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Spectral estimation of wetland carbon dioxide exchange*

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A b s t r a c t. The simultaneous measurements of broadband normalized difference vegetation index and net ecosystem production were carried out at Rzecin wetland in 2009. Additionally, carbon fluxes, ecosystem respiration and gross ecosystem production were estimated on the basis of measured net ecosystem production values. The maximum broadband normalized difference vegetation index value (0.73) was measured on the 6th of July. The minimum broadband normalized difference vegetation index value measured before and after the vegetation period was 0.40. The annual dynamics of carbon fluxes and broadband normalized difference vegetation index runs were different from each other. During the second half of vegetation period greenness of plants decreases more slowly than plants carbon dioxide uptake capacity. These differences are likely to be determined by plants aging. The results presented in this paper show potential applicability of broadband normalized difference vegetation index for the estimation of carbon dioxide exchange in wetlands.

K e y w o r d s: net ecosystem production, broadband normalized difference vegetation index, wetland, eddy covariance, solar radiation

INTRODUCTION

Physical and chemical properties of the atmosphere influence the whole biosphere *eg* carbon cycle in the Earth-atmosphere system (Dawidson and Janssens, 2006; Kirkham, 2011; Kutilek, 2011).Wetland plants absorb CO_2 from the atmosphere during the photosynthesis process. This flux is called gross ecosystem production (GEP) while CO_2 release from ecosystems is called ecosystem respiration (R_{ECO}). GEP value can be calculated on the basis of the following formula:

$$\mathrm{GPP} = \mathrm{NEP} - R_{ECO},$$

where: NEP – net ecosystem production, R_{ECO} – ecosystem respiration (all in μmol C-CO_2 m^{-2} s^{-1}) (Kirschbaum *et al*., 2001). The fluxes entering and leaving the ecosystem surface are marked ‘+’ and ‘-’ respectively in this paper. The absorption process described above results in the formation of organic soils (hydrogenic). They are one of the largest terrestrial carbon pools. Therefore, wetland gas exchange studies become important in the context of the carbon balance in the biosphere. These types of ecosystems are very sensitive to the climate changes because of the strong correlation between water and carbon balances (Bridgham *et al*., 2008).

There are several gas and heat exchange measurement techniques applied recently near the ecosystem active surface (Eulenstein e*t al*., 2005a,b; Olejnik *et al*., 2001) but the spatial range of these observations is limited. The global estimation of the mass and energy exchange between terrestrial ecosystems and the atmosphere can be carried out only with application of large spatial scale methods *eg* remote sensing. The application of remote sensing techniques is particularly justified since wetlands are often located in remote places where direct measurements are limited or even impossible (Prigent *et al*., 2001). The satellite observations allow to assess the physiological state of the vegetation. This characteristic is one of the most important factors that controls carbon dioxide exchange intensity between the terrestrial ecosystems and the atmosphere. Several spectral coefficients have been developed over last decades for the remote estimation of vegetation physiological condition (Liang, 2004). The normalized differential vegetation index (NDVI) is one of the most commonly used spectral coefficients (Jarocińska and Zagajewski, 2008) and its value is calculated on the basis of spectral measurements conducted

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by using specialized hyperspectral sensors (Balzarolo, 2011). Such technically advanced instruments are relatively rarely applied in field conditions. Thus, the broadband NDVI ($NDVI_B$) has been developed as an alternative solution for hiperspectral sensors. This coefficient value can be calculated on the basis of commonly made shortwave and photosynthetic photon flux density measurements (Huemmrich *et al*., 1999).

The measurements of radiation and net production fluxes were carried out with different instruments. Thus, the ecosystem surfaces that are surveyed (footprints) by means of these sensors are different both in shape and size. Those differences between the footprints parameters influence both the quality and representativeness/relevance of the measured fluxes values (Göckede *et al*., 2004). It has been pointed out in the literature that snow cover and cloudiness have an impact on $NDVI_B$ value (Huemmrich *et al*., 1999) while some studies indicate no influence of cloud cover on this index value (Tittebrand *et al*., 2009). The $NDVI_B$ has already been used for the remote estimation of CO_2 uptake capabilities of vegetation (Nagy and Jung, 2005; Tittebrand *et al*., 2009; Wohlfahrt *et al*., 2010) but these studies were conducted only for forest and grasslands.

The main goal is a description of seasonal run of $NDVI_B$ as a parameter of carbon dioxide exchange between the wetland ecosystem and the atmosphere.

MATERIALS AND METHODS

The investigations were was conducted at Rzecin wetland 70 km NW of Poznań (Western Poland). The eddy covariance (EC) tower was erected there (52° 45' 44" N / 16° 18' 34" E) at the end of 2003. The instruments installed on the tower enable one to carry out the comprehensive studies of mass and energy exchange between the wetland ecosystem surface and the atmosphere (Lund *et al*., 2010; Owen *et al*., 2007). The results of the analysis presented in this paper were based on the data collected during the period from the 1st of January to the 31st December 2009. A pair of CM3 pyranometers was applied for shortwave radiation flux density measurements. The upward facing pyranometer was used for measurements of shortwave radiation flux (global radiation) (Rs_{in}) that reaches the ecosystem vegetation surface. However, the reflected shortwave radiation flux density (Rs_{ref}) was measured by a pyranometer facing downward. Both sensors are parts of a net radiometer CNR 1 (Kipp and Zonen, Delft, the Netherlands). The measurements of reflected $PPFD_{ref}$ were conducted with downward facing Quantum sensor (Skye Instruments Ltd., Powys, UK). All radiation sensors described above were installed on a 4.1-meter long steel arm at the height of 2.35 m above the peatland surface. A set of these sensors was applied over *Menyantho-Spahgnetum teretis* Warén 1926 vegetation community type. Additionally, a sunshine sensor, BF3H (Delta-T Devices, Burwell, UK), was installed near the EC tower at the height of 3 m. This device measures both global PPFDg and diffused PPFDd simultaneously. These measurements allow to estimate PPFD diffusivity index (DI_{PPFD}) which is mainly a result of clouds presence.

The meteorological measurements at Rzecin site (also radiation) were carried out automatically at 1Hz sampling rate and 30-min average or total values of measured parameters are stored in the field computer memory (Chojnicki *et al*., 2007). The eddy covariance (EC) system was installed at the top of the tower (4.5 m). This system consists of R3-100 3D sonic anemometer (Gill Instruments Ltd., Limington, UK) and an open path CO_2/H_2O gas analyzer LI-7500 (LI-COR, Lincoln, NE, USA). The time series of 30-min measurements of average values of heat (sensible), CO_2 and H_2O net fluxes were the result of this system application.

The EC technique can only be applied in the conditions of well-developed turbulence and stationary fluxes (Lee *et al*., 2004). These theoretical requirements are not always fulfilled in field conditions and this is the main reason of gaps in the obtained time series. Empirical process oriented models were used to fill gaps in raw time series of NEP and to estimate R_{ECO} value. All PPFD values presented in this article were converted from photon flux density (μmol photons m^{-2} s^{-1}) into energy units (J m^{-2} s^{-1}) using 4.55 μmol photons J^{-1} in order to calculate broadband NDVI (Heummrich *et al*., 1999):

$$NDVI_B = \frac{\rho_{RsIR} - \rho_{PPFD}}{\rho_{RsIR} + \rho_{PPFD}},$$

where:

$$\rho_{PPFD} = \frac{PPFD_{ref}}{PPFD_g} \text{ and } \rho_{RsIR} = \frac{Rs_{ref} - PPFD_{ref}}{Rs_{in} - PPFD_g}.$$

The cloudiness was assessed on the basis of DI_{PPFD} value that was calculated as a ratio between the PPFDd and PPFDg incidence at the earth's surface. Additionally, albedo values were also calculated in order to assess the snow cover occurrence on the surveyed surface since snow occurrence leads to $NDVI_B$ overestimation. The $NDVI_B$ values presented in this article were calculated for the period from 12:00 to 12:30 local time.There were the following reasons of this noon period selection: the reduction of averaging time in the case of manual $NDVI_B$ measurements; $NDVI_B$ averaging time comparable with averaging periods used in common data bases *eg* CARBOEUROPE; the reduction of solar angle impact on $NDVI_B$ value. The snow cover impact on $NDVI_B$ has been reduced by removing all the data calculated for albedo values higher than 0.20.

RESULTS AND DISCUSSION

Publications describing $NDVI_B$ suggest an impact of cloudiness on its values (Huemmrich *et al*., 1999), this fact is not confirmed in the presented study where no correlation between $NDVI_B$ and DI_{PPFD} has been found (Fig. 1). There

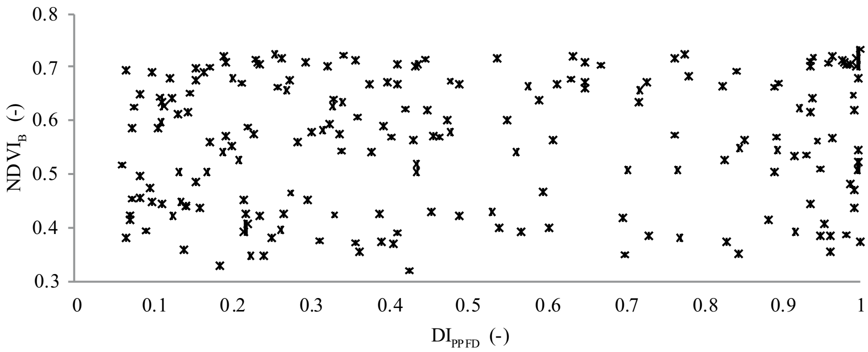

Fig. 1. Broadband NDVI ($NDVI_B$) vs. PPFD diffusivity index (DI_{PPFD}).

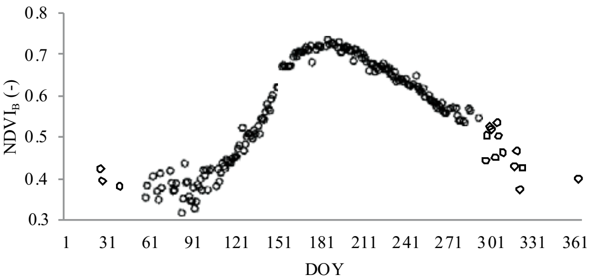

Fig. 2. Calculated seasonal run of broadband NDVI ($NDVI_B$) (values calculated for time 1200 to 1230LT). DOY – day of year.

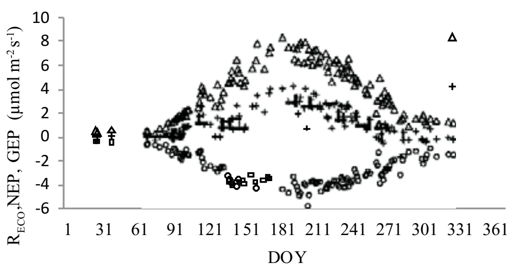

Fig. 3. Seasonal runs of GEP – triangles, net ecosystem production NEP – crosses, R_{ECO} – circles. Explantions as in Fig. 1.

is still an open question of reason of differences between the presented and published results. One of the explanations can be the fact that the cloudiness described in both articles was obtained with two different methods. It is still difficult to answer the question if BF3H measurements are comparable with the measurements carried out by satellites. The studied data analysis reports the underestimation of $NDVI_B$ values in the conditions of very low Rs_{in} (<200W m^{-2}) values. This was the reason why all $NDVI_B$ values collected under minimum shortwave threshold conditions were removed from the finally analyzed dataset.

The meteorological conditions in 2009 were compared to the climate data for the studied area. In comparison to multiannual mean values, 2009 was characterized by mean air temperature value, and higher than average both radiation and rainfall amount that reach the wetland surface. The annual sum of precipitation in 2009 was 705.5 mm while the estimated multiannual mean sum of precipitation for 1970-2001 period is 566 mm (Climate Atlas of Wielkopolska Province). The average air temperature measured 2 m above the peatland surface was 8.2°C in 2009 and the annual mean value of air temperature for 1970-2001 was estimated as 8.0°C (Climate Atlas of Wielkopolska Province). The annual sum of incoming radiation in 2009 was 3845.4 MJ m^{-2} and it exceeded the average quantity for 2005-2009 period, which was 3589.3 MJ m^{-2}.

$NDVI_B$ values oscillated around 0.4 during the first 105 days of 2009 (until 15th of April) and have increased rapidly since that date. The maximum value of $NDVI_B$ (about 0.73) was observed on the 187th day of the year (DOY) (6th of July). There was a slow decrease of NDVIB since the culmination and it lasted until the 330th day of the year (26th of November) when 0.4 value was reached again (Fig. 2). GEP has a slightly different yearly course than $NDVI_B$. The rapid growth of GEP started from the level of 0.5 μmol CO_2-C m^{-2} s^{-1} on the 81st day (22nd of March) and continuously lasted until the 184th (3rd of July) day of the year. GEP reached the maximum flux density value of 8.29 μmol CO_2-C m^{-2} s^{-1} on that day. The rapid decrease of GEP value was observed after the day of culmination until the 285th day of year (12th of October). The GEP varied in the range of 1.0 μmol CO_2-C m^{-2} s^{-1} after this term. The shape of NEP course (maximum 4.27 μmol CO_2-C m^{-2} s^{-1}) was parallel to GEP whereas NEP values were shifted down on the chart because of their reduction by R_{ECO}. The R_{ECO} run was symmetrical to GEP course but the emission of CO_2 from the ecosystem reached negative values (minimum -5.59 μmol CO_2-C m^{-2} s^{-1}) (Fig. 3).

The obtained values were used for estimation the strength of correlations between $NDVI_B$ and GEP. The non-linear relationship between those variables was found. GEP values ranged from 8 to 9 for maximum $NDVI_B$ (0.70-0.75) values while GEP from 1 to 2 μmol m^{-2} s^{-1} is typical for minimal seasonal $NDVI_B$ values (0.30-0.35) (Fig. 4a). The correlation between $NDVI_B$ and R_{ECO} seems to be linear

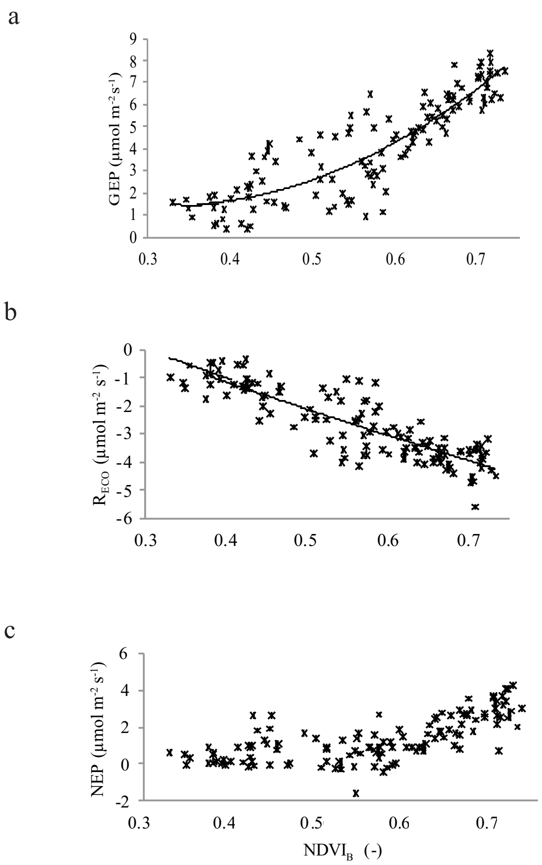

Fig. 4. Broadband NDVI ($NDVI_B$) *vs* average daily: a – gross ecosystem production (GEP), b – ecosystem respiration (R_{ECO}), c – net ecosystem production.

(negative regeression) and average daily emission from the studied ecosystem was around -4.5 μmol CO_2-C m^{-2} s^{-1} when $NDVI_B$ reached the maximum value (Fig. 4b). The relationship between $NDVI_B$ and NEP was non-linear and it was similar to the dependence between $NDVI_B$ and GEP. Maximum NEP values were about 3.5 μmol CO_2-C m^{-2} s^{-1} for maximum $NDVI_B$ values (Fig. 4c). The analysis of the data set presented in this article showed no correlation between $NDVI_B$ values and the atmosphere turbidity (DI_{PPFD}). This conclusion is contrary to the published results (Heummrich *et al.*, 1999). However there is an open question about correlation between ground and satellite measurements. The lack of impact of DI_{PPFD} on $NDVI_B$ was the reason for using broadband NDVI values collected in overcast conditions during further analysis. Low Rs_{in} values (less than 200 W m^{-2}) cause underestimation of $NDVI_B$ values and it corresponds with other authors results (Wittich and Kraft, 2008). However, the results presented in this paper indicate that not only the occurrence of cloud cover but also low Rs_{in} values result in underestimation of the studied $NDVI_B$ values. The analysis presented here was prepared on the basis of the data collected while Rs_{in} was higher than 200 W m^{-2} and snow cover was not present (albedo values lower than 0.20). The $NDVI_B$ data selection described above resulted in obtaining only positive GEP values even in winter time. The positive values of GEP were probably a result of both relatively high air temperature observed at this site at the beginning and at the end of the year 2009 and the presence of mosses that are able to absorb CO_2 from the atmosphere at low temperature (right after a thaw). All seasonal runs of GEP, NEP, R_{ECO} seem to be symmetrical to their culmination values. In other words they both increase before and decrease after reaching the maximum value, which means that have the same dynamics. In contrast, the $NDVI_B$ value increased rapidly at the beginning of the vegetation season and slowly decreased after the culmination. This difference between the dynamics of runs of CO_2 and $NDVI_B$ fluxes in the second half of the vegetation period indicates that CO_2 uptake capability of plants decreased faster than greenness of the observed plant cover. This fact is probably caused by plants ageing (Munne-Bosch and Alegre, 2002). An explicit linear relationship between $NDVI_B$ and R_{ECO} (Fig. 4b) does not seem to be physiologically explicable since greenness is only indirectly related to soil organisms activity. It could be a result of temperature increase since this parameter strongly determines both vegetation development and intensity of R_{ECO}. The lack of clear dependence between carbon dioxide fluxes and $NVDI_B$ can be a result of the fact that the radiation and EC sensor footprints are not the same in shape and size. The EC tower study area is hundreds of times bigger than the surface monitored by radiation sensors. This issue requires more in-depth studies of spatial variability of $NDVI_B$ values within the range of the EC tower footprint. $NDVI_B$ is scientifically very attractive due to low cost of sensors that are commonly applied in ecological studies of ecosystems. A pair of pyranometers and a pair of PPFD sensors can be applied for vegetation physiological status assessment and, thus wetlands plants CO_2 uptake capability estimation.

CONCLUSIONS

1. The cloud cover degree does not impact the broadband normalized difference vegetation index values but the incoming shortwave radiation intensity decrease (below 200 W m^{-2}) reduces this index value considerably.

2. The broadband normalized difference vegetation index value rises quickly in the beginning and slowly decreases in the second half of vegetation season. The gross ecosystem production run is symmetrical to its culmination date in the middle of this period. The comparison of those two runs indicates a reduction of vegetation capability of carbon dioxide uptake from the atmosphere despite relatively high greenness of plant canopy.

3. A linear relationship between ecosystem respiration and broadband normalized difference vegetation index values can be caused by the same determining factor, such as ambient temperature.

4. Lack of strong correlation between carbon dioxide fluxes and broadband normalized difference vegetation index values can be a result of different size and shape of the eddy covariance tower and radiation sensor footprints. Further research on broadband normalized difference vegetation index spatial variability should be helpful to estimate the representativeness/relevance of broadband normalized difference vegetation index measurements conducted close to the eddy covariance tower.

5. Broadband normalized difference vegetation index seems to be a very valuable index for the assessment of plants phenology because of relatively strong interrelation between its value and the vegetation carbon dioxide uptake capability. Additionally, the estimation of broadband normalized difference vegetation index value does not require the application of expensive and technically complicated equipment.

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