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Net CO_2 emissions from a primary boreo-nemoral forest over a 10 year period

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ABSTRACT

Primary forests play an important role in the global carbon balance. With little to no human intervention, primary forests are shaped and characterised by disturbances such as weather extremes, fire, insect and pathogen attacks. Such disturbances have a direct impact on the volume of coarse woody debris (CWD) which contributes to the total ecosystem respiration (Re). There are currently few studies that present continuous long term measurements of the carbon balance of northern primary forests. We used the eddy covariance method to measure continuous carbon dioxide (CO_2) fluxes from a Swedish primary boreo-nemoral forest over a ten year period. By mapping the measured CO_2 fluxes to the forest ecosystem we could indicate that small areas that had some form of disturbance and areas with significant levels of CWD within the eddy covariance footprint contributed to the total Re resulting in the forest being a net carbon source. A weighing algorithm was used to account for directional ecosystem heterogeneity and to estimate a representative carbon balance for the ecosystem. The forest ecosystem was a continuous source of CO_2 to the atmosphere, losing around 25 Mg per hectare of CO_2 over a ten year period.

1. Introduction

Northern forest ecosystems play a key role in removing carbon dioxide (CO_2) from the atmosphere and have the ability to store and sequester large quantities of carbon within the earth's terrestrial system (Bonan, 2008). Much of the boreal zone is classified as unmanaged primary forest, particularly in Russia with 31% primary forest and Canada with 53% (FAO, 2005; Potapov et al., 2008).

In northern Europe however, there are few areas of primary forest remaining. Studies have shown that biodiversity within primary forests is greater than in managed forests (Paillet et al., 2010). Therefore increasing the area of natural woodland through conservation and restoration within Europe has become a major objective (Zerbe, 2002). Understanding the impact that primary and unmanaged forests have on the global carbon balance is therefore highly important when considering climate change mitigation and land use change.

The extent in which unmanaged forests sequester CO_2 has been widely debated. It has been argued that the assimilation of CO_2 from mature unmanaged forests is reduced by a decline in gross primary productivity and increase in respiration as the stand ages (e.g., Jarvis et al., 1989). However more recent studies have shown that old growth and mature forests act as carbon sinks (Desai et al., 2005; Luyssaert et al., 2008). The carbon balance of mature managed forests may however be highly sensitive to small changes in gross primary production (GPP) and ecosystem respiration (Re) as small changes in these components may have a large impact on the net ecosystem exchange (NEE). Previous studies have shown that small changes in either GPP or Re determine whether a forest acts as a carbon sink or a carbon source (e.g., Hadden and Grelle, 2016; Lindroth et al., 1998). The impact from disturbances such as wind throw, fire, and insect outbreaks, may therefore have severe consequences for the carbon balance within primary boreal forests by reducing photosynthesis and increasing heterotrophic respiration. Schmid et al. (2016) showed that forest disturbances resulting in an increase of both standing and fallen coarse woody debris (CWD) contributed significantly to Re. However other studies have contrasted this by showing that small increases in CWD do not have a significant impact on the forests carbon balance (Liu et al., 2006).

With vast areas of unmanaged primary forest globally, it is vital to understand the processes that drive the carbon balance within these ecosystems if the global carbon cycle is to be fully understood. A highly valuable method for understanding the forest dynamics is through the use of continuous long term measurements of the ecosystem carbon balance. Such measurements are important as the forest dynamics and functioning are not static

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and likely alter throughout the forest's life cycle. The eddy covariance technique is a common method for measuring long-term continuous carbon fluxes at an ecosystem scale. One assumption of the eddy covariance technique is that measurements occur above a homogeneous landscape (Baldocchi, 2003; Moncrieff et al., 1996). This is however not always possible, especially in primary forests where there are a variety of tree species, ages, heights, variation in leaf area index and the quantities of dead biomass within an eddy covariance footprint.

To reduce uncertainties through measuring on a heterogeneous site we present a simple correction to the eddy covariance data. We furthermore show a somewhat simplistic method in relating the source areas of measured CO_2 fluxes to the forest's physical properties. Here we present a 10 year (2004–2014) record of eddy covariance data measured from a primary forest in central Sweden. During the measurement period the primary forest was a continuous source of CO_2 to the atmosphere losing ca 25 Mg of carbon dioxide over a ten year period.

2. Methods

2.1. Study site

The measurement site is located at Fiby Urskog in central Sweden (59°54′N, 17°22′E). The site is a nature reserve and can be classified as a boreo-nemoral primary forest (Leemans, 1986). The current forest has not undergone any large scale disturbance since a windstorm in 1796 (Hytteborn and Packham, 1985). The forest site has however had numerous small scale disturbances in the form of sporadic individual tree mortality and wind throw.

The dominating tree species is Norway spruce (*Picae abies* L.). Scots pine (*Pinus sylvestris* L.) is also present in high abundance. Less abundant tree species found in the reserve are aspen (*Populus tremula* L) and birch (*Betula pubescens* Ehrh. and *Betula pendula* Roth.). The forest is heterogeneous with numerous canopy gaps of various sizes (Leemans, 1991), decaying biomass scattered on the forest floor, dead standing trees, patches of spruce saplings and a mosaic of tree species.

Ground vegetation consists of cryptograms and vascular plants with the dominant species being *Hylocomium splendens*, *Pleurozium schreberi*, *Vaccinium myrtillus* and *Vaccinium vitis-idea*.

The average tree height is estimated to 22.5 m. Being a heterogeneous forest stand the leaf area index (LAI) varied within the site ranging from 0.19 to 3.96 with an average of 1.64.

The site is at an elevation of 62 m above sea level. The greatest height difference between the lowest and the highest point within the measurement area is 8 m. The terrain is rocky with numerous granite outcrops varying in size. The forest grows upon the granite outcrops (predominantly pine) and on glacial till between the outcrops. The soil organic matter content and depth varies throughout the site (Table 1). A more detailed site description is given by Leemans (1986).

2.2. Instrumentation

The eddy covariance system consisted basically of a CSAT-3 sonic anemometer (Campbell Scientific, Logan, UT, USA) and an LI-7500 open path infrared gas analyser (LI-COR Inc., Lincoln, NE, USA). The sensors were mounted close to each other (20 cm between the respective sampling volumes) on a boom at the top of a 25-m telescopic antenna mast (Wibe, Mora, Sweden). The mast was placed on a boulder, which increased the effective measurement height to approximately 4 m above the canopy. Data were collected digitally at 10 Hz by a CR-1000 datalogger (Campbell Scientific, Logan, UT, USA). The calibration of the LI-7500 was checked annually and did not change more than ca. one percent per year.

In addition, meteorological measurements were done in 10 s intervals and data were saved as 30 min averages by the same logger. In particular, air temperature T_a and relative humidity RH were measured in 25 m height by an MP103A sensor (ROTRONIC AG, Bassersdorf, Switzerland) placed in a ventilated radiation shield (In Situ Instrument AB, Ockelbo, Sweden), soil temperature at 5 cm depth by 2 type 107 thermistors (Campbell Scientific, Logan, UT, USA), photosynthetically active radiation PAR at 25 m height using an LI 190 quantum sensor (LI-COR Inc., Lincoln, Nebraska, USA), soil water content at 5 cm depth by an ML3 ThetaProbe (Dela T Devices Ltd, Cambridge, United Kingdom), and snow depth by an SR50A sonic ranging sensor (Campbell Scientific, Logan, UT, USA).

As the site was placed within a nature reserve, there were restrictions regarding permanent installations, disturbance, and pollution. Therefore the entire system was powered by solar panels in combination with an EFOY Pro Fuel cell (SFC Energy AG, Brunnthal, Germany). 10-Hz raw data were saved on a CF card within the logger and retrieved manually on a regular basis, while half hourly values were collected twice a day using a GSM modem.

2.3. Data processing

Turbulent fluxes were calculated as 30-min averages, and overall calculation and correction of fluxes followed the EUROFLUX methodology (Aubinet et al., 1999; Lee et al., 2004). In particular, potential errors associated with data gaps, low turbulence conditions at night, edge effects due to fetch limitations, and spatial heterogeneity are described below. Data analysis was done using R version 2.15.2 (R Core Team, 2012) and the package Openair (Carslaw, 2012).

2.3.1. Artificial heating

Open-path gas analyzers measure volume-based concentrations that have to be corrected for air volume fluctuations caused by, e.g., turbulent energy fluxes ("WPL correction", Webb et al., 1980). Generally, the WPL correction may be insufficient if internal heat fluxes are generated within the optical path, caused by analyser surface temperatures that differ significantly from ambient air temperature (Burba et al., 2008). In this study, the LI-7500 sensor was mounted horizontally, which implies that turbulent heat transfer from the sensor surfaces that was correlated with the vertical wind component was directed away from the optical path and thus would not create an internal heat flux. Therefore we concluded that no additional term in the WPL correction ("Burba correction") was needed for this setup. This was confirmed by the fact that no apparent CO_2 uptake was measured at any occasion during periods of frost and ecosystem dormancy.

Table 1
Soil properties in geographical relation to the eddy flux tower.

	North	East	South	West
kg SOM m^{-2}	4.7	5.5	5.8	5.8
Depth of organic matter (cm)	6.2	7.2	9.7	8
PH	3.5	3.4	3.6	4