Scientific Review Engineering and Environmental Sciences (2023), 32 (2), 175–185

Sci. Rev. Eng. Env. Sci. (2023), 32 (2) https://srees.sggw.edu.pl

ISSN 1732-9353 (suspended) eISSN 2543-7496 DOI 10.22630/srees.4889

Received: 28.04.2023
Accepted: 18.05.2023

Stefan IGNAR[1]✉ https://orcid.org/0000-0002-5080-8695
Sylwia SZPORAK-WASILEWSKA[2] https://orcid.org/0000-0001-8012-0894
Małgorzata GREGORCZYK[3]

[1]Warsaw University of Life Sciences – SGGW, Institute of Environmental Engineering, Poland
[2]Warsaw University of Life Sciences – SGGW, Water Centre, Poland
[3]Warsaw University of Life Sciences – SGGW, Foreign Language Teaching Centre, Poland

Spatial mapping of the leaf area index using remote sensing and ground measurements – the Biebrza National Park case study

Keywords: leaf area index, wetlands, remote sensing, spectral vegetation indices, Biebrza

Introduction

The leaf area index (LAI) is one of the most important parameters describing the vegetation structure in terrestrial ecosystems. It is related to many environmental processes, including biophysical processes affecting the exchange of matter and energy between soil, vegetation and the atmosphere, such as photosynthesis, transpiration, evapotranspiration, interception, biomass and net primary production. The parameter is fundamental to studies of the dynamics of vegetation change and, above all, to studies of the exchange of energy and mass fluxes within the vegetation–atmosphere interface. It is defined as the summed ratio of the one-sided leaf area to the substrate area over which it is located:

$$LAI = \frac{one\ sided\ leaf\ \ area}{substrate\ area}[\mathrm{m}^2].$$

✉stefan_ignar@sggw.edu.pl

The parameter is one of the most difficult to estimate correctly due to its considerable spatial as well as temporal variability. In the field, it can be determined by several direct and indirect measurement methods. Direct measurement methods are among the most accurate but are time-consuming and difficult to implement on a large scale. Indirect measurement methods include, but are not limited to, optical methods that infer *LAI* from the transmission of radiation through vegetation cover using the radiative transfer theory (Welles & Cohen, 1996). These are non-invasive methods that describe vegetation structure in a statistical and probabilistic approach. They use Beer–Lambert's law, according to which the total amount of radiation intercepted by a vegetation cover depends on the vegetation structure, optical properties and instantaneous irradiance (Szporak, 2012). Measurements using non-invasive methods enable rapid and efficient acquisition of information about the *LAI* values of the vegetation present in a given area, which can then be used to determine the spatial variability of the index from remotely sensed data.

In the analyses conducted as part of this study, the LAI-2000 Plant Canopy Analyzer from LI-COR Biosciences was used to measure the leaf area index. The instrument measures diffuse blue light (320–490 nm) at a 148-degree viewing angle (fisheye lens). To calculate the *LAI* value at a given research area, it is necessary to take measurements both above the vegetation cover (reference measurement) and in the plant community. Based on the amount and intensity of diffuse blue light reaching the sensor, the projected area of leaves is estimated using algorithms implemented in the control console (LI-COR Biosciences, Inc., 1992). Measurements of the index were made for wetland vegetation of the Biebrza river valley, taking into account selected communities of sedge rushes (*Caricetum appropinquatae*, *Caricetum elatae*), willow scrub (*Salicetum pentandro-cinereae*), alder (*Ribeso nigri-Alnetum*) in the lower Biebrza and acid low sedge mire (*Carici canescentis-Agrostietum caninae*) in the upper Biebrza river valley. Unfortunately, measurements of the *LAI* for this vegetation type are still rare in the national as well as the world literature. Most studies on the formation of this index mainly concern forests and agricultural land. In Europe, studies on the formation of spatial variability of *LAI* for grass or sedge vegetation of wetlands were conducted, among others, by Darvishzadeh, Skidmore, Atzberger and Wieren, (2008), Dąbrowska-Zielińska, Gruszczyńska, Lewiński, Hościło and Bojanowski (2009), Budzyńska, Dąbrowska-Zielińska, Turlej, Małek and Bartold (2011), Darvishzadeh, Atzberger, Skidmore and Schlerf (2011), and Szporak (2012). Measurements of the leaf area index carried out within the framework of these studies made it possible to work out both its seasonal variability in 2007 and to determine its spatial variability using Landsat 5TM remote sensing data.

Study area

The study was carried out in north-eastern Poland in the Biebrza river valley within the boundaries of the Biebrza National Park (Fig. 1). In relation to adjacent areas, the valley is marked as an area with different thermal and humidity characteristics. This is due to the overlapping of climate features associated with the extensive peatlands, the valley form and the general climate features of north-eastern Poland. The climate is close to continental with subboreal elements. It is characterized by a long winter, a long pre-winter and the shortest (except in the mountains) growing season.

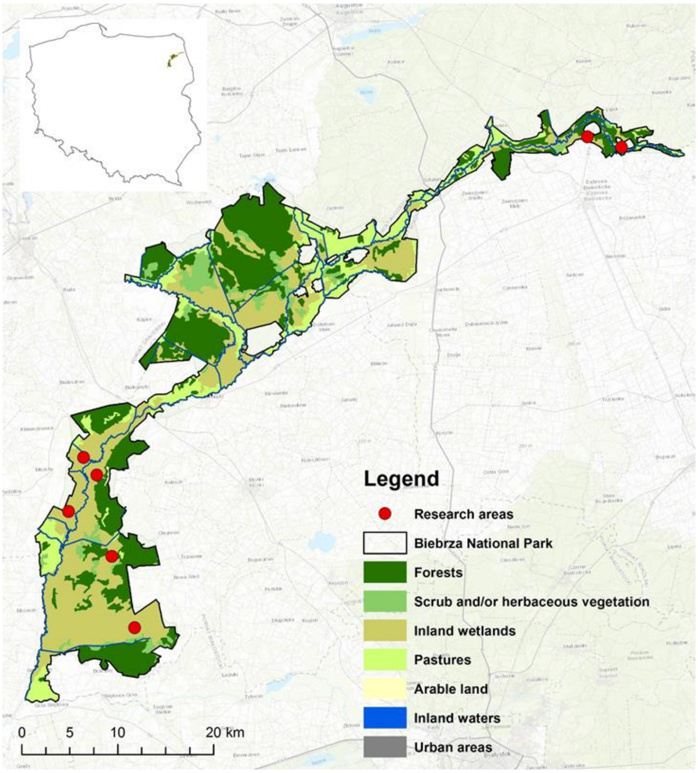

FIGURE 1. Location of research areas in Biebrza National Park

Source: own work.

In the Biebrza basin area, a decrease in temperature from south-west to north-east is observed between November and March. In the coldest month of the year, February, the average monthly temperature decreases from approx. –4.5°C on the south-western edges (lower basin) to approx. –5.5°C at the north-eastern extremities (upper basin), with a maximum average of about –1.5 to 2.5°C and a minimum average of approx. –8.5 to –9.0°C. Winter starts the earliest in the north-east (27 November) and the latest in the south-west (4 December). It lasts 107–108 days in the lower basin and 116–117 days in the upper basin. Average annual precipitation in the northern part of the Biebrza basin ranges from 470 to 550 mm, while in the southern part it is about 550 mm. The highest precipitation falls in summer, with a maximum in July (70–90 mm), and the lowest in January to March, with a minimum in January (20–25 mm). In the north-eastern part of the Biebrza basin, summer semiannual precipitation exceeds 67% of the annual total, while in the rest of the basin it is about 65%. The Biebrza river flows in a valley with low gradients, and groundwater feeding the valley flows slowly towards the riverbed or exfiltrates in the bottom of the wetlands that occur here. The wetlands of the Biebrza valley are primarily peatland ecosystems. Covering an area of over a 100 thous. ha, they form one of the largest peat complexes in Poland.

Methodology

Field measurements

The leaf area index field measurements were made at a fixed altitude with the same azimuthal position of the sensor and at several locations of the plant community under study so as to capture its heterogeneity and obtain a representative sample for the *LAI* models implemented in the LAI-2000 recorder. The *LAI* value at a given measurement point was usually the average of 10–11 measurements. Measurements for the selected plant community were taken within a limited area, the size of which was dictated by the size of the plant community patch, as well as the spatial resolution of the Landsat 5TM satellite image. In the case of *LAI* measurements in the forest, reference measurements were usually taken at the forest edge or in adequately large clearings within them.

Remote sensing data

A medium-resolution satellite image from the Landsat 5TM satellite (U.S. Geological Survey [USGS], 2023) from 28 May 2007 was used in the estimation of the spatial variability of *LAI*. The image was subjected to atmospheric correction using the MODTRAN radiative transfer model based on the physical characteristics of the actual atmospheric conditions. The estimation of the spatial distribution of the *LAI* is based on an empirical relationship between vegetation parameters measured in the field and spectral vegetation indices developed from the satellite image. The vegetation index is calculated based on a combination of several spectral bands, whose values are added, divided or multiplied between each other to obtain a value representing the area and condition of the vegetation cover. Due to the type of remote sensing data processed, selected broadband indices were used in the analyses (Table 1). The simplest spectral index is the simple ratio (SR) representing the ratio between near-infrared and red reflectance.

TABLE 1. Selected spectral indices

Spectral index	Abbreviation	Equation	References
Difference vegetation index	*DVI*	$NIR - Red$	Tucker (1979)
Enhanced vegetation index	*EVI*	$\frac{2.5 \cdot (NIR - Red)}{1 + NIR + 6 \cdot Red - 7.5 \cdot Blue}$	Birth and McVey (1968)
Global environment monitoring index	*GEMI*	$\eta(1-0.25\eta)\frac{Red - 0.125}{1 - Red}$ $\eta = \frac{2(NIR^2 - Red^2) + 1.5 \cdot NIR + 0.5 \cdot Red}{NIR + Red + 0.5}$	Pinty and Verstraete (1992)
Modified soil adjusted vegetation index	*MSAVI2*	$0.5\left[2 \cdot NIR + 1 - \sqrt{(2 \cdot NIR + 1)^2 - 8 \cdot (NIR - Red)}\right]$	Qi, Chehbouni, Huete, Kerr and Sorooshian (1994)
Moisture stress index	*MSI*	$\frac{SWIR}{NIR}$	Rock, Vogelmann, Williams, Vogelmann and Hoshizaki (1986)
Modified simple ratio	*MSR*	$\frac{\left(\frac{NIR}{RED} - 1\right)}{\left(\sqrt{\frac{NIR}{RED}} + 1\right)}$	Chen (1996)
Normalized difference vegetation index	*NDVI*	$\frac{NIR - Red}{NIR + Red}$	Rouse, Haas, Schell and Deering (1974)
Renormalized vegetation index 1	*RDVI1*	$\sqrt{NDVI \cdot DVI}$	Roujean and Breon (1995)
Renormalized vegetation index 2	*RDVI2*	$\frac{NIR - Red}{\sqrt{NIR + Red}}$	Roujean and Breon (1995)
Soil and atmospherically resistant vegetation index	*SARVI*	$\frac{(1+1) \cdot (NIR - Rrb)}{NIR + Rrb + 1}$ $Rrb = Red - 1 \cdot (Blue - Red)$	Kaufman and Tantré (1992)
Soil adjusted vegetation index	*SAVI*	$(1+L)\frac{NIR - Red}{NIR + Red + L}$	Huete (1988)
Simple ratio	*SR*	$\frac{NIR}{Red}$	Jordan (1969)
Triangular vegetation index	*TVI*	$0.5 \cdot [120 \cdot (NIR - Green) - 200 \cdot (Red - Green)]$	Broge and Leblanc (2000)

Source: own work.

Results

Results of field measurements

The study shows that the highest values of the *LAI* coefficient are observed for the majority of plant communities in the Biebrza valley during the full growing season, i.e., in June and July (Fig. 2). The growing season in this part of Poland is quite short (about 192 days), and already in August we observe a decrease in the leaf projection area of the majority of the analyzed plant communities.

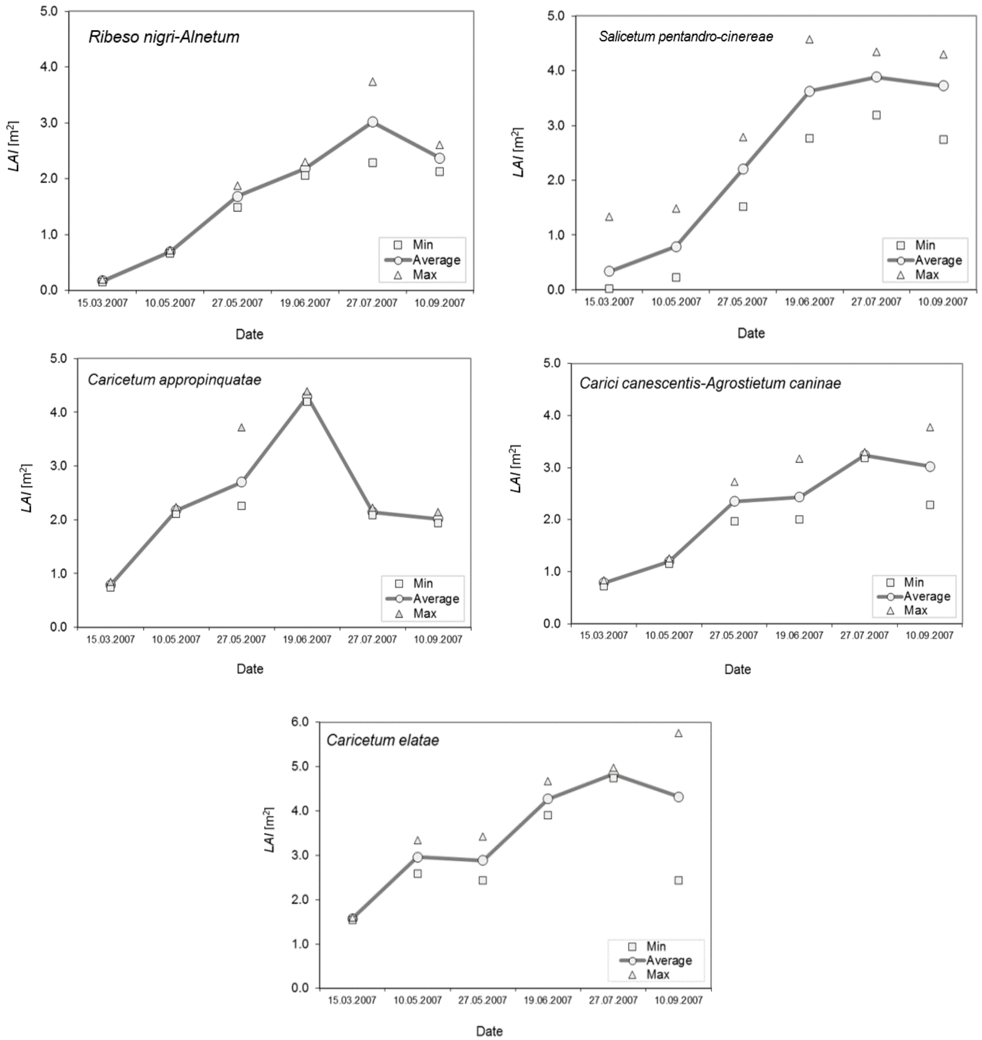

FIGURE 2. Seasonal variation of the leaf area index (*LAI*) for selected plant communities in the Biebrza valley

Source: own work.

The seasonal variation of the *LAI* for low vegetation is somewhat different from that of willow scrub and alder. The difference is particularly marked at the beginning of the growing season when the leaf area index of low vegetation increases more dynamically. The situation reverses in June when there is a gradual, further increase in *LAI* for forest and scrub communities, and a smaller increase for sedge communities and meadows, which are mown at this time. The fieldwork shows that the vegetation of natural river valleys is characterized by a high degree of variability not only in space, but also in the duration of the growing season.

Results of remote sensing analyses

The statistical relationship between the *LAI* values measured in the field and the spectral indices calculated for the satellite image is shown in Table 2 and Figure 3. All spectral indices were significantly correlated with the *LAI* ($p < 0.05$). The highest coefficient of determination and the highest correlation coefficient were obtained for *NDVI* (0.7174). The linear regression models and the obtained coefficients of determination for the analyzed spectral vegetation indices are presented in Table 2.

TABLE 2. Spectral vegetation indices (*SVI*) with developed linear regression model and coefficient of determination

Spectral vegetation indices (*SVI*)	Regression model	R^2
NDVI	$9.7686x - 1.9528$	0.7174
SAVI	$8.886x - 1.9520$	0.7173
MSI	$-3.6807x + 6.4378$	0.6982
MSR	$3.276x - 0.438$	0.6958
SR	$1.1813x - 0.7640$	0.6652
RDVI2	$0.7296x - 1.1814$	0.6290
SARVI	$1.8348x - 2.012$	0.5979
TVI	$0.0008x - 0.2074$	0.5756
RDVI1	$0.8219x - 3.6049$	0.5282
MSAVI2	$0.0482x - 0.2378$	0.5172
DVI	$0.05x - 0.2491$	0.5069
GEMI	$0.0003x + 1.4864$	0.4589
EVI	$-5.2764x + 0.1103$	0.4147

Source: own work.

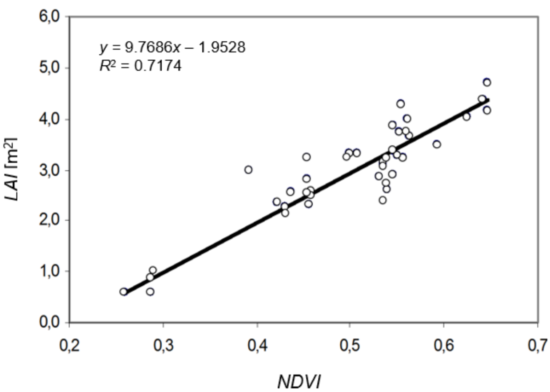

FIGURE 3. Linear regression model (*LAI*), based on normalized difference vegetation index (*NDVI*), selected for further analysis

Source: own work.

Ignar, S., Szporak-Wasilewska, S., Gregorczyk, M. (2023). Spatial mapping of the leaf area index using remote sensing and ground measurements – the Biebrza National Park case study. *Sci. Rev. Eng. Env. Sci.*, *32* (2), 175–185. DOI 10.22630/srees.4889

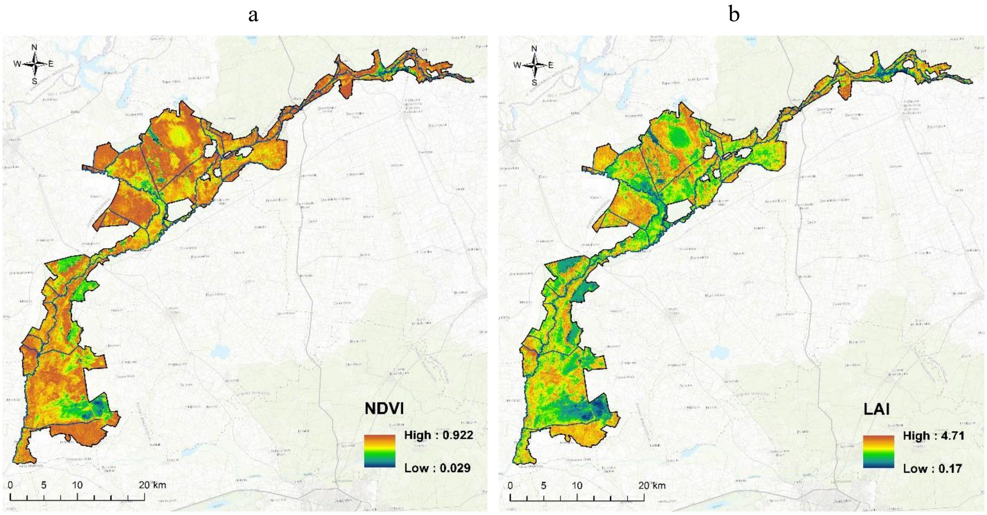

FIGURE 4. Map of the spatial variability of the normalized difference vegetation index – *NDVI* (a) and the leaf area index – *LAI* (b)

Source: own work.

From the analysis of the satellite image taken in May, the *LAI* reached the highest values in that part of the valley where significant areas are covered by reed and sedge rushes and deciduous forests (alder and swamp birch) characterized by high biomass. The lowest values of the index were observed in groundwater-logged areas in the Ławki Marsh, as well as areas directly adjacent to the bed of the Biebrza river and its tributaries, where surface water flooding persisted in places (southern and south-western parts of the middle Biebrza valley and the middle part of the upper Biebrza valley).

Conclusions

The measurements of the leaf area index show that the vegetation of natural river valleys is characterized by high spatial and seasonal variability. The highest values of the *LAI* index were observed from the second half of June to the end of July for all considered plant communities of the Biebrza valley. The seasonal variability of the *LAI* for sedge communities developed differently from that of willow scrub and alder. At the beginning of the growing season, the *LAI* for sedge communities increases more dynamically. The situation changes in June, when, with a gradual increase in the *LAI* for forest and scrub communities reaching its maximum in mid-July, there is a smaller increase in the index for sedge communities. The main reason for this difference is the use of open areas of peatlands, which are mown in June. The study of the *LAI* on such a large extensively used area therefore additionally requires knowledge of the methods of use, as well as the timing of the application of individual agrotechnical measures.

Among the tested vegetation indices developed from the Landsat 5TM satellite imagery, the *NDVI* and *SAVI* indices produced the best results in estimating the spatial variability of the *LAI*. In the analysis carried out, these indices obtained a coefficient of determination value above 0.70.

References

Birth, G. S. & McVey, G. R. (1968). Measuring the colour of growing turf with a reflectance spectrophotometer. *Agronomy Journal*, *60* (6), 640–643. https://doi.org/10.2134/agronj1968.00021962006000060016x

Broge, N. H. & Leblanc, E. (2000). Comparing prediction power and stability of broadband and Hyperspectral vegetation indices for estimating of green leaf area index and canopy chlorophyll density. *Remote Sensing of Environment*, *76* (2), 156–172. https://doi.org/10.1016/S0034-4257(00)00197-8

Budzyńska, M., Dąbrowska-Zielińska, K., Turlej, K. Małek, I. & Bartold, M. (2011). Monitoring przyrodniczy Bagien Biebrzańskich z zastosowaniem teledetekcji. *Woda – Środowisko – Obszary Wiejskie*, *11* (3), 39–64.

Chen, J. M. (1996). Evaluation of vegetation indices and a modified simple ratio for boreal applications. *Canadian Journal of Remote Sensing*, *22* (3), 229–242.

Dąbrowska-Zielińska, K., Gruszczyńska, M., Lewiński, S., Hościło, A. & Bojanowski, J. (2009). Application of remote sensing and in situ information to the management of wetlands in Poland. *Journal of Environmental Management*, *90* (7), 2261–2269. https://doi.org/10.1016/j.jenvman.2008.02.009

Darvishzadeh, R., Skidmore, A., Atzberger, C. & Wieren, S. van (2008). Estimation of vegetation *LAI* from hyperspectral reflectance data: effects of soil type and plant architecture. *International Journal of Applied Earth Observation and Geoinformation*, *10* (3), 358–373. https://doi.org/10.1016/j.jag.2008.02.005

Darvishzadeh, R., Atzberger, C., Skidmore, A. & Schlerf, M. (2011). Mapping grassland leaf area index with airborne Hyperspectral imagery: A comparison study of statistical approaches and inversion of radiative transfer models. *ISPRS Journal of Photogrammetry and Remote Sensing*, *66* (6), 894–906. https://doi.org/10.1016/j.isprsjprs.2011.09.013

Huete, A. R. (1988). A soil-adjusted vegetation index (*SAVI*). *Remote Sensing of Environment*, *25* (3), 295–309. https://doi.org/10.1016/0034-4257(88)90106-X

Jordan, C. F. (1969). Derivation of leaf area index from quality of light on the forest floor. *Ecology*, *50* (4), 663–666. https://doi.org/10.2307/1936256

Kaufman, Y. J. & Tanré, D. (1992). Atmospherically resistant vegetation index (ARVI) for EOS--MODIS. *IEEE Transactions Geoscience of Remote Sensing*, *30* (2), 261–270. https://doi.org/10.1109/36.134076

LI-COR Biosciences, Inc. (1992). *LAI-2000 Plant Canopy Analyzer. Instruction Manual*. Retrieved form: https://licor.app.boxenterprise.net/s/q6hrj6s79psn7o8z2b2s [accessed: 27.04.2023].

Pinty, B. & Verstraete, M. M. (1992). GEMI: A non-linear index to monitor global vegetation from satellites. *Vegetatio*, *101*, 15–20. https://doi.org/10.1007/BF00031911

Qi, J., Chehbouni, A., Huete, A. R., Kerr, Y. H. & Sorooshian, S. (1994). A modified soil adjusted vegetation index. *Remote Sensing of Environment*, *48* (2), 119–126. https://doi.org/10.1016/0034-4257(94)90134-1

Rock, B. N., Vogelmann, J. E., Williams, D. L., Vogelmann, A. F. & Hoshizaki, T. (1986). Remote detection of forest damage. *BioScience*, *36* (7), 439–445. https://doi.org/10.2307/1310339

Roujean, J. L. & Breon, F. M. (1995). Estimating PAR absorbed by vegetation from bidirectional reflectance measurements. *Remote Sensing of Environment*, *51* (3), 375–384. https://doi.org/10.1016/0034-4257(94)00114-3

Rouse, J. W., Haas, R. H., Schell, J. A. & Deering, D. W. (1973). Monitoring vegetation systems in the Great Plains with ERTS. *NASA Special Publications*, *351* (1), 309–317.

Szporak, S. (2012). *Zastosowanie metod teledetekcyjnych dla szacowania ewapotranspiracji na przykładzie Dolnego Basenu rzeki Biebrzy* [*Remote sensing methods in assessment of evapotranspiration in the Biebrza River Lower Basin*] (doctoral thesis). Warsaw University of Life Sciences, Warsaw.

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, *8* (2), 127–150. http://dx.doi.org/10.1016/0034-4257(79)90013-0

U.S. Geological Survey [USGS] (2023). Earth Explorer portal. Retrieved from: https://earthexplorer.usgs.gov [accessed 27.04.2023].

Welles, J. M. & Cohen, S. (1996). Canopy structure measurement by gap fraction analysis using commercial instrumentation. *Journal of Experimental Botany*, *47* (9), 1335–1342. https://doi.org/10.1093/jxb/47.9.1335

Summary

Spatial mapping of leaf area index using remote sensing and ground measurements – the Biebrza National Park case study. The purpose of the described research was an attempt to estimate the leaf area index (*LAI*) parameter describing the structure of the vegetation based on Landsat 5TM satellite imagery and field measurements made with the use of an optical plant canopy analyzer. The study was carried out in north-eastern Poland in the Biebrza river valley within the boundaries of the Biebrza National Park during the growing season of the year 2007. There were 13 spectral indices given in the literature known to be

correlated with the *LAI*. The highest coefficient of determination and the highest correlation coefficient was obtained for the normalized difference vegetation index (*NDVI*) and the soil adjusted vegetation index (*SAVI*) indices for wetland areas in the Biebrza river valley. The field measurements of the leaf area index and its spatial representation on satellite image show that the vegetation of natural river valleys is characterized by high spatial and seasonal variability. The study of *LAI* on such large natural areas that are extensively used also requires knowledge of the methods of land use and the application of individual agrotechnical measures.