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Review

Potential for using remote sensing to estimate carbon fluxes across northern peatlands – A review

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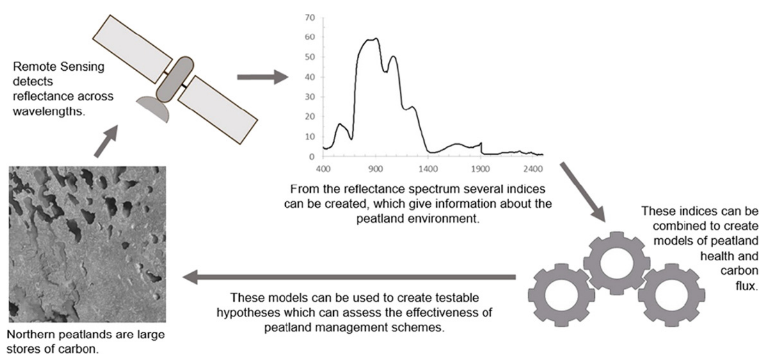
HIGHLIGHTS

- Optical data can be used to drive models of peatland carbon flux.
- Water, temperature and vegetation indices are important model factors.
- Challenges from peatland heterogeneity and vegetation composition
- Remote sensing driven models have the potential to fill gaps in current research

GRAPHICAL ABSTRACT



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ABSTRACT

Peatlands store large amounts of terrestrial carbon and any changes to their carbon balance could cause large changes in the greenhouse gas (GHG) balance of the Earth's atmosphere. There is still much uncertainty about how the GHG dynamics of peatlands are affected by climate and land use change. Current field-based methods of estimating annual carbon exchange between peatlands and the atmosphere include flux chambers and eddy covariance towers. However, remote sensing has several advantages over these traditional approaches in terms of cost, spatial coverage and accessibility to remote locations. In this paper, we outline the basic principles of using remote sensing to estimate ecosystem carbon fluxes and explain the range of satellite data available for

Abbreviations: µm, micrometer (10^{-6}); APAR, Absorbed Photosynthetically Active Radiation; AVHRR, Advanced Very High Resolution Radiometer; CAI, Cloud and Aerosol Imager; CH_4, Methane; CO_2, Carbon dioxide; DIC, Dissolved Inorganic Carbon; DOC, Dissolved Organic Carbon; DoD, Department of Defence; EC, Eddy Covariance; EF, Evaporative Fraction; EO, Earth Observation; EOM, Ecosystem Organic Matter; ESA, European Space Agency; ETM+, Enhanced Thematic Mapper Plus; EUMETSAT, European Organization for the Exploration of Meteorological Satellites; EVI, Enhanced Vegetation Index; fBWI, floating Water Band Index; FIR, Far-Infrared; FTS, Fourier Transform Spectrometer; GHG, Greenhouse Gas; GLO-PEM, Global Production Efficiency Model; GMAO, Global Modelling and Assimilation Office; GOSAT, The Greenhouse Gases Observing Satellite; GPP, Gross Primary Productivity; H_2O, water; InSAR, Interferometric Synthetic Aperture Radar; IR, Infra-Red; IRGA, Infra-Red Gas Analyser; JAXA, Japan's Aerospace Exploration Agency; LAI, Leaf Area Index; LiDAR, Light Detection and Ranging; LST, Land Surface Temperature; LSWI, Land Surface Water Index; LUE, Light Use Efficiency; MERIS, Medium Resolution Imaging Spectrometer; MIR, Mid-Infrared; MODIS, Moderate Resolution Imaging Spectrometer; MSI, Multi-Spectral Imager; MTCI, MERIS Terrestrial Chlorophyll Index; NASA, National Aeronautics and Space Administration; NDVI, Normalised Difference Vegetation Index; NDWI, Normalised Difference Water Index; NEE, Net Ecosystem Exchange; nm, nanometer (10^{-9}); O_2, Oxygen; OCO, Orbiting Carbon Observatory; OLI, Operational Land Imager; PAR, Photosynthetically Active Radiation; POC, Particulate Organic Carbon; PRI, Photosynthetic Reflectance Index; Ra, autotrophic Respiration; R_{eco}, ecosystem Respiration; REP, Red Edge Position; Rg, growth Respiration; Rh, heterotrophic Respiration; Rm, maintenance Respiration; RS, Remote Sensing; RSPB, Royal Society for the Protection of Birds; SAR, Synthetic Aperture Radar; SIF, Solar Induced Fluorescence; SLSTR, Sea and Land Surface Temperature Radiometer; SOM, Soil Organic Matter; SPOT, Satellite Pour l'Observation de la Terre; Suomi-NPP, Suomi National Polar Orbiting Partnership; SWIR, Short-Wave Infrared; TANSO, Thermal and Near-infrared Sensor for carbon Observation; TIR, Thermal Infra-Red; USGS, United States Geological Survey; VI, Vegetation Index; VIIRS, Visible Infrared Imaging Radiometer Suite; VPM, Vegetation Photosynthesis Model; VPD, Vapour Pressure Deficit; WI, Water Index; WTD, Water Table Depth.

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such estimations, considering the indices and models developed to make use of the data. Past studies, which have used remote sensing data in comparison with ground-based calculations of carbon fluxes over Northern peatland landscapes, are discussed, as well as the challenges of working with remote sensing on peatlands. Finally, we suggest areas in need of future work on this topic. We conclude that the application of remote sensing to models of carbon fluxes is a viable research method over Northern peatlands but further work is needed to develop more comprehensive carbon cycle models and to improve the long-term reliability of models, particularly on peatland sites undergoing restoration.

Contents

1. Introduction

Peatlands are a large store of terrestrial carbon and any change in their carbon balance could therefore cause large changes in the atmospheric greenhouse gases (GHGs) of the planet. The atmospheric store of carbon is estimated to be about 750 Gt C, compared to an estimated 500 ± 100 Gt C stored in Northern peatlands (Yu, 2012). Although peatlands are an important part of the terrestrial carbon cycle and store approximately a third of the world's soil carbon (Gorham, 1991; Limpens et al., 2008), there is still much uncertainty about how these areas are affected by climate and land use change. There is also much variation between peatland types, with the greatest difference between acidic rain-fed bogs and more nutrient rich minerotrophic fens. Peat bogs in pristine condition are considered to be net carbon sinks (Yu, 2012), yet many areas of peatland have experienced degradation through human activity (such as draining, grazing and burning and conversion to plantation forestry), which decreases the net carbon uptake from the atmosphere (Fleischer et al., 2016). Peatland restoration is recognised as one of the ways to reach carbon emission reduction targets under the Kyoto Protocol (Hiraishi et al., 2013; IPCC, 2014), and it is therefore essential to develop ways of verifying and quantifying the effect of such restoration procedures. Field measurement techniques are limited by scale and cost, whereas Remote Sensing (RS) presents an opportunity to provide data to carbon flux models over large areas quickly and cheaply.

Peatland ecosystems differ from other areas due to their high water table and very distinctive vegetation composition. Fluctuations in the water table influence the amount and distribution of oxygen available in the soil profile, which in turn influences carbon emissions. The carbon cycle of peatland ecosystems is complex and includes many components (a conceptual diagram of key components of the cycle in peat bogs is shown in Fig. 1). CO_2 enters the peatland system though photosynthesis of the vegetation (Gross Primary Productivity or GPP), and leaves it through autotrophic (plant) respiration (Ra), and heterotrophic respiration (Rh) (microbial decomposition). The sum of Ra and Rh gives ecosystem respiration (R_{eco}), whilst the difference between R_{eco} and GPP equals Net Ecosystem Exchange (NEE).

Models using RS data focus on estimating GPP, R_{eco} and also NPP – Net Primary Productivity, which is the difference between GPP and Ra. The various flux processes in the peatland carbon cycle are typically considered at timescales from hours to a few years, largely due to the short monitoring records currently available. Over the course of a peatland's lifetime which often spans several millennia, however, natural (e.g. natural fires) and human (e.g. afforestation) disturbances should also be considered to capture the full breadth of a peatland's carbon cycle, as should shifts in climatic conditions. Methane (CH_4) is not considered in this review, as methane and carbon dioxide are often studied separately and require different methodologies. At this time, RS methods for estimating CH_4 emissions are still in their infancy compared to those of CO_2 estimates (see Tagesson et al., 2013). In peatland, carbon can also leave the system as dissolved organic/inorganic carbon (DOC/DIC) in streams and pipe outflow, or as particulate organic carbon (POC) due to surface erosion through wind and washout; these are not included in RS estimations of NEE. For more information about the peatland carbon cycle see Limpens et al. (2008). The current review focuses on biogenic CO_2 fluxes, which are the largest and most variable component at annual timescales (Helfter et al., 2015).

Field based studies show that several factors affect the spatial and temporal variance of carbon fluxes across peatlands, particularly water table depth (WTD) and temperature (Lafleur et al., 2003; Bubier et al., 2003; Dinsmore et al., 2009; Lund et al., 2012; Strachan et al., 2016). Temperature and WTD help to determine plant species composition in the long term, while, in the shorter term, changes in these climatic variables affect plant photosynthesis and soil respiration (Bubier et al., 2003). Unusually dry or drained peatlands produce more CO_2 but less CH_4, whilst in wet peatlands this is reversed (Waddington and Price, 2000).

Peatland NEE is also strongly linked to vegetation composition, as different plant species have differing responses to climatic variables, and provide differing quantities of available organic matter for microbial