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Crop production intensity and haNDVI indicator – amplitude of NDVI related to harvest

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Abstract. In response to the growing needs of spatial recognition of the intensity of agricultural crop production, a new haNDVI indicator was developed, that measures the amplitude of the NDVI indicator related to the harvest. The proposed way of calculating haNDVI is to use the minimum and maximum functions for the raster layers set from the growing season. This avoids the need for preliminary classification of crops, including to determine the moment of harvest. It has been shown that the haNDVI indicator calculated on aggregated NDVI layers with a resolution of 1 km is correlated with soil quality indexes, NPK fertilization intensity (r = 0.69) and the share of crops in the total area (r = 0.86) for municipalities. The properties of the haNDVI indicator make it particularly useful for the initial, rapid scanning of environmental quality in terms of the intensity of plant production and indicating the hazards locations associated with the use of fertilizers and plant protection products.

Keywords: remote sensing, NDVI, nitrogen fertilizers, Sentinel, MODIS

INTRODUCTION

Today, a growing demand exists for more accurate mapping of the extent of the soil production potential use and the level of production factors. Methods are still missing for quick and cheap delineation of risk areas for the quality of the environment and in particular threats related to the emission of biogenic nutrients from farmland. Institutions monitoring agricultural production and the state of the rural environment need to obtain recognition of the aforementioned agro-environmental parameters on a macro-scale. There is also a demand on the microscale from agricultural producers themselves, using precision farming systems. However, the costs of field inspections and tests are still so high that terrestial methods are supported by the application of remote ones.

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The NDVI (Normalized Difference Vegetation Index) indicator proved to be particularly useful in remote sensing of plant condition (Tucker, 1979). The NDVI is proportional to the fraction of the plant-covered area and thus the fraction of photosynthetically active radiation PAR absorbed by the plants per unit area. The integral after the whole plant development period from the product of the properly standardized NDVI and PAR is thus proportional to the dry biomass produced per unit area and assuming constant proportions of assimilates allocation to individual plant organs, used in yield models. However, the direct use of NDVI as a measure of yield (without integration) encounters the problem of saturation of the growth of NDVI when the leaf area index LAI significantly exceeds the value of 1. Many modifications of the indicator and competitive indicators have been proposed, but most of them are strongly correlated with the NDVI and all have some disadvantages associated with their greater specialization (Jones, Vaughan 2010).

Despite the above-mentioned limitations in terms of direct yield forecasting, the NDVI as a measure of the fraction of the area covered by plants seems to be a useful parameter for the construction of the indicator of the level of production factors related to the leaf area, such as fertilizers (especially foliar application) or pesticides. The proposal of such use of the NDVI indicator is presented in the further part of the paper.

MATERIALS AND METHODS

Definition and meaning of the new indicator haNDVI

A characteristic feature of agricultural crops is the occurrence of a clear minimum value of NDVI in the post-harvest period (e.g. Sicre et al., 2016), while forests, orchards or grasslands, apart from short episodes of mowing and grazing, have relatively constant NDVI, decreasing only in the autumn. The NDVI values for crops reach a minimum after the harvest, which is related to the reflection of radiation from the soil surface and harvest residues. The maximum NDVI values recorded before the harvest (or slightly earlier in the case of plants whose yield are generative organs) are related to the reflection of radiation from the field with maximum plant density. It has been shown that the NDVI values for crops are linearly related to a fraction of plant cover, with the constant of this relationship corresponding to the minimum NDVI values recorded in the season. It follows that the near to the harvest period difference between maximum and minimum NDVI values, hereinafter referred to as the haNDVI indicator, is approximately proportional to the maximum fraction of plant cover.

At this stage there is good reason to ask a question: cannot the NDVI maxima and minima from the whole year be used to estimate the plant coverage? The answer is negative because in a calendar year there may be several NDVI minima and several NDVI maxima. In winter and sometimes in spring and autumn there may be minima associated with the presence of snow cover, while in autumn or even winter there may be additional maxima linked to the development of winter crops sown in the autumn.

The differences in the length of the development period of crop species and varieties and the influence of meteorological conditions (such as the sum of temperatures) on sowing moments and growth rates make the key periods for the analysis of maximum and minimum NDVI values for crops spatially different. Therefore, before further interpretation of NDVI layers (but also in relation to other satellite data used in agriculture), an initial land use classification is most often carried out, allowing for identification of crops in individual cells of the image raster. Satisfactory quality of differentiation of individual crops, however, is only possible thanks to quite complicated multitemporal techniques employing information about the specificity of phenological development (e.g. Bargiel, 2017; Heupel et al., 2018), which makes it justified to look for other ways of solving the described problem.

The new method described below consists in bypassing the need to classify crops on the image by creating two layers comprising respectively a minimum and a maximum NDVI value for the corresponding pixel positions from the collection of all cloudless NDVI layers recorded for the analyzed area. Such calculations are easy to perform because in most GIS programs (e.g. QGIS, ArcGIS) maximum and minimum functions are available for the raster layer collection. According to the presented interpretation, the layers necessary to determine the maximum NDVI should include the period starting before the beginning of the harvest t_{hi} for the earliest harvested crops and ending just before the moment of the harvest t_{hf} of plants ripening at the latest.

In order to determine the minimum NDVI (the moment when there are either no plants or only harvest residues in the field), layers covering the period starting just after the moment of harvesting the plants collected at the earliest date and ending a certain period after harvesting the plants gathered the latest are necessary:

$$mxNDVI = \max\left[NDVI(t_l),...,NDVI(t_k)\right]; \quad t_l < t_{hi} < t_k \le t_{hf} \qquad [1]$$

$$mnNDVI = \min\left[NDVI(t_m),...,NDVI(t_n)\right]; \quad t_{hi} \le t_m < t_{hf} < t_n \qquad [2]$$

$$haNDVI = mxNDVI - mnNDVI \qquad [3]$$

For the purpose of further consideration, it has been assumed that in Poland the first crops harvested since mid-June are barley and rapeseed, while the crops harvested since the end of September at the latest are sugar beet and maize for grain. Assuming that the monthly period before and after the harvest is sufficient to capture the maximum and minimum, for plants harvested at the beginning and the end of the season, the following restrictions have been adopted for the period of imaging: $t_l \ge$ 15 May, $t_m \ge$ 15 June, $t_k \le$ 30 September, $t_n \le$ 30 October.

Aggregation of the haNDVI indicator

The practical application of the above mentioned definition of haNDVI requires such a raster resolution of the NDVI layer, where the pixel of the raster is much smaller than the size of agricultural parcels, which in most cases guarantees that the NDVI value recorded in a pixel concerns only one plant. This condition is fulfilled in case of recording spectral characteristics from devices placed e.g. on agricultural machines, for the aerial images or for satellite images of large homogeneous agricultural parcels. Unfortunately, in regions with a fragmented crop structure as in south-eastern Poland, the width of the narrowest agricultural parcels is even less than the 20 m pixels of satellite imaginery of the Sentinel 2 mission. In such regions, the spectral characteristics of single pixels of satellite images is a mixture of the characteristics of many crops, and often also of fallow land, balks and mid-field afforestation. Similar problems are encountered in the analysis of spatially aggregated NDVI (e.g. MODIS sensor aggregates with 1 km pixels), which is a useful source of information for analysis on a national or continental scale.

In the case of aggregated data, the NDVI is the weighted mean of the $NDVI_k$ values for the individual k-land uses, where the weights are their shares A_k/A in total area A. In case of the NDVI aggregation for annual crops, it can happen that one pixel of the picture covers the area of crops with different harvesting moments. As a result of the averaging, the extreme NDVI values are then mitigated and the haNDVI values are reduced. For the purpose of further consideration it was assumed that such situations are rare, e.g. because the pixel size is small enough or because the share of crops with similar harvest dates in the sowing structure is very high. It should be noted that other areas that are not sown, i.e. with a relatively constant NDVI during the growing season, may occur in any configuration in the same pixel. The division of the land use, due to the NDVI behaviour in the growing season, into two groups has been implemented:

– annual harvested crops and therefore with a clear minimum for the NDVI during the growing season, hereinafter signed by subscript h,
– other agricultural land (permanent crops, meadows and pastures) and non-agricultural land (forests, waters, wetlands, rocks, beaches and dunes, sealed urban areas, etc.), showing in the growing season a slight variability of the NDVI, hereinafter signed by subscript nh,

For the above classification, the NDVI minimum and maximum weighted means were calculated, according to the following equations [1] and [2]:

$$\langle mxNDVI \rangle \approx mxNDVI_h \frac{A_h}{A} + mxNDVI_{nh} \frac{A - A_h}{A} \quad [1a]$$

$$\langle mnNDVI \rangle \approx mnNDVI_h \frac{A_h}{A} + mnNDVI_{nh} \frac{A - A_h}{A} \quad [2a]$$

where the <> symbol means the average over the area. Substitution of [1a] and [2a] to averaged relation [3] and application of the definition of haNDVI [3] gives:

$$\langle haNDVI \rangle \approx haNDVI_h \frac{A_h}{A} - haNDVI_{nh} \frac{A_h}{A} + haNDVI_{nh} \quad [3a]$$

where the $haNDVI_h$ is, according to previous arrangements, proportional to the maximum plant cover density and can be assumed to contain information on the intensity of plant production in the sown area.

If, for example, we take as a measure of production intensity the consumption of mineral NPK fertilizers expressed in kg per ha, then in the first approximation the plant cover density can be recorded as a linear NPK function:

$$\begin{aligned} \langle haNDVI \rangle &\approx (\alpha\, NPK + \beta) \frac{A_h}{A} - haNDVI_{nh} \frac{A_h}{A} + haNDVI_{nh} \\ &= \alpha\, NPK \frac{A_h}{A} + (\beta - haNDVI_{nh}) \frac{A_h}{A} + haNDVI_{nh} \end{aligned} \quad [4]$$

Equation [4] is also a linear function of A_h/A i.e. the percentage of annual crops sown in the total area. Aggregated haNDVI is therefore an indicator of cultivation intensity, similarly to non-aggregated haNDVI. In addition, when aggregation does not take place, e.g. due to the high resolution of the images used for calculation, the A_h/A ratio is equal to 1 and equation [4] is reduced to equation [3], as expected.

The parameters of the above formula [4] can be estimated using multiple linear regression. Since the NDVI should increase with increasing fertilizer doses, α should be positive. Coefficient β should be positive because even when no fertilizer is applied to the crop, plant growth is based on the resources of nutrients present in the soil. The vigour of the natural vegetation changes during the growing season so that $haNDVI_{nh}$ should also be greater than zero. The estimation of the parameters of equation [4] is at the same time an indirect test of the correctness of the presented considerations and introduced approximations.

haNDVI indicator (Sentinel-2 20 m) and soil quality and fertilization in the Puławy region

The aim of the first test was to check the correctness of the assumptions concerning the seasonal variability of the NDVI indicator, in an area where the land use of fields is well recognized and data on the mineral NPK fertilizers consumption are available. Data from the fields of the Agricultural Experimental Station „Kępa-Puławy" (Harasim, 2015; Harasim, Matyka, 2017), as well as statistics from the surrounding municipalities were used (GUS PSR 2010), assuming a sufficiently large variation in the haNDVI index. The test used NDVI values read for Sentinel-2 satellite images with 20 m resolution, after L2A atmospheric correction, for all cloudless days in 2018–2019. The haNDVI layer used for comparisons with fertilization was calculated according to formulas [1-3] for data from 2019 year (days: 14.06, 29.07, 28.08, 22.09, 12.10, 27.10).

Aggregated haNDVI (MODIS 1 km) and soil quality and fertilization in Polish municipalities (gminas)

The aim of the second test was to verify the correctness of prediction of the aggregated haNDVI relationship with the intensity of production measured by the consumption of mineral fertilizers and the share of annual crops, expressed by equation [4]. It was assumed that the variable best characterizing the area of annual crops A_h in municipalities is the sown area of $A_{h\,NAC}$ recorded during the National Agricultural Censuses (not measured by geodesic methods). Since the data of the agricultural censuses of the sown area $A_{h\,NAC}$ are assigned to the headquarters of farms that may possess land in different municipalities, it is theoretically possible that the sown area determined in this way is larger than the area of the municipality. Therefore, the area $A_{h\,NAC}$ attributed to the seat of the municipality requires correction, which can be done in the simplest way by multiplying it by the inverse of relations of two other but similar areas measured in the municipality, both by geodesic methods and by agricultural census. Thus it was assumed that:

$A_h \approx A_{h\,NAC}\ (A_{a\,geod}/A_{a\,NAC})$, where $A_{a\,geod}$ is geodetic agricultural area and $A_{a\,NAC}$ agricultural area recorded during the National Agricultural Censuses.

In the case of the NPK variable (kg ha^{-1}), denoting the average mineral fertilization per unit of annual sowing area, it was assumed that its closest readily available equivalent is the ratio of total consumption of mineral fertilizers (kg) in pure ingredients to the agricultural area in good agricultural condition A_{gac} (ha) calculated on the basis of data from the National Agricultural Censuses.

In the calculations performed, both with regard to area and fertilization, the data from the last National Agricultural Census of 2010 (GUS PSR 2010) were used. Data on geodetic plots were taken for the year 2013 (GUS GUGiK 2012).

NDVI values were read from two-week MODIS cloudless satellite imaging aggregates with a resolution of 1 km, in the years 2000–2018. For each year the value of haNDVI was calculated and then the arithmetic mean was calculated from the values for 19 years. The average value of the aggregated haNDVI obtained in this way was used in comparisons with the intensity of fertilization and scoring of soil complexes in municipalities. The complex scores obtained from the Soil Agricultural Map in the scale 1:25000 where non-agricultural areas were assigned 0 points, counted in raster cells identical to those for haNDVI and then averaged over the area of municipalities. Moreover, the variability in the country of the arithmetic means from 19 years of the mnNDVI and mxNDVI values was illustrated.

RESULTS AND DISCUSSION

haNDVI indicator (Sentinel-2 20 m) and soil quality and fertilization in the Puławy region

Seasonal variability of the NDVI indicator read for several points representative for the main land use classes: arable land, permanent grassland, forests and built-up areas, confirms the assumption of a significantly higher amplitude of NDVI changes during the growing season in the sowing areas and the occurrence of a clear minimum NDVI in the period from 170 to 240 days of the year (Fig. 1), which corresponds to harvesting dates for most crops.

The map of the haNDVI index for the vicinity of Puławy in 2019 (Fig. 2 on the left) reveals the existence of several larger areas on agricultural land with significantly higher index values (above 0.6) than in their surroundings (on average about 0.4). These areas are mostly fields of the „Kępa-Puławy" Agricultural Experimental Station with fertilization at the level of 274 kg ha^{-1} A_{gac} in 2008–2016 (Harasim, 2015; Harasim, Matyka, 2017). The surrounding agricultural land is located in the area of four municipalities: urban Puławy with average rate of NPK fertilization of 163 kg ha^{-1} A_{gac}, rural Puławy with fertilization of 66 kg ha^{-1} A_{gac}, Końskowola municipality with fertilization of 91 kg ha^{-1} A_{gac} and Żyrzyn municipality with fertilization of 59 kg/ha A_{gac} (GUS PSR 2010). Fertilization in RZD „Kępa-Puławy" is therefore 2–4 times higher than in average surrounding farms and it can be concluded that the haNDVI index reflects these differences correctly. Within

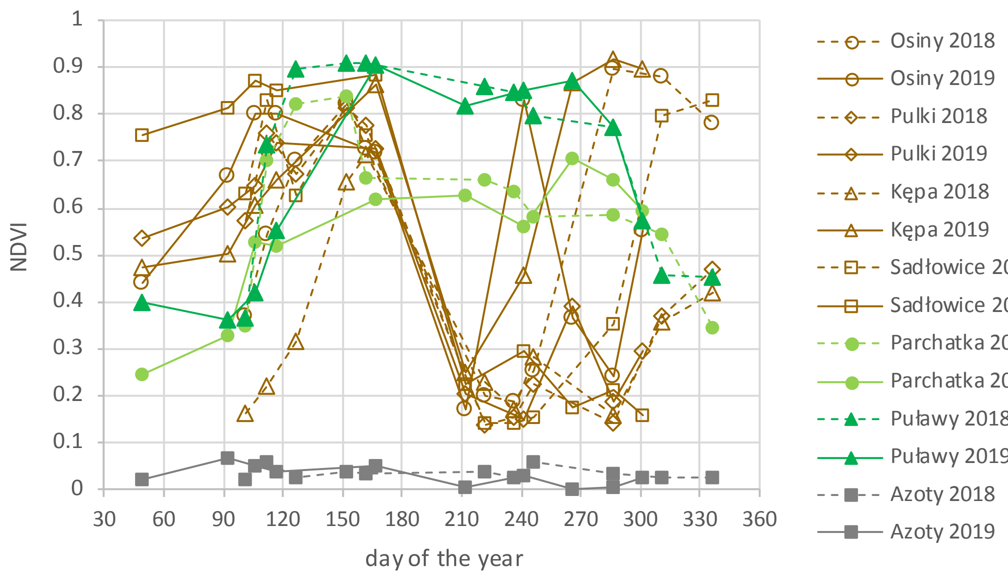

Figure1. Seasonal variability of the NDVI at several points in the Puławy surroundings in 2018–2019 (brown – arable land, light green – permanent grassland, dark green – forest, grey – built-up area; built-up area was selected as a completely sealed to avoid the influence of vegetation on the NDVI).
Authors' own study based on Sentinel-2 data.

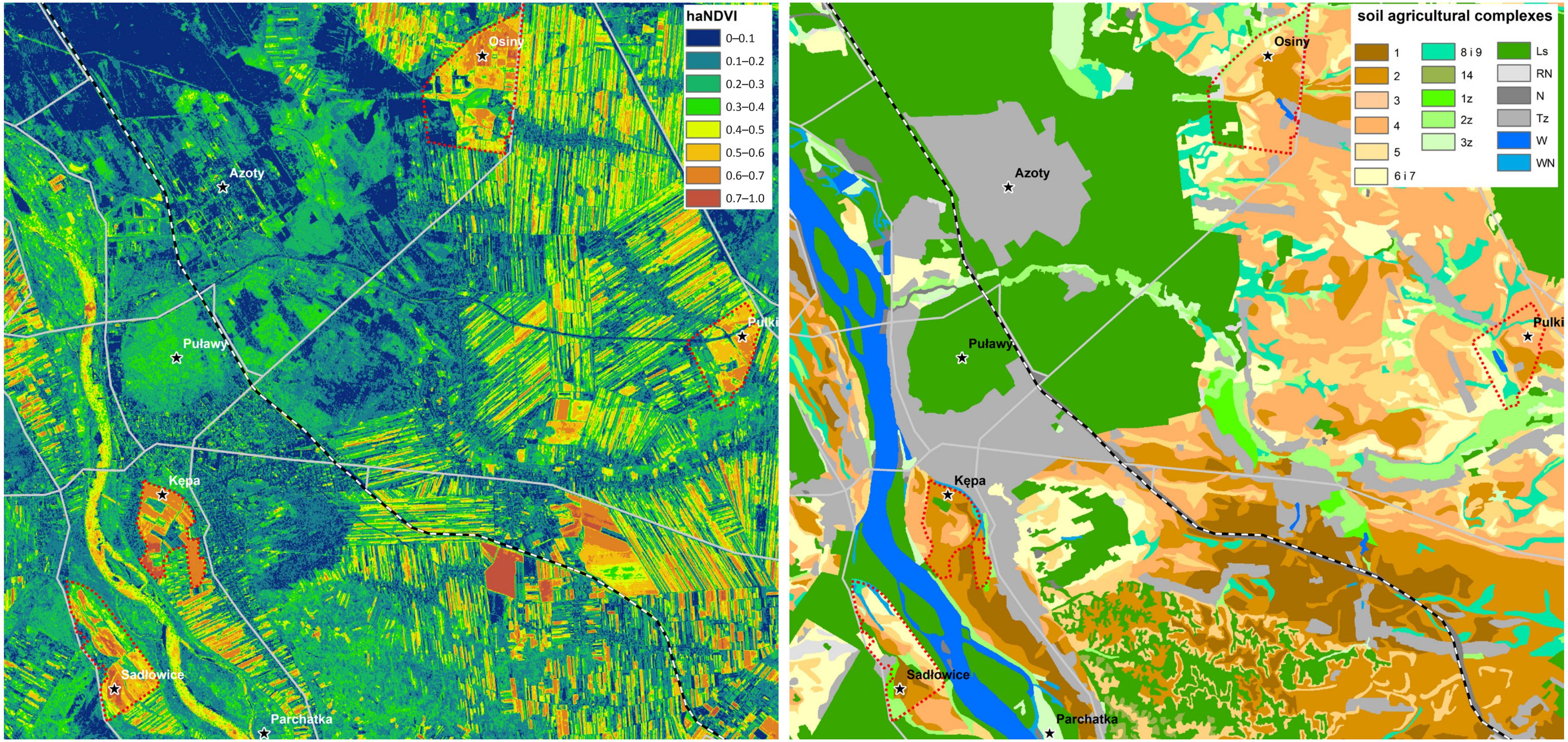

Figure 2. Variability of haNDVI index in Puławy area (map on the left) in comparison with land use and soil quality according to Soil-Agricultural Map data (map on the right). The points in which the NDVI values shown in Fig. 1 were registered are marked with black stars and the range of RZD „Kępa-Puławy" is represented by a red dotted line.
Authors' own study based on Sentinel-2 data from 2018–2019 and Digital Soil-Agricultural Map in the scale 1:25 000.

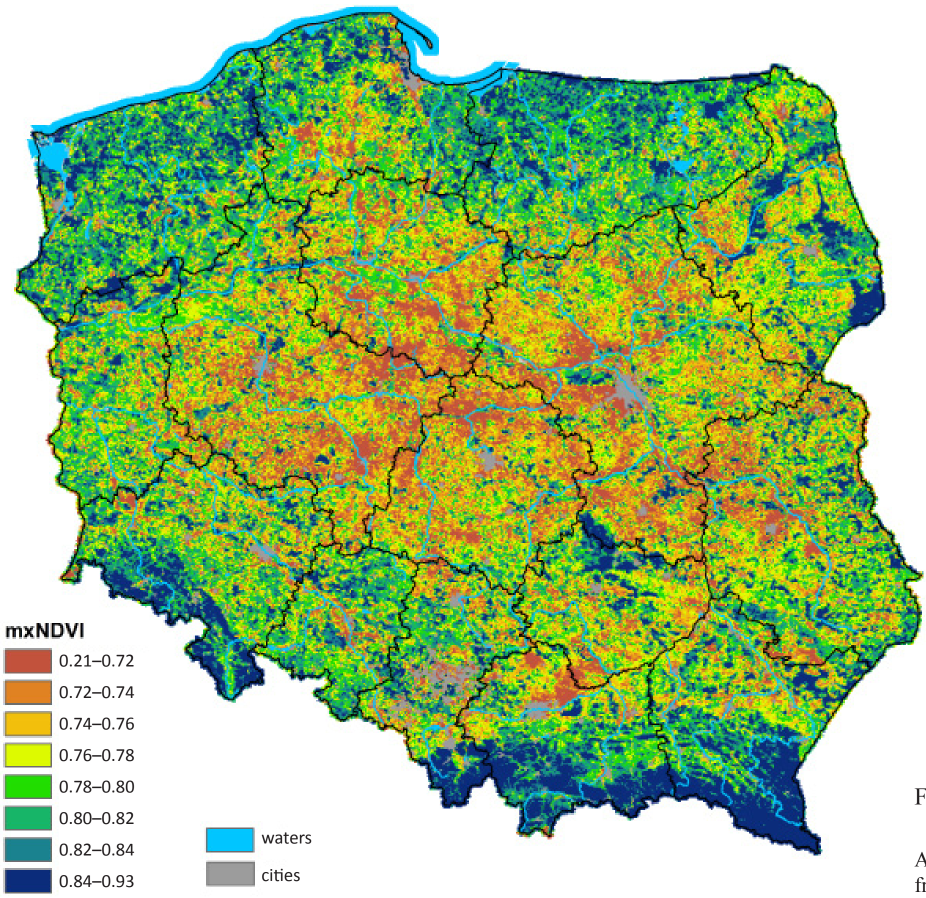

Figure 3. Average values of mxNDVI in Poland in 1 km grid.

Authors' own study based on MODIS data from 2000–2018.

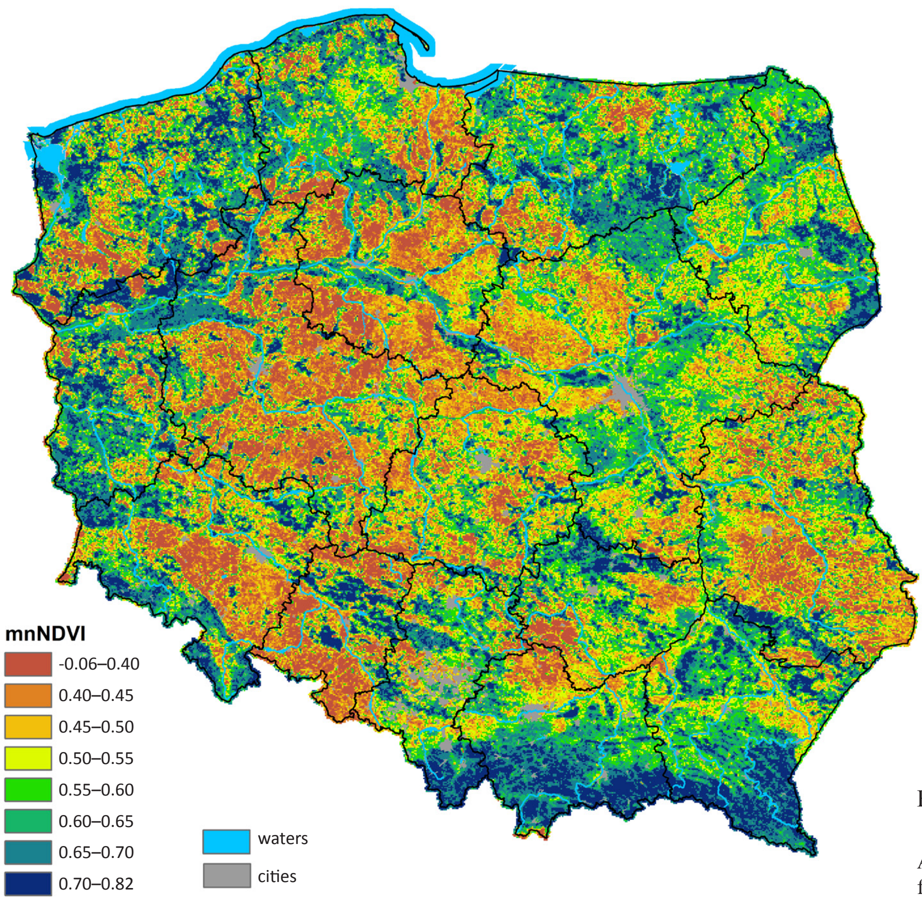

Figure 4. Average values of mnNDVI in Poland in 1 km grid.

Authors' own study based on MODIS data from 2000–2018.

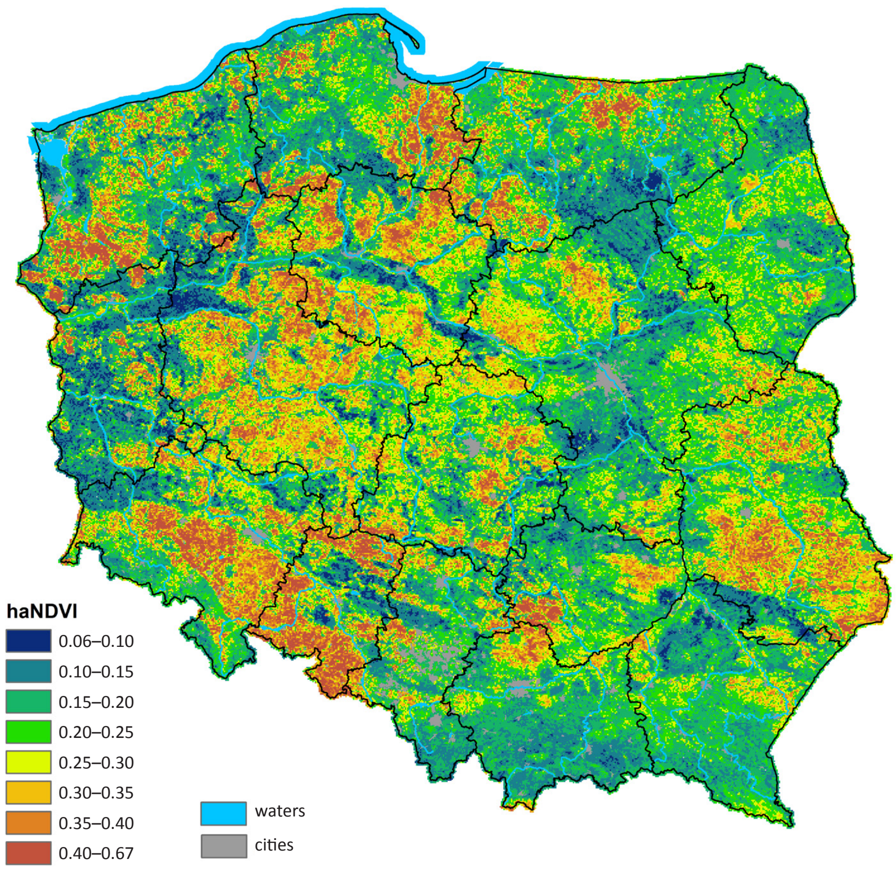

Figure 5. Average values of haNDVI in Poland in 1 km grid.

Authors' own study based on MODIS data from 2000–2018.

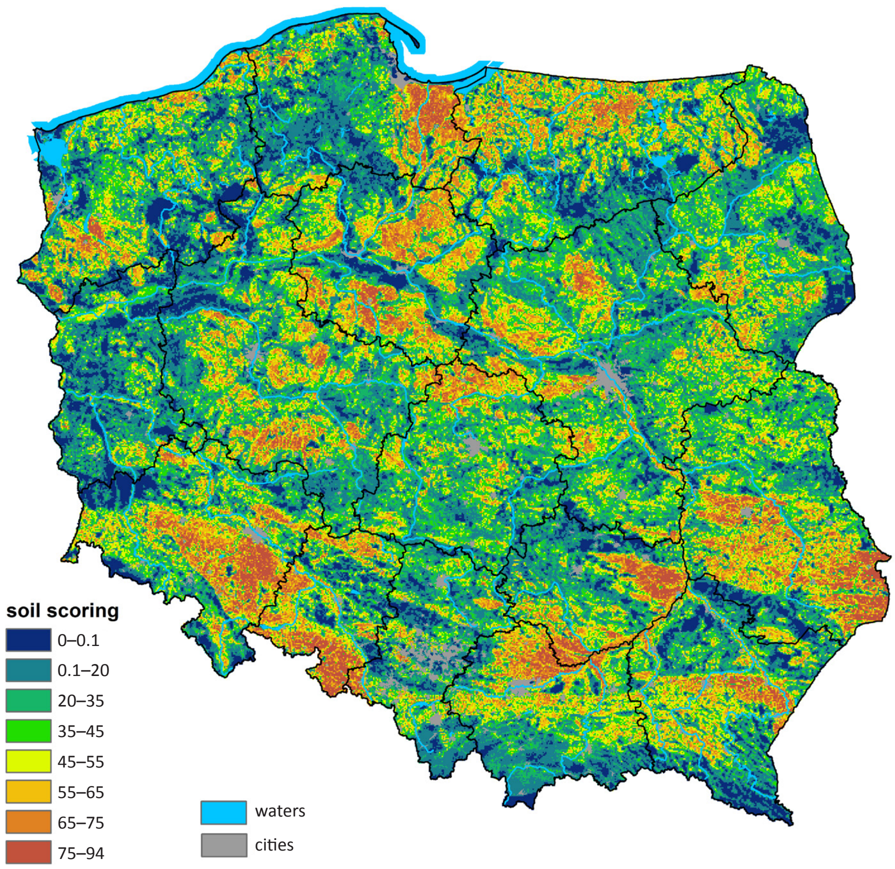

Figure 6. Scoring of agricultural soil complexes in 1 km grid.

Authors' own study based on data from the Soil-Agricultural Map in the scale 1:25000.

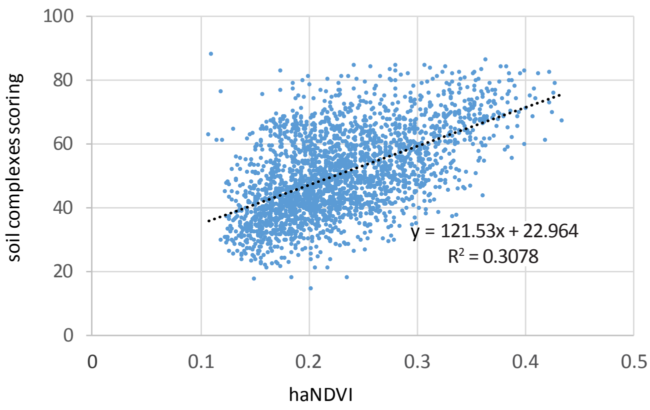

Figure 7. The relation between the scoring of soil complexes and haNDVI in municipalities. Authors' own study.

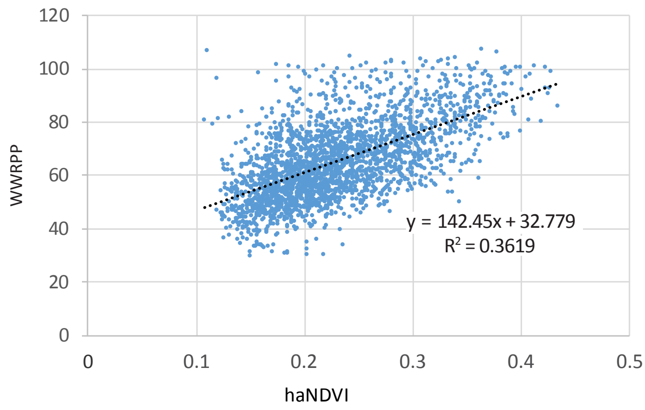

Figure 8. Relationship between WWRPP and haNDVI in municipalities. Authors' own study.

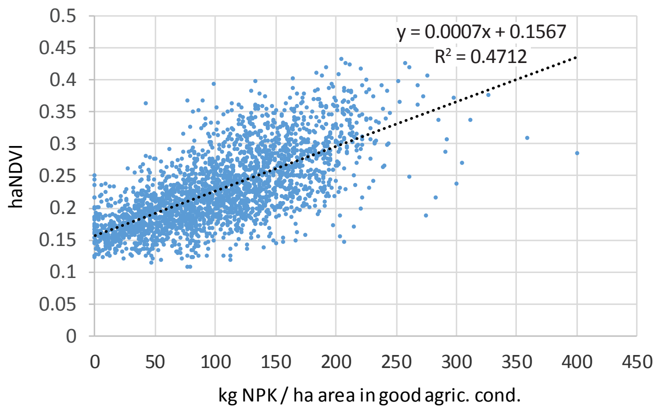

Figure 9. The relation between the haNDVI and NPK in municipalities. Authors' own study.

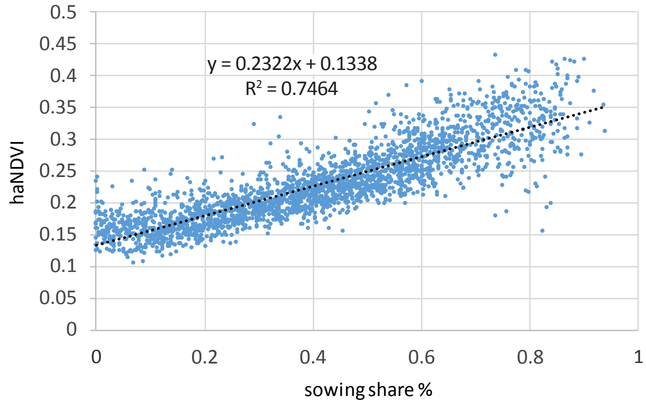

Figure 10. Relationship between the haNDVI and the share of sowing in municipalities. Authors' own study.

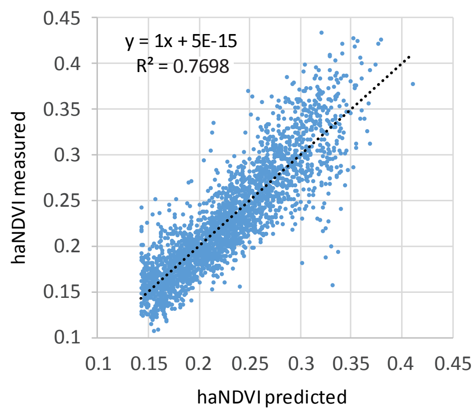

Figure 11. Relation between the haNDVI measured and predicted in municipalities. Authors' own study.

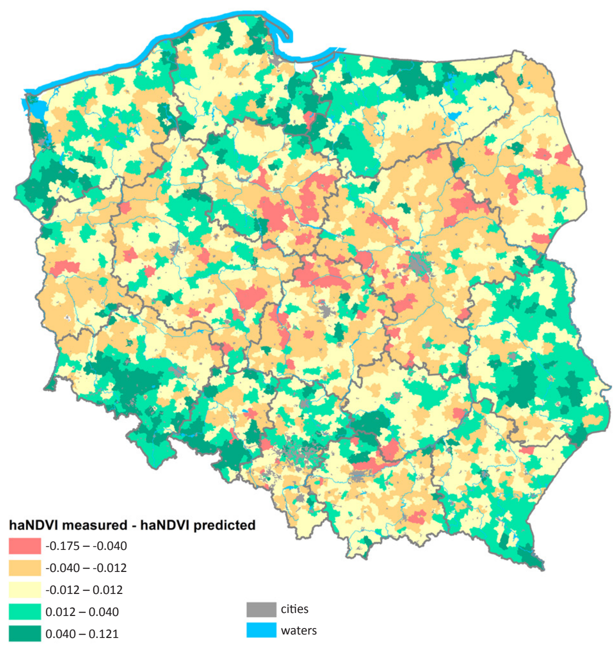

Figure 12. The rest of the relation between haNDVI and NPK and A_h/A. Authors' own study.

the large fields of RZD „Kępa-Puławy", higher haNDVI values can also be seen on soils of higher quality (Fig. 2 on the left and right), which proves their rational use.

Aggregated haNDVI (MODIS 1 km) and soil quality and fertilization in Polish municipalities

The arithmetic mean values of mnNDVI and mxNDVI, calculated from equations [1] and [2] for the years 2000–2018 (Fig. 3-4), clearly differ in terms of spatial distribution in Poland. Areas of low mxNDVI values (Fig. 3) are located mainly in regions of low precipitation and drought in the lowlands of central Poland, whereas areas with high mxNDVI are situated in the mountains and in the north of Poland, where precipitation is higher. In turn, the mnNDVI values are lowest in areas with a high share of arable land and the highest in forests. Due to much lower variability of mxNDVI than mnNDVI, related to the saturation of the increase in the NDVI value when the leaf area significantly exceeds the size of the area above which they are located (LAI>>1), the values of haNDVI (Fig. 5) are most strongly influenced by the variability of mnNDVI.

Due to the fact that optimum use of agricultural soil potential means higher intensity of production on soils with higher quality (e.g. Witek, 1973), the values of the haNDVI index should also correlate with the quality of soils measured e.g. by the scoring of soil agricultural complexes or the value of agricultural land quality index WWRPP (Witek et al., 1993). Such correlation is visible on the maps of scoring values of complexes and haNDVI in 1 km of rasters (Fig. 5 and 6), on the graph of dependence of scoring values of complexes and average haNDVI in municipalities (Fig. 7) and on the graph of dependence of WWRPP index and average haNDVI in municipalities (Fig. 8), which confirms postulated interpretation of haNDVI index.

According to equation [4] haNDVI is also linearly proportional to the intensity of fertilization and the share of sowing (Fig. 9) in the total area of municipalities (Fig. 10).

The parameters of the equation [4] linking haNDVI with a linear combination of NPK fertilization intensity and the share of crops A_h/A, estimated by multiple linear regression, are statistically significant at the level of <0.01 and amount: $\alpha = 0.00041$; $(\beta\text{-haNDVI}_{nh}) = 0.157$; $\text{haNDVI}_{nh} = 0.143$ at n = 2472 (number of municipalities; out of the total number of 2479 municipalities those in which $A_h = 0$ were rejected). The fit of the regression line is good $R^2 = 0.77$ (Fig. 11) and the spatial autocorrelations visible as larger clusters of model errors of similar value (Fig. 12) are so scattered that they may result from the error of determining mnNDVI and mxNDVI, related to the availability of cloudless images. As seen, coefficients α, β and haNDVI_{nh} are greater than zero as predicted.

The high match of the predicted values with the measured ones indicates that relation [4] has been confirmed.

CONCLUSIONS

1. The proposed new haNDVI indicator, being the amplitude of the NDVI value related to the harvest, has the following characteristics:
   - is theoretically linearly dependent on the maximum share of plant cover on the sown area and the share of sown area in the total area;
   - in aggregate form (1 km) is well correlated with soil quality index (r = 0.55–0.60), NPK fertilization in kg ha^{-1} A_{gac} (r = 0.69) and land under crops in the total area (r = 0.86) for municipalities of Poland;
   - it can be quickly calculated also using free GIS software;
   - it can be updated annually, on the basis of free satellite imagery.
2. The above mentioned properties of the haNDVI index make it particularly useful for an initial, quick recognition of agricultural space in terms of intensity of plant production, including the analysis of soil quality variability, as well as environmental threats arising from the use of fertilizers and plant protection products.

REFERENCES

Bargiel D., 2017. A new method for crop classification combining time series of radar images and crop phenology information, Remote Sensing of Environment, 198: 369-383, doi: 10.1016/j.rse.2017.06.022.

GUS GUGiK, 2012. Powierzchnia geodezyjna kraju. Kierunki wykorzystania powierzchni, rok 2012; Available at: https://bdl.stat.gov.pl/BDL/dane/podgrup/temat (accessed 20.12.2019).

GUS PSR, 2010. Powszechny Spis Rolny 2010 r. – wg siedziby gospodarstwa. Użytkowanie gruntów; Available at: https://bdl.stat.gov.pl/BDL/dane/podgrup/temat (accessed 20.12.2019).

Harasim A., 2016. Zarys organizacji i działalności Rolniczych Zakładów Doświadczalnych IUNG w latach 1950-2015. IUNG-PIB, ISBN 978-83-7562-241-6.

Harasim A., Matyka M., 2017. Informator o Rolniczych Zakładach Doświadczalnych IUNG-PIB. Puławy, 28 pp., ISBN: 978-83-7562-241-6.

Heupel K., Spengler D., Itzerott S., 2018. A Progressive Crop--Type Classification Using Multitemporal Remote Sensing Data and Phenological Information. 86: 53-69, doi: 10.1007/s41064-018-0050-7.

Jones H.G., Vaughan R.A., 2010. Remote sensing of vegetation – Principles, techniques, and applications. Oxford University Press, 353 pp., ISBN: 978-0199207794.

MODIS, 2019. Aggregated 16-days data for NDVI available at: https://modis.gsfc.nasa.gov/data/dataprod/mod13.php (accessed 20/12/2019).

Prabhakara K., Hively W.D., McCarty G.W., 2015. Evaluating the relationship between biomass, percent groundcover and remote sensing indices across six winter cover crop fields in Maryland, United States, International Journal of Applied Earth Observation and Geoinformation, 39: 88-102, doi: 10.1016/j.jag.2015.03.002.

Sentinel-2, 2019. Zobrazowania dla pasm 3 i 4, korekta L2A, Available at: https://apps.sentinel-hub.com/eo-browser/ (accessed 20/12/2019).

Sicre M.C., Inglada J., Fieuzal R., Baup F., Valero S., Cros J., Huc M., Demarez V., 2016. Early Detection of Summer Crops Using High Spatial Resolution Optical Image Time Series. Remote Sensing, 8, 591, doi: 10.3390/rs8070591.

Tucker C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment, 8: 127-150, doi: 10.1016/0034-4257(79)90013-0.

Witek T. et al., 1993. Waloryzacja rolniczej przestrzeni produkcyjnej Polski według gmin. IUNG Puławy, Seria (A), 56.

Witek T., 1973. Mapy glebowo-rolnicze oraz kierunki ich wykorzystania. IUNG Puławy, Seria P(18), 74 pp.

LIST OF SYMBOLS USED IN THE PAPER

A – area
NDVI – Normalized Difference Vegetation Index
mxNDVI – maximum NDVI related to harvest
mnNDVI – minimum NDVI related to harvest
haNDVI – amplitude of NDVI related to harvest
NPK – mineral fertilization in pure ingredients per unit area
t – time

SUBSCRIPTS:

h – harvested
nh – non harvested
gac – in good agricultural condition
geod – registered by geodetic methods
NAC – registered during National Agricultural Census
a – agricultural

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