Changing temperature response of respiration turns boreal forest from carbon sink into carbon source

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ABSTRACT

Seventeen years (1997–2013) of carbon dioxide (CO_2) fluxes were measured in a boreal forest stand in northern Sweden using the eddy covariance technique. During the measurement period the forest turned from a net carbon sink into a net carbon source. The net ecosystem exchange (*NEE*) was separated using values from periods of darkness into the gross components of total ecosystem respiration (*TER*) and gross primary productivity (*GPP*), which was calculated as *GPP* = −*NEE* + *TER*. From the gross components we could determine that an increase in *TER* during the autumn (September to end of November) and spring (March to end of May) periods resulted in the forest becoming a net source of CO_2. We observed no increase in the *GPP* from the eddy covariance measurements. This was further supported by measurements of tree growth rings. The increased *TER* was attributed to a change in the forest's temperature response at lower temperatures (−5 to 10 °C) rather than to a temperature increase. This study shows that changes in ecosystem functioning can have a larger impact on the carbon balance than climate warming *per se*.

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1. Introduction

In 2013 the daily mean concentration of atmospheric carbon dioxide (CO_2) surpassed 400 ppm globally (Showstack, 2013). Anthropogenic emissions of CO_2 are on the rise, which is having a direct impact on global warming. With an increasing concentration of atmospheric CO_2 the ability of terrestrial ecosystems to sequester carbon is of great importance. Global forests play a vital role in cycling CO_2 between the atmosphere and terrestrial biosphere and are capable of sequestering 4.0 Pg C year^{-1} (Pan et al., 2011). The Boreal forest in particular has been acting as a carbon sink for thousands of years and contains some of the world's largest soil carbon stocks (Harden et al., 1997).

The net uptake of CO_2 within the forest ecosystem is the difference between the gross primary productivity (*GPP*) and the total ecosystem respiration (*TER*). A small change in either of the gross fluxes is therefore crucial in determining whether a forest may act as a sink or source of CO_2 (Lindroth et al., 1998).

Air temperature has been shown to be one of the main drivers of both carbon uptake and ecosystem respiration (Barr et al., 2007; Bergeron et al., 2007). The onset of the growth period in the spring is largely regulated by air temperatures and has a direct impact on

net annual uptake of CO_2 from the atmosphere (Krishnan et al., 2008; Tanja et al., 2003). An increase in air temperature however also increases ecosystem respiration which has been shown to result in a net loss of carbon from the terrestrial system during the autumn months (Piao et al., 2008; Ueyama et al., 2014; Vesala et al., 2010). Furthermore, there are indications that a change in ecosystem function has a large impact on the ecosystem carbon balance and dominates the interannual variations to a greater extent than climatic variability which appears to impact the carbon fluxes at short time scales (Wu et al., 2012). These findings have rendered it difficult to evaluate future consequences of climate change on the Boreal zone's carbon balance. One of the keys to predicting future consequences of warming on the Boreal forest carbon balance is to understand the underlying processes that drive the forest's response to temperature. Due to the stochastic nature of weather and climate combined with the long life cycle of the boreal forest and changes within ecosystem functioning, long term measurements are needed to gain a detailed understanding of the carbon cycle on a large temporal scale. We must also consider the forest dynamics and how these change as the forest ages when evaluating the carbon balance.

There are relatively few datasets of continuous long term carbon fluxes from the boreal zone (more than 15 years in length) where the interannual variations of climate and fluxes can be evaluated. Most long term measurements have been done by the eddy covariance technique (*e.g.*, Ge et al., 2011; Ueyama et al., 2014; Vesala

et al., 2010). There are numerous studies showing the impact that a changing climate may have on the boreal forest's carbon balance. There are however no studies that we are aware of that evaluate a change in the forests functioning and the impacts that this has on the carbon balance with the prospects of a changing climate.

The objectives of this study are to report the interannual variations of CO_2 fluxes within the boreal forest ecosystem and identify the underlying processes controlling the fluxes. We present a 17 year record (1997–2013) of eddy covariance data measured in northern Sweden. During this period we observed a change in the ecosystem function resulting in the forest turning from a carbon sink to a carbon source.

2. Materials and methods

2.1. Study site

The experimental site is located at Flakaliden in northern Sweden (64°07′N, 19°27′E, 310 m above sea level).

Flakaliden has a boreal climate, experiencing long and cold, dark winters and short, cool summers with long daylight hours. The mean temperature during the measurement period was 2.4 °C. The site is a managed forest on a shallow till soil that consists predominantly of Norwegian spruce (Picea abies) with an average age of ca. 50 years. The average tree height in 2013 was ca. 12 m with an average diameter of 13 cm. The forest stand had a leaf area index (projected LAI) of 3.40 as of September 2014.

2.2. Instrumentation

Turbulent fluxes of CO_2 were measured by an eddy-covariance system (In Situ Instrument AB, Ockelbo, Sweden), consisting basically of a solent 1012R2 sonic anemometer (Gill Instruments, Lymington, UK) and a closed path infrared gas analyzer LI-6262 (LI-COR inc., Lincoln, Nebraska, USA) as described by Grelle and Lindroth (1996).

The eddy covariance instrumentation was mounted on an 18 m tall guyed mast with a triangular cross section of 28 cm width. The flux measurements were taken at 15 m height on a boom extending 2 m from the mast. Extensive flux source area analyses have been applied to confirm that the appropriate height for flux measurements was chosen to represent the surrounding forest both during day- and night-time (Grelle, 1997). To minimize damping of high-frequency concentration fluctuations in a long intake tube, the entire system was mounted at the tower close to measurement height. The tube inlet was placed 10 cm below the sampling volume of the sonic anemometer. Air was drawn from the inlet through a 6 mm diameter, 6 m long high-density polyethylene tube to the IRGA, which was mounted at the mast in a heated, ventilated, and insulated enclosure at a height of 13 m. The air flow rate was 12 ln/min (litre at 0 °C, 1013 hPa), measured and controlled by a mass flow regulator (Brooks Instrument, Hatfield, PA, USA). The time lag between data samples from the anemometer and the gas analyser was continuously determined by autocovariance analysis on a half-hourly basis, and the signals were shifted accordingly prior to further analysis. Energy balance closure indicated adequate performance of the measurement system (Grelle, 1997). Overall calculation and correction of fluxes followed the EUROFLUX methodology (Aubinet et al., 2000) and Lee et al. (2004).

Soil temperature was measured in two profiles from 5 cm to 50 cm depth by 10 type 107 thermistors (Campbell Scientific, Logan, UT, USA), and air temperature and -humidity by an MP103A sensor (ROTRONIC AG, Bassersdorf, Switzerland) placed in a ventilated radiation shield (In Situ Instrument AB, Ockelbo, Sweden) at 18 m height. Photosynthetically active radiation (PAR) was measured at

18 m height using an LI 190 quantum sensor (LI-COR inc., Lincoln, Nebraska, USA).

Leaf area index (LAI) was measured using an LAI-2000 plant canopy analyser (LI-COR inc., Lincoln, Nebraska, USA) on a regular basis throughout the measurement period. This was done by manual multi-point measurements at 10 m intervals in North, East, South and Westerly directions from the tower.

2.3. Temperature response

There is a correlation between air temperature and total ecosystem respiration which has resulted in air temperature being largely regarded as a main driver for TER (Barr et al., 2007; Bergeron et al., 2007). Due to this we chose to study the response of TER to air temperature rather than soil temperatures. Furthermore, this study is based upon eddy covariance measurements which measure the carbon exchange at the ecosystem level. It could therefore be misleading to analyse the carbon exchange at the ecosystem level with only soil temperatures as a driver. Indeed, generally our CO_2 fluxes correlated better with air temperature than with soil temperatures and we therefore chose to carry out our analysis of respiration response to air temperatures rather than soil temperatures.

The gross respiration was calculated with the equation:

$$TER = a + b \cdot e^{c \cdot T} \tag{1}$$

with a representing the offset and b and c represent curve coefficients.

2.4. Growth period

Following a widely used convention, the growth period is defined as starting when the daily average temperature is ≥ 5 °C for 5 consecutive days and ending when the daily average temperature is <5 °C for 5 consecutive days (e.g., Frich et al., 2002).

2.5. Tree growth

Tree growth was measured using core samples taken from 40 trees. Each sample was taken at breast height and from the south side of the trunk.

Each sample was photographed and the year rings were measured in width with the use of a pixel counting software (Pixel Ruler inc.). Each year ring was calculated into area as follows:

$$A_i = \pi \left[\left(\frac{D_i}{2} \right)^2 - \left(\frac{D_{i+1}}{2} \right)^2 \right] \tag{2}$$

$$D_i = D_{i+1} + 2W_i$$

$$i = \left\{ 1, 2, 3, .., N \right\}$$

The index number of a given year ring, i, is counted from outside towards the pith of the stem. N is the total number of year rings measured. A_i is the portion of the whole stem area represented by the area of the year ring growing from i + 1 to i. D_{i+1} is the diameter of the whole stem area when growth of the year ring began. D_i is the diameter of the whole stem area including the growth represented by the width, W_i, of the year ring produced from i + 1 to i. D_1 is stem diameter under bark.

2.6. Gap filling

After quality control, there was an average fraction of 24.9% gaps in the flux data and 6.4% in the climatic data throughout the 17 years of measurements. For periods when climatic data were available, gaps in the flux data were filled by a neural network (NNDT, Saxén