
# Assessing the Nutritional Status of Field Crops Using Remote Sensing During the Growing Season

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**Abstract**

Plant nutritional status is one of the most important indicators of stand vigour that can be monitored using remote sensing techniques. In this study, we focused on the possibility of assessing crop nutritional status, which was evaluated by plant nitrogen content, using different multispectral Earth remote sensing systems throughout the growing season. Core data were obtained from Sentinel-2 and PlanetScope satellites, and the data were compared with data obtained from ground-based measurements (Trimble Greenseeker Handheld, YARA N-tester). The study focused on comparing data from the Sentinel-2 satellite, which provides images with a resolution of 10 meters per pixel (B, G, R, NIR) and 20 meters per pixel (RE, SWIR) every 3-4 days, depending on the area surveyed and the satellite's flyby path. Another system compared was the PlanetScope satellite constellation, which has a higher spatial resolution of 3.7 meters per pixel (R, G, B, NIR) at a temporal resolution of 1-2 days; 8-band resolution imagery was used here. Based on a field experiment conducted in 2023 at the Uhercice site, where regular biomass sampling (winter barley) was conducted throughout the growing season. The results showed a high degree of correlation between vegetation indices calculated from multispectral imagery and stand parameters measured by ground survey (nitrogen content, NDVI, chlorophyll content, aboveground biomass). The highest correlation values were achieved for vegetation indices calculated from the NIR band (NDMI, NDVI, NRERI), with the highest correlation values achieved on the first biomass sampling date, and lower correlations on the other two dates. Thus, the results suggest that satellite data can be used to determine the nutritional status of plants, especially in the early stages of vegetation development. These data can then be used as prescription maps for variability of fertilizer or growth regulator rates.

**Keywords**

Vegetation indices, Multispectral images, PlanetScope, Sentinel-2

## Introduction

Precision Farming (PF), also known as Site-Specific Crop Management, is a modern and innovative approach to managing agricultural operations. Precision farming uses advanced technology and data analysis to optimise the use of inputs such as fertiliser, seeds and pesticides to increase production efficiency while minimising negative environmental impacts. The main principle of precision agriculture is to apply the right amount of inputs at the right place and time based on their specific needs. Using modern technologies such as Global Positioning Systems (GPS), Variable Rate Application (VRA), Remote Sensing Systems (RS-Remote Sensing) and crop yield monitoring, precision agriculture is becoming an increasingly important tool for sustainable and efficient management of agricultural production. The benefits of applying this new farming approach are mainly the reduction of environmental burdens due to the reduction of the amount of fertilizers and pesticides applied and the increase of economic efficiency due to yield optimization and cost reduction (Bongiovanni and Lowenberg-Deboer, 2004).

Yields of field crops must meet the demand of an ever-increasing world population that demands ever-higher yields while maintaining the same quality of food. This situation is largely determined by the continuous supply of predominantly nitrogen fertilizers to the soil to maintain both yield and grain quality. One of the main indicators of nitrogen nutrition is the Nitrogen Nutrition Index (NNI), which reflects the nitrogen status of the plant when it is rapidly diluted during the growing season (Aranguren et al., 2020; Klem et al., 2021; Pereira et al., 2022; Zheng et al., 2022). The NNI index is calculated as the ratio of the actual nitrogen content to the critical nitrogen content required for optimal plant growth and development, while accounting for biomass growth. This index is independent of the growth stage of the crop and takes into account the fact that as the growth stage of the plant increases, the nitrogen concentration in the plant decreases due to the dilution effect (Lemaire et al., 2008).

Earth remote sensing methods are an important tool in the field of agriculture that allow indirect and rapid determination of plant nitrogen content. These methods include both handheld instruments (chlorophyll Yara N-tester, Greenseeker HandHeld) and instruments mounted on satellites, for example, which allow for immediate and non-destructive measurements of large areas in near real time. Sensors mounted on carriers record data on the reflectance of electromagnetic waves from crop surfaces (Zheng et al., 2022). The spectral reflectance of vegetation is determined by a variety of factors ranging from the morphological arrangement of the tissues to the different chemical content inside the plant cells. The spectral bands obtained from the sensors used can then be fed into equations to calculate so-called vegetation indices (Aranguren et al., 2020; Xue and Su, 2017).

Using available public and private satellite systems, such as Sentinel-2 and PlanetScope, we can easily and efficiently monitor changes on the Earth's surface at high temporal, spectral and spatial resolution. The Sentinel-2 satellite, operated by the European Space Agency (ESA) as part of the Copernicus project, provides data with a spatial resolution of 10, 20 and 60 metres per pixel in 13 spectral bands that are key for vegetation monitoring (RGB-Red Green Blue, NIR-Near Infrared, SWIR-Short-wave Infrared) thanks to its multispectral imaging (MSI) system. Sentinel-2 images are widely used for nitrogen and chlorophyll content assessment (Dimitrov et al., 2019; Schlemmer et al., 2013), leaf area index (LAI-Leaf Area Index) estimation, crop type assessment, or crop health assessment (Phiri et al., 2020).

The second remote sensing system used in this study is the PlanetScope system of the private company Planet Labs, Inc. PlanetScope is a constellation of more than 180 mini satellites called CubeSats (Breunig et al., 2020), 10 x 10 x 30 cm in size and weighing approximately 4 kg (Zhou et al., 2022), which provide images with a peridot of 1-2 days in the visible (RGB) and near-infrared (NIR) spectral bands with a spatial resolution of 3 meters per pixel (Moon et al., 2021). The use of PlanetScope satellite imagery for estimating the nutritional status of crop biomass was addressed by (Sadeh et al., 2021), who compared vegetation indices with LAI values measured in the field.

To estimate the parameters of the nutritional status of field crops, so-called vegetation indices are used, which highlight a certain component in the picture. The reflected electromagnetic radiation from the plant surface is fed as single wavelength values into the mathematical equations of the corresponding vegetation indices (Xue and Su, 2017). Over time, many vegetation indices have been found capable of estimating the chlorophyll or nitrogen content of crop vegetation, mainly due to the regions of electromagnetic radiation in the red and infrared parts of the spectrum (Clevers and Gitelson, 2013).

## Material and methods

This research was carried out at a field experimental site in the Czech Republic in 2023. The experimental site was on a 29 ha plot of land in the cadastral area of the village of Uhercice, located in the district of Breclav in the South Moravian Region (48°58' N, 16°38' E) (Figure 2). The land is managed by Zemos a.s. Velké Němčice, Czech Republic. The Breclav district is located in one of the hottest and driest regions of the Czech Republic. The long-term average temperature between 1961-2000 was 9.4 °C. The long-term average annual rainfall between 1961-2000 was 476 mm (Kolář et al., 2014). The experimental field is located at an altitude of 175 m above sea level. The predominant soil type is fluvisite, as the site is located near the Svratka River. Winter barley (Hordeum vulgare) was grown on the plot.

Biomass extraction was carried out according to a pre-established sampling grid, which was designed based on the delineation of production zones from time-series of Sentinel-2 data acquired between 2014 and 2021 (Figure 1).

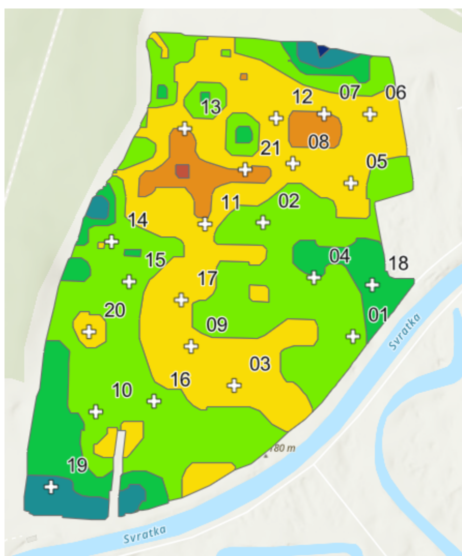


**Figure 1 Proposal of points of the collection network based on the yield potential maps**

Biomass sampling was carried out during the growing season at three developmental stages, namely at the end of the tillering stage (BBCH 29), the second sampling date was at the stem elongation stage (BBCH 30-35) and the third sampling date was at the beginning of the heading stage (BBCH 50-51).

The actual aboveground biomass sampling at the specified points was carried out from an area of 0.25 $m^2$. The vegetation was taken just above the ground and then the biomass was placed in paper bags to prevent any deterioration of the biomass taken. Subsequently, the samples were transported to the laboratory located at Mendel University in Brno where the samples were weighed fresh (g). After weighing, the samples were dried in a hot air oven at 60 °C for 72 hours. During the drying process, the samples were rotated several times to achieve uniform drying of the samples. After complete drying, the dry biomass (g) was weighed and then the nitrogen content (%) was determined by the method Coulometric determination of nitrogen content. The nitrogen uptake index (Nupt-Nitrogen Uptake) per unit area and nitrogen nutrition index (NNI-Nitrogen nutrition index) were calculated from the parameters dry weight (Biom_D-Biomass dry) and fresh weight (Biom_F-Biomass fresh) and nitrogen content (Ncont-Nitrogen content).


**Figure 2 Detail of the research field located near the village of Uhercice in the Czech Republic**

Sensor measurements of vegetation cover using handheld instruments were carried out simultaneously with biomass sampling. For this purpose, two instruments were used - Yara N-tester chlorophyll meter to determine chlorophyll content and Trimble GreenSeeker 2 Handheld to measure NDVI index. These measurements were then used for comparison with satellite data.

Satellite data from the Sentinel-2 satellite were obtained from the freely available Sci Hub Copernicus web portal (https://scihub.copernicus.eu). The multispectral data were downloaded as a surface reflectance products after radiometric and atmospheric corrections (processing level L2A) in 13 spectral bands with a spatial resolution of 10 meters per pixel. Data were downloaded at dates around the biomass sampling dates (+-5 days). PlanetScope satellite data were downloaded from Planet Explorer (https://www.planet.com/explorer/) at dates close to the crop sampling dates. Images were downloaded as surface reflectance product in 8 spectral bands with a spatial resolution of 3.7 meters per pixel. All images were downloaded without cloud cover.

The images were processed using the Python toolkit and edited in ESRI ArcGIS Pro. Vegetation indices were calculated from the images by plugging individual wavelengths into the appropriate equations. Vegetation index values were extracted for each sampling point in ESRI ArcGIS Pro.

## Results ans discussion

The use of earth observation and ground-based mapping of field crop stands in precision agriculture allows us to successfully assess the nutritional status of the stand at different developmental stages on a large scale. To assess the relationship between vegetation indices calculated from remote sensing data and the observed stand parameters, a correlation analysis was performed to demonstrate the relevance of each vegetation index to a particular stand developmental stage. The vegetation indices calculated from Sentinel-2 satellite data were mainly from Red, Red-Edge, NIR (Near InfraRed) and SWIR (ShortWave InfraRed) spectral bands. The vegetation indices calculated from PlanetScope satellite data were only from the RGB (Red, Green, Blue), Red-Edge and NIR bands because this sensor does not have other spectral bands. The choice of vegetation indices was based on a literature search.

To assess the relationship between the vegetation indices calculated from the remote sensing data and the observed vegetation parameters, correlation analysis was performed using Statistica software (Tibco, USA) to determine the relationship between the variables. The vegetation parameters monitored were NNI index calculated from current and critical plant nitrogen concentration (Lemaire et al., 2008), NDVI values from Greenseeker meter (GS), values from YARA N-tester (N-tester), plant nitrogen content (Ncont), dry aboveground biomass (Biom_D t/ha), fresh aboveground biomass (Bioma_F t/ha) and nitrogen uptake per hectare (Nupt kg/ha).

In the first observation date, which took place in the first week of April at the end of the tillering stage (BBCH 29), in which aboveground biomass sampling was also carried out, high values of correlation between vegetation indices and stand parameters were obtained for Sentinel-2 and PlanetScope satellites. The results obtained from Sentinel-2 satellite showed that the highest correlation values were achieved for almost all vegetation indices compared to the parameters obtained from Greenseeker handheld instrument (GS), fresh and dry biomass (Biom_D t/ha, Biom_F t/ha), NNI and Nupt (kg/ha). The results obtained from the PlanetScope satellite also showed high correlations, especially for the vegetation indices TCARI, SRI, NDVI, NDRE and others. High values of correlations were also demonstrated by a study of Pereira et al. (2022), which used PlanetScope satellite images to detect nitrogen content in plants. The high frequency of correlations found with vegetation indices was probably due to the low stand density, where some indices were not burdened by the so-called saturation, which occurs more in the later stages of vegetation, when some indices are less sensitive to nitrogen content at higher biomass densities, such as the NDVI index (Xue and Su, 2017). Based on these data, we can conclude that it is possible to use these Earth remote sensing sensor systems to monitor and estimate the nutritional status of field crop stands in the early stages of vegetation.

**Table 1 Correlation coefficients between ground measurement parameters and vegetation indices obtained from Sentinel-2 satellite (BBCH 29, year 2023, Uhercice). Values in bold are significant at the p < .05000 level.**

| Variable | EVI | GNDVI | IRECI | NDMI | NDRE | NDVI | NRERI | REIP1 | SRI |
|---|---|---|---|---|---|---|---|---|---|
| **GS** | 0.696 | 0.787 | 0.854 | 0.684 | 0.846 | 0.707 | 0.311 | 0.779 | 0.707 |
| **N-tester** | 0.136 | 0.133 | 0.086 | 0.044 | 0.090 | 0.116 | 0.281 | 0.111 | 0.116 |
| **Biom_F (t/ha)** | 0.779 | 0.819 | 0.761 | 0.791 | 0.823 | 0.795 | 0.536 | 0.817 | 0.795 |
| **Biom_D (t/ha)** | 0.753 | 0.784 | 0.723 | 0.765 | 0.783 | 0.761 | 0.523 | 0.765 | 0.761 |
| **Ncont (%)** | 0.258 | 0.291 | 0.262 | 0.249 | 0.340 | 0.264 | 0.144 | 0.399 | 0.264 |
| **NNI** | 0.666 | 0.714 | 0.643 | 0.698 | 0.714 | 0.695 | 0.512 | 0.730 | 0.695 |
| **Nupt (kg/ha)** | 0.756 | 0.799 | 0.740 | 0.774 | 0.803 | 0.779 | 0.538 | 0.792 | 0.779 |

**Table 2 Correlation coefficients between ground measurement parameters and vegetation indices obtained from PlanetScope satellite (BBCH 29, year 2023, Uhercice). Values in bold are significant at the p < .05000 level.**

| Variable | TCARI | SRI | NDYI | NDVI | NDRE | MCARI | GNDVI | EVI | EVI2 |
|---|---|---|---|---|---|---|---|---|---|
| **GS** | -0.665 | 0.687 | 0.089 | 0.687 | 0.781 | -0.203 | 0.753 | 0.426 | 0.687 |
| **N-tester** | 0.042 | -0.018 | 0.363 | -0.018 | 0.084 | -0.090 | -0.069 | 0.115 | -0.018 |
| **Biom_F (t/ha)** | -0.709 | 0.762 | -0.086 | 0.762 | 0.844 | -0.094 | 0.879 | 0.471 | 0.762 |
| **Biom_D (t/ha)** | -0.732 | 0.799 | -0.070 | 0.799 | 0.888 | -0.094 | 0.904 | 0.512 | 0.799 |
| **Ncont (%)** | -0.298 | 0.340 | -0.161 | 0.340 | 0.409 | -0.073 | 0.448 | 0.148 | 0.340 |
| **NNI** | -0.637 | 0.729 | -0.108 | 0.729 | 0.797 | -0.058 | 0.852 | 0.449 | 0.729 |
| **Nupt (kg/ha)** | -0.714 | 0.786 | -0.075 | 0.786 | 0.868 | -0.084 | 0.896 | 0.496 | 0.786 |

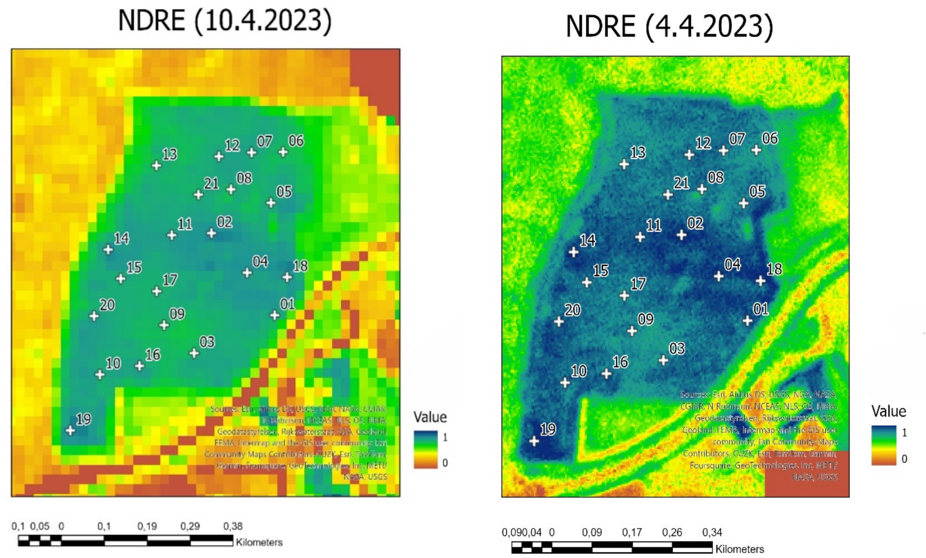


**Figure. 3 Comparison of the NDRE vegetation index visualization from Sentinel-2 images acquired on April 10, 2023 at a spectral resolution of 10 m/pixel (left) and PlanetScope images acquired on April 4, 2023 at a spectral resolution of 3.7 m/pixel (right), adjusted using ArcGis Pro (ESRI)**

In the second monitored date, which took place in the first half of April in the initial phase of stem elongation (BBCH 30-35), there was a significant change in the frequency of the correlations found. Only the Sentinel-2 data showed very high correlation values, especially for the vegetation indices EVI, NDMI, NRERI, NDVI and SRI. Similar correlation values were achieved in a study by Horniacek et al. (2020) who also dealt with the estimation of nutritional status using vegetation indices, in their study they showed a correlation of the NNI index with the NDRE vegetation index of R = 0.6. From the results obtained from the PlanetScope satellite, there was a significant reduction in the number of relevant correlations that would have statistical significance. The PlanetScope satellite data results indicated that only the TCARI vegetation index had statistical significance. Based on the results obtained, we can say that only Sentinel-2 satellite data can be used to estimate the nutritional status of biomass at the early stage of barley heading.

**Table 3 Correlation coefficients between ground measurement parameters and vegetation indices obtained from Sentinel-2 satellite (BBCH 30-35, year 2023, Uhercice). Values in bold are significant at the p < .05000 level.**

| Variable | EVI | IRECI | NDMI | NDRE | NDVI | NRERI | REIP1 | SRI |
|---|---|---|---|---|---|---|---|---|
| **GS** | 0.705 | 0.583 | 0.730 | 0.682 | 0.743 | 0.805 | 0.633 | 0.743 |
| **N-tester** | 0.310 | 0.087 | 0.378 | 0.287 | 0.270 | 0.403 | 0.484 | 0.270 |
| **Biom_F (t/ha)** | 0.742 | 0.583 | 0.740 | 0.600 | 0.700 | 0.760 | 0.653 | 0.700 |
| **Biom_D (t/ha)** | 0.674 | 0.582 | 0.601 | 0.534 | 0.590 | 0.625 | 0.600 | 0.590 |
| **Ncont (%)** | 0.410 | 0.298 | 0.542 | 0.324 | 0.430 | 0.518 | 0.190 | 0.430 |
| **NNI** | 0.626 | 0.484 | 0.708 | 0.503 | 0.575 | 0.679 | 0.464 | 0.575 |
| **Nupt (kg/ha)** | 0.709 | 0.568 | 0.794 | 0.587 | 0.639 | 0.771 | 0.603 | 0.639 |

**Table 4 Correlation coefficients between ground measurement parameters and vegetation indices obtained from PlanetScope satellite (BBCH 30-35, year 2023, Uhercice). Values in bold are significant at the p < .05000 level.**

| Variable | TCARI | SRI | NDYI | NDVI | NDRE | MCARI | GNDVI | EVI | EVI2 |
|---|---|---|---|---|---|---|---|---|---|
| **GS** | -0.700 | 0.298 | -0.510 | 0.298 | 0.646 | -0.482 | 0.454 | -0.163 | 0.298 |
| **N-tester** | -0.515 | -0.099 | -0.214 | -0.099 | 0.320 | -0.496 | 0.276 | -0.223 | -0.099 |
| **Biom_F (t/ha)** | -0.725 | 0.278 | -0.412 | 0.278 | 0.500 | -0.340 | 0.464 | -0.179 | 0.278 |
| **Biom_D (t/ha)** | -0.529 | 0.327 | -0.352 | 0.327 | 0.513 | -0.166 | 0.448 | -0.016 | 0.327 |
| **Ncont (%)** | -0.311 | 0.178 | -0.293 | 0.178 | 0.206 | -0.136 | 0.120 | -0.059 | 0.178 |
| **NNI** | -0.510 | 0.248 | -0.351 | 0.248 | 0.344 | -0.188 | 0.253 | -0.074 | 0.248 |
| **Nupt (kg/ha)** | -0.648 | 0.313 | -0.357 | 0.313 | 0.479 | -0.300 | 0.334 | -0.144 | 0.313 |

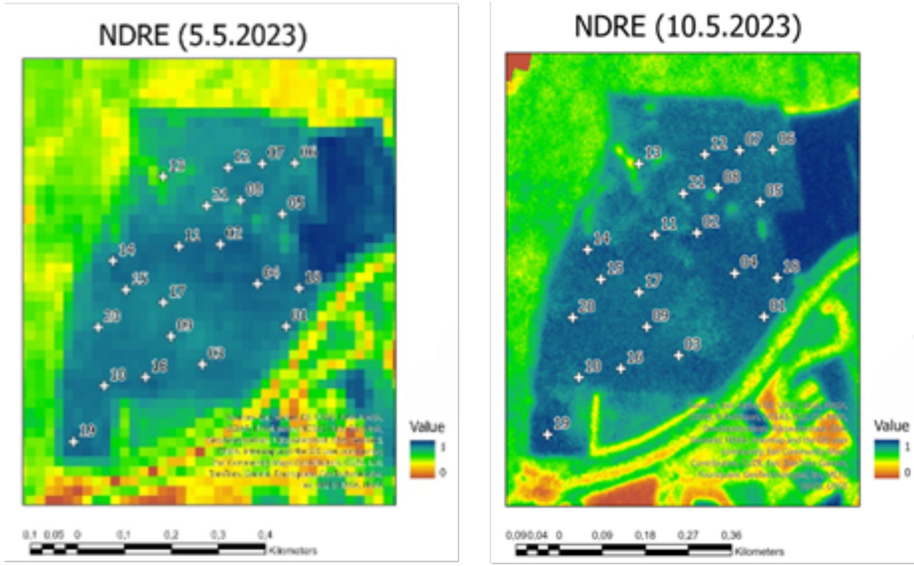

Figure 4 Comparison of the NDRE vegetation index visualisation from Sentinel-2 images acquired on 5 May 2023 at a spectral resolution of 10 m/pixel (left) and PlanetScope images acquired on 10 May 2023 at a spectral resolution of 3.7 m/pixel (right), adjusted using ArcGis Pro (ESRI)

At the last monitored date of aboveground biomass sampling, which took place at the time of shedding at the developmental stage BBCH 50-51, conclusive values were found only for the Sentinel-2 data. PlanetScope data did not reach statistically significant values in subsequent correlations. Of the Sentinel-2 data results, the highest correlation values were achieved for the vegetation indices SRI, NRERI, NDVI, NDRE and others. These are mostly vegetation indices that include the red-edge band, which is sensitive to changes in chlorophyll content; these indices are not burdened by the saturation effect that can occur at this late stage of vegetation.

**Table 5 Correlation coefficients between ground measurement parameters and vegetation indices obtained from Sentinel-2 satellite (BBCH 50-51, year 2023, Uhercice). Values in bold are significant at the p < .05000 level.**

| Variable | EVI | IRECI | NDMI | NDRE | NDVI | NRERI | REIP1 | SRI |
|---|---|---|---|---|---|---|---|---|
| N-tester | -0.234 | -0.333 | -0.159 | -0.159 | -0.242 | 0.077 | -0.195 | -0.242 |
| GS | 0.669 | 0.498 | 0.648 | 0.648 | 0.654 | 0.582 | 0.578 | 0.654 |
| Biom_F (t/ha) | 0.509 | 0.473 | 0.510 | 0.510 | 0.561 | 0.527 | 0.497 | 0.561 |
| Biom_D (t/ha) | 0.462 | 0.482 | 0.416 | 0.416 | 0.516 | 0.386 | 0.457 | 0.516 |
| Ncont (%) | 0.014 | -0.158 | 0.173 | 0.173 | 0.002 | 0.422 | -0.073 | 0.002 |
| NNI | 0.227 | 0.068 | 0.313 | 0.313 | 0.217 | 0.523 | 0.094 | 0.217 |
| Nupt (kg/ha) | 0.390 | 0.358 | 0.399 | 0.399 | 0.414 | 0.473 | 0.291 | 0.414 |

**Table 6 Correlation coefficients between ground measurement parameters and vegetation indices obtained from PlanetScope satellite (BBCH 50-51, year 2023, Uhercice). Values in bold are significant at the level of p < .05000.**

| Variable | TCARI | SRI | NDYI | NDVI | NDRE | MCARI | GNDVI | EVI | EVI2 |
|---|---|---|---|---|---|---|---|---|---|
| GS | -0.428 | 0.356 | 0.356 | 0.356 | 0.385 | 0.171 | 0.501 | 0.343 | 0.356 |
| N-tester | 0.023 | 0.135 | 0.135 | 0.135 | 0.239 | -0.128 | 0.056 | 0.080 | 0.135 |
| Biom_F (t/ha) | -0.343 | 0.419 | 0.419 | 0.419 | 0.277 | 0.330 | 0.475 | 0.387 | 0.419 |
| Biom_D (t/ha) | -0.381 | 0.388 | 0.388 | 0.388 | 0.183 | 0.334 | 0.490 | 0.319 | 0.388 |
| Ncont (%) | -0.209 | 0.459 | 0.459 | 0.459 | 0.009 | 0.394 | 0.195 | 0.213 | 0.459 |
| NNI | -0.360 | 0.579 | 0.579 | 0.579 | 0.062 | 0.522 | 0.410 | 0.368 | 0.579 |
| Nupt (kg/ha) | -0.401 | 0.562 | 0.562 | 0.562 | 0.165 | 0.516 | 0.496 | 0.414 | 0.562 |

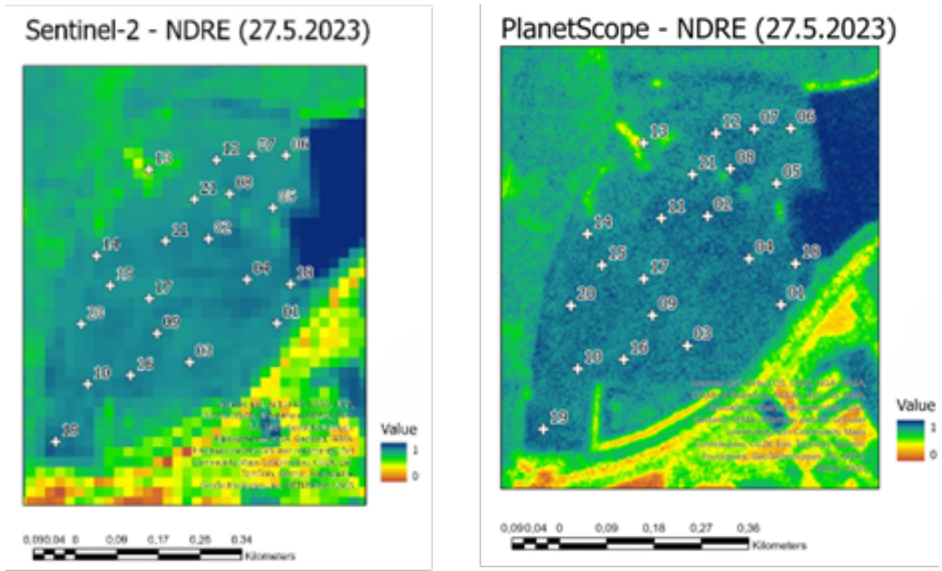


**Figure 5 Comparison of the NDRE vegetation index visualization from Sentinel-2 images acquired on May 27, 2023 at a spectral resolution of 10 m/pixel (left) and PlanetScope images acquired on May 27, 2023 at a spectral resolution of 3.7 m/pixel (right), adjusted using ArcGis Pro (ESRI)**

## Conclusions

Based on the obtained research results, it is concluded that remote sensing methods can be used to estimate the nutritional status of a crop stand, namely data from Sentinel-2 and PlanetScope satellites at certain stages of crop stand development. For estimating the nutritional status of the crop stand throughout the growing season, it is most appropriate to use data from Sentinel-2 satellite, despite its medium spatial resolution, which is 10 meters per pixel, and high temporal resolution when the orbital period is 4-5 days, as high correlation values have been demonstrated in all three terms. The PlanetScope satellite data should be used in the early vegetation stages of stand development (beginning of stem elongation) and in the advanced development stage of the stand (beginning of heading). There is room and potential for further refinement and testing of additional vegetation indices with PlanetScope due to the high temporal resolution of the satellite, which is 1-2 days of the Earth's surface orbit, as well as the high spatial resolution (3.7 meters per pixel). Furthermore, remote sensing data can be used to detect low and high yield potential sites within individual plots and to create application maps based on long-term monitoring of changes in stand development.

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## References

Aranguren, M., Castellón, A. and Aizpurua, A. (2020), “Crop Sensor Based Non-Destructive Estimation of Nitrogen Nutritional Status, Yield, and Grain Protein Content in Wheat”, *Agriculture*, Multidisciplinary Digital Publishing Institute, Vol. 10 No. 5, p. 148, doi: 10.3390/agriculture10050148.

Bongiovanni, R. and Lowenberg-Deboer, J. (2004), “Precision Agriculture and Sustainability”, *Precision Agriculture*, Vol. 5 No. 4, pp. 359–387, doi: 10.1023/B:PRAG.0000040806.39604.aa.

Breunig, F.M., Galvão, L.S., Dalagnol, R., Dauve, C.E., Parraga, A., Santi, A.L., Della Flora, D.P., *et al.* (2020), “Delineation of Management Zones in Agricultural Fields Using Cover–Crop Biomass Estimates from Planetscope

Data", *International Journal of Applied Earth Observation and Geoinformation*, Vol. 85, p. 102004, doi: 10.1016/j.jag.2019.102004.

Clevers, J.G.P.W. and Gitelson, A.A. (2013), "Remote Estimation of Crop and Grass Chlorophyll and Nitrogen Content Using Red-Edge Bands on Sentinel-2 and -3", *International Journal of Applied Earth Observation and Geoinformation*, Vol. 23, pp. 344–351, doi: 10.1016/j.jag.2012.10.008.

Dimitrov, P., Kamenova, I., Roumenina, E., Filchev, L., Ilieva, I., Jelev, G., Gikov, A., *et al.* (2019), "Estimation of Biophysical and Biochemical Variables of Winter Wheat Through Sentinel-2 Vegetation Indices", *Bulgarian Journal of Agricultural Science*, Vol. 25 No. 5, pp. 819–832.

Horniaček, I., Lukas, V., Neudert, L., Duffková, R. and Smutný, V. (2020), "Assessing the Nutritional Status of Crops Using Unmanned Aerial Surveys for Local Targeted Soil Management", *Časopis Úroda*, p. s. 341-346.

Klem, K., Křen, J., Šimor, J., Kováč, D., Holub, P., Míša, P., Svobodová, I., *et al.* (2021), "Improving Nitrogen Status Estimation in Malting Barley Based on Hyperspectral Reflectance and Artificial Neural Networks", *Agronomy*, Multidisciplinary Digital Publishing Institute, Vol. 11 No. 12, p. 2592, doi: 10.3390/agronomy11122592.

Kolář, P., Trnka, M., Brázdil, R. and Hlavinka, P. (2014), "Influence of Climatic Factors on the Low Yields of Spring Barley and Winter Wheat in Southern Moravia (Czech Republic) During the 1961–2007 Period", *Theoretical and Applied Climatology*, Vol. 117 No. 3, pp. 707–721, doi: 10.1007/s00704-013-1037-3.

Lemaire, G., Jeuffroy, M.-H. and Gastal, F. (2008), "Diagnosis Tool for Plant and Crop N Status in Vegetative Stage: Theory and Practices for Crop N Management", *European Journal of Agronomy*, Vol. 28 No. 4, pp. 614–624, doi: 10.1016/j.eja.2008.01.005.

Moon, M., Richardson, A.D. and Friedl, M.A. (2021), "Multiscale Assessment of Land Surface Phenology from Harmonized Landsat 8 and Sentinel-2, Planetscope, and Phenocam Imagery", *Remote Sensing of Environment*, Vol. 266, p. 112716, doi: 10.1016/j.rse.2021.112716.

Pereira, F.R. da S., Lime, J.P. de, Freitas, R.G., Dos Reis, A.A., Amaral, L.R. do, Figueiredo, G.K.D.A., Lamparelli, R.A.C., *et al.* (2022), "Nitrogen Variability Assessment of Pasture Fields Under an Integrated Crop-Livestock System Using UAV, Planetscope, and Sentinel-2 Data", *Computers and Electronics in Agriculture*, Elsevier, Vol. 193, p. 106645, doi: 10.1016/j.compag.2021.106645.

Phiri, D., Simwanda, M., Salekin, S., Nyirenda, V.R., Murayama, Y. and Ranagalage, M. (2020), "Sentinel-2 Data for Land Cover/Use Mapping: A Review", *Remote Sensing*, Multidisciplinary Digital Publishing Institute, Vol. 12 No. 14, p. 2291, doi: 10.3390/rs12142291.

Sadeh, Y., Zhu, X., Dunkerley, D., Walker, J.P., Zhang, Y., Rozenstein, O., Manivasagam, V.S., *et al.* (2021), "Fusion of Sentinel-2 and Planetscope Time-Series Data into Daily 3 M Surface Reflectance and Wheat LAI Monitoring", *International Journal of Applied Earth Observation and Geoinformation*, Vol. 96, p. 102260, doi: 10.1016/j.jag.2020.102260.

Schlemmer, M., Gitelson, A., Schepers, J., Ferguson, R., Peng, Y., Shanahan, J. and Rundquist, D. (2013), "Remote Estimation of Nitrogen and Chlorophyll Contents in Maize at Leaf and Canopy Levels", *International Journal of Applied Earth Observation and Geoinformation*, Vol. 25, pp. 47–54, doi: 10.1016/j.jag.2013.04.003.

Xue, J. and Su, B. (2017), "Significant Remote Sensing Vegetation Indices: A Review of Developments and Applications", *Journal of Sensors*, Hindawi, Vol. 2017, p. e1353691, doi: 10.1155/2017/1353691.

Zheng, J., Song, X., Yang, G., Du, X., Mei, X. and Yang, X. (2022), "Remote Sensing Monitoring of Rice and Wheat Canopy Nitrogen: A Review", *Remote Sensing*, Vol. 14 No. 22, p. 5712, doi: 10.3390/rs14225712.

Zhou, X., Li, Y., Sun, Y., Su, Y., Li, Y., Yi, Y. and Liu, Y. (2022), "Research on Dynamic Monitoring of Grain Filling Process of Winter Wheat from Time-Series Planet Imageries", *Agronomy*, Multidisciplinary Digital Publishing Institute, Vol. 12 No. 10, p. 2451, doi: 10.3390/agronomy12102451.