Especially noticeable are the differences for the water indices. Comparing the MSI for P64LE25 and Line 3607 A x 12.51R, the stress, caused by water deficiency during the flowering stage is greater in P64LE25 and increases to a greater extent in development of fruit stage (Table 6). Under the more favorable conditions in 2020, greater differences are observed in the vegetation indices than in the water ones, and Dara again is with the higher indices values (Table 6).

Another factor, affecting the spectral reflectance characteristics of the studied fields is the presence of aggressive weed vegetation (*Cannabis sativa* L.), which distinguishes with its own phenological development, influencing the indices values. Most pronounced is that effect in the ripening stage of sunflower phenological development (Figure 12).

Industrial hemp (*Cannabis sativa* L.) has been grown in Bulgaria in the past (before 1989). The seeds of this plant are very persistent and can remain in the soil for years, until favorable conditions for their germination arise. In addition to residual seeds in the farmlands used for industrial hemp cultivation, its distribution has been facilitated by the widespread use of irrigation systems. Control measures to remove unwanted vegetation are taken every growing season in Northwestern Bulgaria, where the fields, object of the study are located. The measures include application of the herbicides and hoeing. Commercially available herbicides, however, are not effective enough against the industrial hemp and despite the weed control measures, every season in the fields with spring crops grows this unwanted vegetation. In the wetter and warmer growing seasons, the industrial hemp develops to a greater extent than in the dry ones. The vegetative development of industrial hemp is longer than those of sunflower and lasts about 160 days. Industrial hemp is in a phase of intensive growth and flowering about 120 days after germination, when sunflower is in ripening stage, shortly before the harvest. In 2020, the industrial hemp is in flowering stage around 20 August. At this time, there is an increase in the indices values, including NDGI and to a lesser extent of NDWNI (Figures 4b, 5b).

The growing season 2020 is distinguished with more favorable conditions for industrial hemp development than 2019. Due to the drier conditions in growing season 2019, including at the time of pre-planting operations and sowing of the sunflower crops, the industrial hemp has not developed very well. The drought during the pre-planting operations in 2019 makes plowing and soil cultivation more difficult and thus hinders the hemp seeds to be brought to the surface and to germinate. In 2019, the flowering of the industrial hemp is in the beginning of August, when a noticeable increase in NDGI of P64LE25 is observed (Figure 4a). The increase in the values of the other vegetation indices is almost imperceptible. The indices, which are sensitive to variations in water content (NDWI, MSI, and NDWNI), do not record this change in 2019 (Figures 5a, 10a, 11a).

Conclusion

Despite factors such as environment and climate, phenological characteristics, genetic modifications, and agrotechnical activities, which affect the spectral reflectance characteristics of the studied fields and complicate interpretation of the obtained results, the methodology is distinguished with sufficient efficiency for monitoring of phenological development of sunflower hybrids and determination of their state. The proposed methodology and obtained results can be used for development of predictable models in agriculture, which to be implemented in operational monitoring systems for practical use.

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References

Ali, Md. H. & Shui, L. T. (2009). Potential evapotranspiration model for Muda Irrigation Project, Malaysia. *Water Resour. Manage, 23*, 57-69.

Avetisyan, D., Nedkov, R., Borisova, D. & Cvetanova, G. (2019). Application of spectral indices and spectral transformation methods for assessment of winter wheat state and functioning. In: *Proc. SPIE 11149, Remote Sensing for Agriculture, Ecosystems, and Hydrology, XXI, 1114929* ,doi: 10.1117/12.2538117.

Baychev, V. & Mihova, G. (2014). Variations in the production potential of barley and triticale under contrasting conditions of the environment. *Scientific Works of the Institute of Agriculture – Karnobat, 3(1),* 107-120, (Bg).

Beyazgul, M., Kayam, Y. & Engelsman, F. (2000). Estimation methods for crop water requirements in the Gediz Basin of western Turkey. *Journal of Hydrology, 229*, 19-26.

Bouranis, D. L., Dionias, A., Chorianopoulou, S. N., Liakopoulos, G. & Nikolopoulos, D. (2014). Distribution profiles and interrelations of stomatal conductance, transpiration rate and water dynamics in young maize laminas under nitrogen deprivation. *Am. J. Plant Sci., 5,* 659–670.

Carter, G. A. (1993). Responses of leaf spectral reflectance to plant stress. *Am. J. Bot.,* 239–243.

Ceccato, P., Flasse, S., Tarantola, S., Jacquemond, S. & Gregoire, J. M. (2001). Detecting vegetation water content using reflectance in the optical domain. *Remote Sensing of Environment, 77,* 22–33.

Christov, I. D. (1992). Energy levels of soil moisture and bioproductivity. *International Agrophysics, 6(1-2): 89–94*.

Daughtry, C. S. T., Walthall, C. L., Kim, M. S. et al., **Brown de Colstoun, E., J.E. McMurtrey III** .(2000). Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. *Remote Sens.Environment, 74*, 229 – 239.

de la Vega, A., Cantore, M. A., Sposaro, M., Trápani, N., López Pereira, M. & Hall, A. J. (2011). Canopy stay-green and yield in non-stressed sunflower. *Field Crops Research, 121,* 175-185. 10.1016/j.fcr.2010.12.015.

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. *Bulg. J. Agric. Sci., 25(5*), 819–832.

Doorenbos, J. & Kassam, A. H. (1979). Yield response to water. Irrigation and drainage paper 33. In: *Booker tropical soil manual,* Landon, J. R. (Ed.)., *Longman Inc*., New York, USA.

Eerens, H., Haesen, D., Rembold, F., Urbano, F., Tote, C. & Bydekerke, L. (2014). Image time series processing for agriculture monitoring. *Environmental Modelling and Software, 53,* 154-162.

ESA (2015). Sentinel-2 User Handbook; Revision 2; ESA Standard Document; ESA: Paris, France; 64.

Fox, P. & Rockstrom, J. (2000). Water harvesting for supplemental irrigation of cereal crops to overcome intraseasonal dry-spells in the Sahel. *Phys. Chem. Earth. Part B: Hydrol. Oceans Atmos, 25(3)*, 289-296.

Gamon, J. A. & Surfus, J. S. (1999). Assessing leaf pigment content and activity with a reflectometer. *New Phytol.,* 143, 105–117.

Gao, Bo-cai (1996). NDWI – A Normalized Difference Water Index for Remote Sensing of Vegetation Liquid Water from Space. *Remote Sensing of Environment, 58 (3*), 257 – 266.

Georgiev, G., Encheva, V., Encheva, Y., Nenova, N., Valkova, D., Peevska, P. & Georgiev, G. (2019). Breeding of Sunflower (*Helianthus annuus* L.) at Dobrudzha Agricultural Institute – General Toshevo. *Field Crop Studies, XII(2),* 5-16.

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

Haboudane, D., Miller, J. R., Pattey, E., Zarco-Tejada, P. J. & Strachan, I. B. (2004). Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: Modeling and validation in the context of precision agriculture. *Remote Sensing of Environment, 90,* 337-352.

Hernandez, L. F. & Larsen, A. O. (2013). Visual definition of physiological maturity in sunflower (*Helianthus annuus* L.) is associated with receptacle quantitative color parameters. *Spanish Journal of Agricultural Research, 11(2),* 447-454.

Huete, A. R. (1988). A soil-adjusted vegetation index (SAVI). *Remote Sens. Environ. 25,* 295-309.

Hunt, Jr E. R. & Rock, B. N. (1989). Detection of changes in leaf water content using Near- and Middle-Infrared reflectances. *Remote Sens. Environ., 30*, 43-54.

Integrated Water Management in Bulgaria, JICA Project (2008).

Kauth, R. J. & Thomas, G. S. (1976). The Tasseled Cap – a graphical description of the spectral-temporal development of agricultural crops as seen by Landsat. In: *Proc. Symp. Machine Processing of Remotely Sensed Data.* Purdue University, West Lafayette, Indiana, 4B41–4B51.

Kim, M. S., Daughtry, C. S. T., Chappelle, E. W., Mcmurtrey, J. E., Walthall, C. L. (1994). The use of high spectral resolution bands for estimating absorbed photosynthetically active radiation (APAR). In: *Proceedings of the 6th Symp. on Physical Measurements and Signatures in Remote Sensing,* 299 – 306.

Lisanti, S., Datsira, R., Hall, A. J. & Chimenti, C. (2012). Influence of water deficit and canopy senescence pattern on sunflower root functionality during the grain-filling phase. In: *Proc. 18th Intl. Sunflower Conf.,* Mar del Plata & Balcarce, Argentina, February 27– March 1, 2012. Intl. Sunflower Assoc., Paris, France, 120.

Luis, F., Hernández, A., Larsen, O., Lindström, L. I. & Iriarte, L. B. (2008). Physiological maturity in sunflower. Correspondence between the quantitative and the visual definition. In: *Proc. 17th International Sunflower Conference*, Córdoba, Spain, June 8 to 12, 337-340.

Mahajan, S. & Tuteja, N. (2005). Cold, salinity and drought stresses: An overview. *Arch Biochem Biophys., 444*, 139–158.

Meier, U. (editor). (2001). Growth stages of mono-and dicotyledonous plants. Federal Biological Research Centre for Agriculture and Forestry. Berlin and Braunschweig.

Milev, G., Georgiev, G., Nenova, N. & Peevska, P. (2019). Effect of the plant density and foliar fertilization on the yield from new Bulgarian hybrids of sunflower (*Helianthus annuus* L.). *Field Crop Studies, XII(2),* 135-146.

Moran, M. S., Inoue, Y. & Barnes, E. M. (1997). Opportunities and limitations for image-based remote sensing in precision crop management. *Remote Sens. Environment, 61*, 319 – 346.

Mutava, R. N., Prince, S. J. K., Syed, N. H., Song, L., Valliyodan, B., Chen, W. & Nguyen, H. (2015). Understanding abiotic stress tolerance mechanisms in soybean: A comparative evaluation of soybean response to drought and flooding stress. *Plant Physiol. Biochem., 86*, 109–120.

Nedkov, R. (2017a). Orthogonal Transformation of Segmented Images from the Satellite Sentinel-2. *Comptes rendus de l'Academie bulgare des Sciences, 70 (5),* 687- 692,(Eng).

Nedkov, R. (2017b). Normalized Differential Greenness Index for vegetation dynamics assessment. *Comptes rendus de l'Academie bulgare des Sciences, 70 (8*), (Eng).

Nemeskeri, E., Molnar, K., Vigh, R., Nagy, J. & Dobos, A. (2015). Relationships between stomatal behaviour, spectral traits and water use and productivity of green peas (*Pisum sativum* L.) in dry seasons. *Acta Physiol. Plant., 37*, 1–16.

Pan, Z., Huang, J., Zhou, Q., Wang, L., Cheng, Y., Zhang, H.,

Blackburn, G. A., Yan, J. & Liu, J. (2015). Mapping crop phenology using NDVI time-series derived from HJ-1A/B data. *International Journal of Applied Earth Observation and Geoinformation. 34,* 188-197.

Panaitescu, L., Pricop, S. M., Munteanu, E., Niţă, S. & Niţă, L. (2015). Contributions to the Implementation of Some Modern Technologies in Sunflower Crop, on a Typical Chernozem from the Area of Locality Slobozia Noua, Ialomita County. *Research Journal of Agricultural Science, 47 (3)*.

Pirasteh-Anosheh, H., Emam, Y. & Pessarakli, M. (2013). Changes in endogenous hormonal status in corn (*Zea mays*) hybrids under drought stress. *J. Plant Nut., 36,* 1695–1707.

Piro, P., Porti, M., Veltri, S., Lupo, E. & Moroni, M. (2017). Hyperspectral Monitoring of Green Roof Vegetation Health State in Sub-Mediterranean Climate: Preliminary Results. *Sensors, 17,* 662, doi:10.3390/s170406622017.

Qi, J., Chehbouni, A., Huete, A. R., Kerr, Y. H. & Sorooshian, S. (1994). A Modified Soil Adjusted Vegetation Index. *Remote Sensing of Environment, 48*, 119-126.

Qinghan, D., Herman, E. & Zhongxin, C. (2008). Crop area assessment using remote sensing on the north China plain. *The International Archives of the Photogrammetry. Remote Sensing and Spatial Information Sciences. XXXVII (B8)*, 957-962.

Rondanini, D. P., Mantese, A. I., Savin, R. & Hall, A. J. (2009). Water content dynamics of achene, pericarp and embryo in sunflower: Associations with achene potential size and dry-down. *European Journal of Agronomy, 30*, 53–62, doi:10.1016/j.eja.2008.07.002.

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.

Rouse, W., Haas, R. H., Schell, J. A. & Deering, D. W. (1974). Monitoring vegetation systems in the Great Plains with ERTS. In: *Proceedings of the Third Earth Resources Technology Satellite – 1 Symposium,* 301–317.

Sakamoto, T., Yokozawa, M., Toritani, H., Shibayama, M., Ishitsuka, N. & Ohno, H. (2005). A crop phenology detection method using time-series MODIS data. *Remote Sensing of Environment, 96(3-4),* 366-374.

Sellers, P. J. (1987). Canopy Reflectance, Photosynthesis and Transpiration. II. The Role of Biophysics in the Linearity of their Interdependence. *International Journal of Remote Sensing, 21,* 143–183.

Sexton, T. & Woolhouse, H. W. (1985). Senescence and abscission. Advanced Plant Physiology. M.B. Wilkins (Ed.)., 468-497.

Shang, J., Liu, J., Huffman, T.C., Qian, B., Pattey, E., Wang, J., Zhao, T., Geng, X., Kroetsch, D., Dong, T. & Lantz, N. (2014). Estimating plant area index for monitoring crop growth dynamics using Landsat-8 and RapidEye images. *Journal of Applied Remote Sensing. 8(1),* 085196-1 – 085196-12.

Shishkov, T. & Kolev, N. (2014). The Soils of Bulgaria. World Soils Book Series. *Springer* Netherlands, DOI 10.1007/978-94-007-7784-2.

Sinecker, P., Gomes, M. S., Arêas, J. A., Lanfer-Marquez, U. M. (2002). Relationship between color (instrumental and visual) and chlorophyll contents in soybean seeds during ripening. *J. Agric. Food Chem., 50,* 3961-3966.

Taiz, L. & Zeiger, E. (2002). Plant Physiology. 3rd Edn. Sinauer Associates, Inc. Sunderland, USA. 647.

Teoharov, M., Shishkov, T., Hristov, B., Filcheva, E., Ilieva, R., Lubenova, I., Kirilov, I., Dimitrov, G., Krasteva, V., Georgiev, B., Banov, M., Ivanov, P., Hristova, M. & Mitreva, Z. (2014). Chernozems in Bulgaria – Systematic, Specific Features and Problems. *Soil Science, Agrochemistry and Ecology, XLVIII* (3-4), (Bg).

Tucker, C. J. (1980). Remote sensing of leaf water content in the near infrared. *Rem. Sens. of Environ., 10,* 23-32.

Wardlow, B. D., Anderson, M. C. & Verdin, J. P. (2012). Remote Sensing of Drought. Innovative Monitoring Approaches, *CRC Press Taylor & Francis Group*, New York,

Welikhe, P., Quansah, J. E., Fall, S. & Elhenney, W. Mc. (2017). Estimation of Soil Moisture Percentage Using LANDSAT based Moisture Stress Index. *J. Remote Sensing & GIS, 6*, 200, doi: 10.4172/2469-4134.1000200.

Wu, Y. & Cosgrove, D. J. (2000). Adoption of roots to low water potentials by changes in cell wall extensibility cell wall proteins. *J. Exp. Bot., 51*, 1543-1553.

Xiao, G., Zhang, Q., Xiong, Y., Lin, M. & Wang, J. (2007). Integrating rainwater harvesting with supplemental irrigation into rain-fed spring wheat farming. *Soil and Tillage Research, 93*, 429-437.

Zarco-Tejada, P. J., Miller, J. R., Mohammed, G. H. & Noland, T. L. (2000). Chlorophyll fluorescence effects on vegetation apparent reflectance: I. Leaf-level measurements and model simulation. *Remote Sens. Environ., 74,* 582 -595.

Sunflower Oil Production in Bulgaria. www.nationmaster.com/nmx/timeseries/bulgaria-sunflower-oil-production#related-data. (accessed on 22 May 2021).

Crop Production Data Ministry of Agriculture, Food and Forestry https://www.mzh.government.bg/bg/statistika-i-analizi/izsledvane-rastenievadstvo/danni/. (accessed on 22 may 2021). (Bg).

P64LE136 – Sunflower Pioneer®|Corteva Agriscience.P64LE136 Pioneer® Corteva Agriscience. https://www.corteva.bg/produkti-i-reshenia/semena/p64le136.html. (accessed on 22 May 2021). (Bg).

P64LE25 – Sunflower Pioneer®| Corteva Agriscience . P64LE25 – Pioneer® | Corteva Agriscience. https://www.corteva.bg/produkti-i-reshenia/semena/p64le25.html. (accessed on 22 May 2021). (Bg).

P64LE99 – Sunflower Pioneer®| Corteva Agriscience . P64LE99 – Pioneer® | Corteva Agriscience. https://www.corteva.bg/produkti-i-reshenia/semena/p64le99.html. (accessed on 22 May 2021). (Bg).

Sunflower Hybrid Sunny IMI . SUNNY IMI. https://agrokontakt.bg/bg/hybrids/2/. (accessed on 22 May 2021),(Bg).

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