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Estimating northern peatland CO_2 exchange from MODIS time series data

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ABSTRACT

Studies using satellite sensor-derived data as input to models for CO_2 exchange show promising results for closed forest stands. There is a need for extending this approach to other land cover types, in order to carry out large-scale monitoring of CO_2 exchange. In this study, three years of eddy covariance data from two peatlands in Sweden were averaged for 16-day composite periods and related to data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and modeled photosynthetic photon flux density (PPFD). Noise in the time series of MODIS 250 m vegetation indices was reduced by using double logistic curve fits. Smoothed normalized difference vegetation index (NDVI) showed saturation during summertime, and the enhanced vegetation index (EVI) generally gave better results in explaining gross primary productivity (GPP). The strong linear relationships found between GPP and the product of EVI and modeled PPFD ($R^2 = 0.85$ and 0.76) were only slightly stronger than for the product of EVI and MODIS daytime 1 km land surface temperature (LST) ($R^2 = 0.84$ and 0.71). One probable reason for these results is that several controls on GPP were related to both modeled PPFD and daytime LST. Since ecosystem respiration (ER) was largely explained by diurnal LST in exponential relationships ($R^2 = 0.89$ and 0.83), net ecosystem exchange (NEE) was directly related to diurnal LST in combination with the product of EVI and modeled PPFD in multiple exponential regressions ($R^2 = 0.81$ and 0.73). Even though the R^2 values were somewhat weaker for NEE, compared to GPP and ER, the RMSE values were much lower than if NEE would have been estimated as the sum of GPP and ER. The overall conclusion of this study is that regression models driven by satellite sensor-derived data and modeled PPFD can be used to estimate CO_2 fluxes in peatlands.

1. Introduction

Studies have shown that mid- to high-latitude forests at the Northern Hemisphere probably can explain the so-called “missing sink” for atmospheric carbon dioxide (CO_2) (Keeling et al., 1996; Prentice et al., 2001). Research has therefore focused on forest CO_2 exchange, with less attention given to other ecosystem types, until recently. Peatlands are important in the carbon cycle, since they may store 30% of the global soil carbon or 50% of the carbon currently in the atmosphere (Gorham, 1991; Turunen et al., 2002). The major fraction of all peatlands is located in northern temperate and cold climates (Aselmann & Crutzen, 1989). Because of waterlogged, anoxic, and cool conditions, peatlands are characterized by slow decomposition rates, which together with photosynthesis results in the accumulation of atmospheric CO_2. However, there are concerns that increased temperatures and evapotranspiration rates will cause drought conditions and a subsequent release of CO_2 (Gorham, 1991; Tarnocai, 2006; Aurela et al., 2007). In sub-arctic peatlands, temperature increases may lead to permafrost melting, affecting the physical stability of the ground and the biological dynamics of the soil and potentially having severe consequences for the carbon storage (Gorham, 1991; Johansson et al., 2006; Tarnocai, 2006). For these reasons, it is of particular interest to find suitable ways of extending estimates of CO_2 exchange in peatlands, across time and space.

An important method of measuring CO_2 exchange for extended time periods is the eddy covariance technique (Wofsy et al., 1993; Lindroth et al., 1998; Aubinet et al., 2000; Falge et al., 2001). In the mid- and high-latitudes, an increasing number of eddy covariance tower sites cover a variety of ecosystems, such as forests, grasslands, wetlands, and agricultural lands (Baldocchi et al., 2001; Baldocchi, 2003). Still, these on-site measurements are restricted in space, and therefore, do not represent the diversity of different species, age classes, and site conditions at a larger scale (Lagergren et al., 2006).

One way to extend estimates of CO_2 exchange to a larger spatial scale is to use satellite sensor-derived data as input to a light use efficiency (LUE, see Appendix for abbreviations and symbols) model, developed by e.g. Monteith (1972, 1977) and Prince (1991). It is well known that the LUE model comes in the two versions where either gross primary productivity (GPP) or net primary productivity (NPP) is expressed as the product of the photosynthetically active radiation absorbed by vegetation (APAR) and the light use efficiency factor (ε). While GPP is the total amount of CO_2 taken up by photosynthesis, NPP

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is the CO_2 uptake after subtraction of autotrophic respiration, and ε is the vegetation capacity to convert radiation energy into biomass. It has been shown that the fraction of absorbed photosynthetically active radiation (FAPAR) is dependent on the normalized difference vegetation index (NDVI; Rouse et al., 1973) and that the relationship is linear (Asrar et al., 1984, 1992; Goward & Huemmrich, 1992; Myneni & Williams, 1994). Therefore, satellite sensor-derived NDVI has been used to derive FAPAR (Tucker et al., 1986; Chen, 1996; Fensholt et al., 2004; Olofsson & Eklundh, 2007), and when FAPAR is available, APAR is easily calculated by multiplying FAPAR with the incoming photosynthetically active radiation (PAR).

For Scandinavian coniferous forests, Olofsson et al. (2007) used NDVI from the Moderate Resolution Imaging Spectroradiometer (MODIS) to derive FAPAR, and then, calculated APAR by multiplying FAPAR with modeled PAR. The LUE model was used to estimate NPP, with ε dependent on latitude, air temperature (AT), and the day of the year (DOY) (Lagergren et al., 2005). For North European coniferous and deciduous forests, Olofsson et al. (2008) adopted another approach without any separate estimation of ε. Eddy covariance GPP was modeled with a regression function driven by APAR and the MODIS enhanced vegetation index (EVI; Huete et al., 2002). By reducing atmosphere and canopy background influences, EVI enhance the vegetation signal and maintains sensitivity in high biomass regions:

$$EVI = G\frac{\rho_{\mathrm{NIR}}-\rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}}+C_1\rho_{\mathrm{red}}-C_2\rho_{\mathrm{blue}}+L}, \tag{1}$$

where ρ_{NIR}, ρ_{red}, and ρ_{blue}, are surface reflectance values in the near infrared (NIR), red, and blue wavelength bands, respectively. The coefficients $C_1 = 6$ and $C_2 = 7.5$ correct for atmosphere influences, while $L = 1$ adjust for the canopy background. The factor $G = 2.5$ is the gain factor. To achieve APAR, Olofsson et al. (2008) derived FAPAR from NDVI and multiplied it with measured PAR. Furthermore, ecosystem respiration (ER) was modeled with a regression function driven by AT, and net ecosystem exchange (NEE) was finally calculated from GPP and ER. Both Olofsson et al. (2007) and Olofsson et al. (2008) used eddy covariance data to validate modeled CO_2 fluxes, and stronger relationships were obtained for GPP and ER, than for NEE.

For North American coniferous and deciduous forests, Rahman et al. (2005) found an equally strong relationship between eddy covariance GPP and MODIS EVI as for eddy covariance GPP and the MODIS GPP product (MOD17; Running et al., 2004). It was also found that nighttime ER was related to nighttime MODIS land surface temperature (LST). In a subsequent study with additional sites, Sims et al. (2006) found that EVI performed even better than MODIS GPP. This was later confirmed by Sims et al. (2008) and implemented in their temperature and greenness (TG) model, which improved the results by combining EVI and LST. Therefore, it was suggested that simpler models based entirely on satellite sensor-derived data could be as good as the MODIS GPP product.

Heinsch et al. (2006) evaluated the LUE-based 1 km MODIS GPP product (MOD17) and indicated that the input of coarse resolution meteorological data is the most limiting factor in the quality of the product. It was also pointed out that the 1 km land cover product (MOD12Q1), used in the MOD17 algorithm, has a too coarse resolution to be applied in regions with heterogeneous vegetation. An additional problem is that the particular land cover classification scheme in MOD12Q1 (the product contains multiple schemes) used to extract ε from lookup tables does not have any category for peatlands (Heinsch et al., 2003). In their study of peatland representation on global maps, Krankina et al. (2008) investigated the MOD12Q1 product based on another classification scheme that includes a category for peatlands. This scheme is used to derive FAPAR as input to the MOD17 algorithm. It was found that peatlands are highly underrepresented, compared to a detailed map of the St. Petersburg region in Russia. Since peatlands often are smaller areas located within a mosaic of other land cover types, such as temperate and boreal forests, it seems that the MOD17 product cannot account for the site-specific conditions in peatlands. Although these studies focused on 1 km MODIS products, it is reasonable to assume general resolution difficulties associated with peatlands.

An additional problem with peatlands is that investigations both in the laboratory and in the field have demonstrated that *Sphagnum* mosses, which dominate most peatland types, have distinctively different spectral signatures compared to vascular vegetation (Vogelmann & Moss, 1993; Hall et al., 1995; Bubier et al., 1997; Bryant & Baird, 2003). According to Bubier et al. (1997), the narrow red absorptions and near-infrared (NIR) peaks of *Sphagnum* mosses, which are dominant in this study, make NDVI and the simple vegetation index ratio inappropriate for characterizing biomass or greenness. Also, Vogelmann & Moss (1993) and Bubier et al. (1997) show that the differences between the red and NIR reflectance values are smaller for *Sphagnum* mosses, which generates lower NDVI values. For the seasonal variation in NDVI, this should mean that the errors in data are larger in relation to the range, making it harder to find strong relationships with other seasonal variables.

Evidently, there are problems to be solved, but satellite sensor-derived data have successfully been used in regression models for CO_2 fluxes in forests. There is a need for exploring similar relationships for other ecosystem types, such as peatlands, in order to carry out large-scale monitoring of CO_2 exchange. Failure to account for ecosystem differences is likely to result in either an over- or underestimation of CO_2 exchange at the regional or global level. The aim of this study is to assess the possibility of using satellite sensor-derived data and modeled photosynthetic photon flux density (PPFD) in regression models for CO_2 fluxes in peatlands. To achieve this, eddy covariance NEE from two Swedish peatlands were used as ground truth data. First, different environmental controls on GPP were related to modeled PPFD and MODIS LST, and then, GPP, ER, and NEE were related to various combinations of modeled PPFD, MODIS EVI, and MODIS LST.

2. Material and methods

2.1. Study sites

Two sites were used: Fäjemyr and Degerö Stormyr. Fäjemyr is a raised temperate ombrotrophic bog, surrounded by forest (see Appendix for peatland-related concepts). It is located 50 km east of the coast of Kattegat Bay in southern Sweden (56°15′N, 13°33′E) and covers about 2.9 km^2. The temperate climate has a mean (1961–1990) annual AT and precipitation of 6.2 °C (January: −2.4 °C, July: 15.1 °C) and 700 mm, respectively (Lund et al., 2007). The average (2005–2007) vegetation period is 199 days (AT > 5 °C), and the snow period is intermittent. The average (2005–2007) water table depth (WTD) is 16 cm below the surface. Peat has accumulated to the depth of about 5 m. Scattered dwarf pines (*Pinus sylvestris* L.) grow on the drier patches. Dominant vascular plant species on the hummocks are dwarf shrubs (*Calluna vulgaris* L. Hull and *Erica tetralix* L.). Sedges (mainly *Eriophorum vaginatum* L.) are common in the lawns and carpets. *Sphagnum* mosses (mainly *S. magellanicum* Brid. and *S. rubellum* Wils.) constitute the bottom layer of the lawns and carpets. Lund et al. (2009b) estimated the proportions of the hummocks, lawns/carpets, and hollows to 13%, 83%, and 4%, respectively. The moss cover was estimated to 60%. Lindroth et al. (2007) estimated the leaf area index (LAI) to about 1. The eddy covariance tower is located about 250 m from the bog edge, and the eddy covariance system, consisting of a closed-path infrared gas analyzer (IRGA, Li-Cor 6262, Li-Cor Inc, USA) and a three-dimensional sonic anemometer (Gill R3, Gill Instruments, UK), is mounted 3.4 m above the ground. Further information on site and instrumentation details can be found in Lund et al. (2007).

Degerö Stormyr (only “Degerö” in this text) is a boreal oligotrophic minerotrophic fen, surrounded by forest. It is located 70 km west of