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Light use efficiency of peatlands: Variability and suitability for modeling ecosystem production

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ABSTRACT

Peatland net ecosystem production is a key variable to assess changes in the functional role of peatlands in the global carbon cycle. Light use efficiency (LUE) models in combination with satellite data have been used to estimate production for most major ecosystems, but peatlands have been largely ignored. The objectives of this study were: 1) to examine how the LUE parameter epsilon, ε (the amount of carbon fixed or converted to biomass per unit absorbed photosynthetically active radiation), varies between and within four different peatlands; 2) to examine how the variations in ε relate to variations in environmental conditions; and 3) to evaluate a LUE-based model for estimation of ε in peatlands. We achieve these objectives using a combination of eddy covariance flux measurements, climate data and satellite data and estimate ε using the LUE-based vegetation photosynthesis model (VPM). The results show that: 1) mean site-specific flux-derived ε values ($\pm$ standard deviation) were split into three statistically different groups: lowest values at the two colder fens, Kaamanen and Sandhill (0.22 ± 0.18 and 0.23 ± 0.20 g C MJ^{-1}, respectively), highest values at the treed fen La Biche (0.47 ± 0.27 g C MJ^{-1}) and intermediate values at the bog, Mer Bleue (0.34 ± 0.18 g C MJ^{-1}); 2) Variations in monthly ε within sites related mainly to air temperature, while variations in annual ε within sites related mainly to wetness variables; 3) relative mean absolute errors of estimates of ε for the four sites ranged between 19% and 35%, with r^2 values ranging between 72% and 93%. LUE models are appealing as they are relatively simple formulations of variables that are easily obtained from satellite data. Challenges associated with the use of satellite data derived input variables are further discussed in the paper.

1. Introduction

Northern peatlands play an important role in the global carbon (C) cycle (e.g. Dise, 2009; Gorham, 1991). These ecosystems, characterized by moderate primary production but slow decomposition rates, have accumulated ~550 Gt C since the end of the last glaciation (e.g. Tarnocai et al., 2009; Yu et al., 2010). Studying the C cycle in peatlands at regional and global scales is challenging because of their remote locations and extensive area. Ecosystem models in combination with in situ data and remote sensing technologies have been used to address similar challenges for several other ecosystems (e.g. BIOME-BGC: Running and Hunt, 1993). Some ecosystem process models have been adapted to include wetland and peatland ecosystems (e.g. Wetland-DNDC: Cui, Li, & Trettin, 2005; BIOME4: Wania, Ross, & Prentice, 2009; BEPS-TerrainLab: Sonnentag, 2008) but their application to larger areas becomes complicated, mainly because of the necessity to obtain input data for describing the complex peatland hydrology. One class of ecosystem models that has potential for regional and global estimates of primary production is based on the light use efficiency (LUE: Monteith, 1972) concept. The advantage of LUE models over the more detailed ecosystem process based models is their relatively simple formulation and their easy adaptation to assimilate data obtained from satellite observations. The limitations of the LUE models are that they require a well constrained LUE parameter or *epsilon* (ε), and accurate estimates of solar energy absorption by the vegetation. These parameters have been studied and established for some of the major ecosystems including forests and grasslands, but little attention has been given to northern peatlands. Consequently, in this study we examine the variability of ε using eddy covariance (EC) flux measurements of the gross primary production (GPP) and photosynthetically active radiation (PAR) across four

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contrasting northern peatlands; and evaluate the suitability of LUE models for the estimation of epsilon for northern peatlands.

Epsilon expresses the amount of C either fixed (e.g. GPP) or converted to biomass (e.g. net ecosystem production or net primary production, NPP) per unit of absorbed PAR (APAR). Monteith (1977, 1972) initially proposed ε as:

$$\varepsilon = \frac{NPP}{fPAR \times iPAR} \quad (1)$$

where *fPAR* and *iPAR* are the fraction and incident photosynthetically absorbed radiation, respectively. PAR, the total amount of incident radiation modified by clouds and atmospheric conditions, is determined by geographic location and season. *fPAR* is determined based on the extent and geometry of the vegetation canopy. Thus, LUE models combine the meteorological and ecophysiological factors that determine the absorption of the solar radiation by a plant canopy (Running, Ramakrishna Nemani, Glassy, & Thornton, 1999).

1.1. Parameterization of ε

For LUE models, ε has been determined by both direct and indirect methods. Direct methods include the use of field measurements of production (e.g. destructive sampling, EC measurements) and radiation (e.g. quantum sensor and net radiometer measurements) (e.g. Lagergren et al., 2005; Rosati, Metcalf, & Lampinen, 2004; Turner et al., 2003). Studies have used both gross and net production for the production variable, but it is preferable to use the gross production in the calculation of ε (Goetz, Prince, Goward, Thawley, & Small, 1999; Gower, Kucharik, & Norman, 1999) because the resultant ε is expected to be more conservative. NPP is related to GPP through the addition of autotrophic respiration (AR: NPP = GPP − AR). Similarly to the production variable, the radiation variable has also been described by multiple measures, including intercepted, incident, absorbed total shortwave or PAR. Gower et al. (1999) suggest basing the LUE estimation on PAR and not on shortwave radiation. Both production and radiation have also been indirectly estimated using satellite data-derived vegetation indices (e.g. Fensholt, Sandholt, & Rasmusses, 2004; Goward & Huemmrich, 1992) or process-based production models (e.g. Ito & Oikawa, 2004).

Studies have used such direct or indirect measurements of ε to determine a single global or biome-specific ε value (e.g. Field, Randerson, & Malmstrom, 1995; Ruimy, Saugier, & Dedieu, 1994) or a potential maximum value that is reduced under stress conditions (e.g. Seaquist, Olsson, & Ardo, 2003; Xiao et al., 2004). The vegetation photosynthesis model (VPM, Xiao et al., 2004), for example, uses scalars derived from the land surface water index (LSWI) to characterize the variability in vegetation wetness and phenology, and to reduce a maximum ε value. Vegetation indices that use the short wave infrared (SWIR) and near infrared (NIR) band reflectances (e.g. land surface water index, LSWI; moisture stress index, MSI; and the normalized difference water index, NDWI) are assumed to be sensitive to changes in leaf area and soil moisture. The moderate resolution imaging spectroradiometer (MODIS) GPP algorithm uses a LUE approach to estimate GPP at 8-day intervals across the terrestrial ecosystems of the globe. The model uses a maximum (modelled) biome-specific ε value that is reduced by scalars derived from minimum temperature and vapour pressure deficit. Indirect methods for estimation of ε include the use of empirical relationships between ε and vegetation indices (Drolet et al., 2005; Gamon, Serrano, & Surfus, 1997).

1.2. LUE models and peatlands

Several studies have evaluated LUE models and the results are promising for a wide range of ecosystems (e.g. Coops, Black, Jassal, Trofymow, & Morgenstern, 2007; Yuan et al., 2007). A few studies have evaluated the variability and controls of ε, and the applicability of LUE models for peatland ecosystems (e.g. Connolly et al., 2009; Harris & Dash, 2011; Kross, Seaquist, Roulet, Fernandes, & Sonnentag, 2013; Schubert, Eklundh, Lund, & Nilsson, 2010). Harris and Dash (2011), for example, studied three LUE model approaches using a combination of the medium resolution imaging spectrometer (MERIS) terrestrial chlorophyll index (MTCI), fPAR and PAR. The linear model based on the product of MTCI, fPAR and PAR performed best for estimation of GPP, with r^2 values of 75% and 89% for the Mer Bleue peatland (Ontario, Canada) and the LaBiche peatland (Alberta, Canada), respectively. Schubert et al. (2010) evaluated the performance of LUE models based on combinations of the enhanced vegetation index (EVI), land surface temperature (LST) and PAR. The model based on the product of EVI and PAR performed slightly better for estimating GPP of their two study sites (r^2 of 76%–85%). PAR is a critical input to LUE models and both previous studies (Schubert et al., 2010; Harris & Dash, 2011) used local and regional measured or modelled PAR.

1.3. Objectives

The present study builds upon findings from our earlier research (Kross et al., 2013) using the same study sites. Kross et al. (2013) compared several remote sensing approaches (linear regression models based on vegetation indices and MODIS gross primary productivity, GPP product) for the estimation of peatland production and reported superior performance of the MODIS GPP product which uses a LUE model. The MODIS GPP model however uses fixed input variables (landcover, epsilon) and model parameters often do not account for peatlands specifically. The current study evaluates and customizes an existing LUE model for peatlands, using satellite input data and a global modelled PAR dataset.

The specific objectives of this study were to: 1) to examine how ε varies between and within functionally different peatlands; 2) to examine how the variations in ε relate to variations in environmental conditions; and 3) to evaluate a LUE-based model for estimation of epsilon in peatlands.

LUE models are an appealing approach for obtaining estimates of regional and global C exchange in peatlands but their success depends on their ability to capture the variation in C exchange and on their broad applicability. We hypothesize that LUE models are suitable for peatlands because: 1) There is a unique maximum ε for peatlands and it is consistent across peatland types; and 2) The maximum ε scales consistently across and within peatlands due to environmental constraints; thus LUE models can give useful estimates of GPP for northern peatlands.

2. Data and methods

2.1. Study sites

We used data from three Canadian sites (Mer Bleue bog, MB: Roulet et al., 2007; LaBiche fen, LB: Flanagan & Syed, 2011; and Sandhill fen, SH: Sonnentag, Kamp, Barr, & Chen, 2010) and one Finnish site (Kaamanen arctic fen, KM:) (Table 1).

The Canadian sites were part of the Canadian Carbon Program (CCP, http://fluxnet.ornl.gov/site_list/Network/3) while the Finnish site was part of the CarboEurope network (http://fluxnet.ornl.gov/site/449).

All study sites are equipped with EC flux systems that measure the exchange of energy and gases between the vegetation canopy and the atmosphere. Flux and PAR measurements are made at 5 m, 9 m, 3 m and 2.5 m at KM, LB, MB and SH, respectively. Air temperature was measured at 5 m, 5 m, 2 m and 2.5 m at KM, LB, MB and SH, respectively. Further details of the systems at each site, the data processing and the gap filling procedures are extensively described in the references associated with each site (Table 1).

Besides the flux tower measurements, each site also had measures of peak leaf area index (LAI, measured at the peak of the growing season), pH and vegetation composition. Peak LAI at MB was calculated from leaf