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Increasing net CO_2 uptake by a Danish beech forest during the period from 1996 to 2009

Kim Pilegaard[a,*], Andreas Ibrom[a], Michael S. Courtney[b], Poul Hummelshøj[b], Niels Otto Jensen[b]

[a] *Biosystems Division, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, Denmark*
[b] *Wind Energy Division, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, Denmark*

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ABSTRACT

The exchange of CO_2 between the atmosphere and a beech forest near Sorø, Denmark, was measured continuously over 14 years (1996–2009). The simultaneous measurement of many parameters that influence CO_2 uptake makes it possible to relate the CO_2 exchange to recent changes in e.g. temperature and atmospheric CO_2 concentration. The net CO_2 exchange (NEE) was measured by the eddy covariance method. Ecosystem respiration (RE) was estimated from nighttime values and gross ecosystem exchange (GEE) was calculated as the sum of RE and NEE. Over the years the beech forest acted as a sink of on average of 157 g C m^{-2} yr^{-1}. In one of the years only, the forest acted as a small source. During 1996–2009 a significant increase in annual NEE was observed. A significant increase in GEE and a smaller and not significant increase in RE was also found. Thus the increased NEE was mainly attributed to an increase in GEE. The overall trend in NEE was significant with an average increase in uptake of 23 g C m^{-2} yr^{-2}. The carbon uptake period (i.e. the period with daily net CO_2 gain) increased by 1.9 days per year, whereas there was a non significant tendency of increase of the leafed period. This means that the leaves stayed active longer. The analysis of CO_2 uptake by the forest by use of light response curves, revealed that the maximum rate of photosynthetic assimilation increased by 15% during the 14-year period. We conclude that the increase in the overall CO_2 uptake of the forest is due to a combination of increased growing season length and increased uptake capacity. We also conclude that long time series of flux measurements are necessary to reveal trends in the data because of the substantial inter-annual variation in the flux.

1. Introduction

Future climate change is one of the most important challenges of mankind. Climate change may directly affect ecosystem functioning and thus global food production. The major cause of climate change is the anthropogenic emission of greenhouse gases, especially CO_2 emitted from combustion of fossil fuels. Other major anthropogenic greenhouse gas emissions are related to agriculture such as CH_4 from rice paddies and N_2O resulting from fertilization of agricultural fields. Over the latest decades global CO_2 concentration has increased by 1.3–1.9 ppm yr^{-1} and has reached 387 ppm in 2009. Emissions from fossil fuels and cement production amount to 8.8 Gt C yr^{-1} (2009) and constitute 87.5% of the total anthropogenic emissions (Friedlingstein et al., 2010). Compared to the anthropogenic emissions, however, the natural cycling of greenhouse gases between the terrestrial biosphere and the atmosphere is much larger (about 120 Gt C yr^{-1}) (Denman et al., 2007). Small changes in these fluxes are therefore crucial for the climate. Terrestrial ecosystems play a very important role in this respect and presently act as a sink for atmospheric CO_2. The ability of plants to take up CO_2 is closely connected to climate and changes in major factors like temperature, light, and precipitation can result in either a positive or a negative feedback to climate change.

Forests play a major role in carbon sequestration with tropical forests accounting for the largest terrestrial carbon sink. Temperate forests also play an important role and for the forests of the European Union (EU-25) the mean long-term carbon forest sink (net biome production, NBP) amounts to 75 ± 20 g C m^{-2} yr^{-1} (Luyssaert et al., 2010).

The climate in Denmark has changed since 1874 (start of systematic meteorological measurements) resulting in a 100 mm higher annual precipitation to the present amount of 745 mm (mean 1990–2009), and an increase in the annual mean temperature of 1.5 °C to the present 8.5 °C (mean 1990–2009) (Jørgensen and Cappelen, 2007 and updates from the Danish Meteorological Institute). The amount of hours of sunshine has fluctuated, but shows an increasing trend since 1980. In the period considered in this paper (1996–2009) the increase in annual mean temperature was approximately 0.5 °C and the annual precipitation increased approximately 20 mm.

* Corresponding author. Tel.: +45 46 77 41 01; fax: +45 46 77 41 09.
E-mail address: kipi@risoe.dtu.dk (K. Pilegaard).

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Nomenclature

Symbols

u	Wind speed ($m\,s^{-1}$)
w	Vertical wind speed ($m\,s^{-1}$)
u_*	Friction velocity ($m\,s^{-1}$)
T_a	Air temperature (°C)
T_s	Soil temperature (°C)
Q	Photosynthetic photon flux density ($\mu mol\,m^{-2}\,s^{-1}$)
LT_r	Relative light transmission
F_c	CO_2 flux ($\mu mol\,m^{-2}\,s^{-1}$)
F_g	Gross photosynthetic assimilation ($\mu mol\,m^{-2}\,s^{-1}$)
F_r	Ecosystem respiration ($\mu mol\,m^{-2}\,s^{-1}$)
F_{1800}	CO_2 flux at Q = 1800 ($\mu mol\,m^{-2}\,s^{-1}$)
F_∞	CO_2 flux at saturating Q ($\mu mol\,m^{-2}\,s^{-1}$)
α	Quantum efficiency ($mol\,mol^{-1}$)
K_M	Michaelis–Menten constant
Q_{comp}	Light compensation point for F_c ($\mu mol\,m^{-2}\,s^{-1}$)
NEE	Annual net ecosystem exchange ($g\,C\,m^{-2}\,yr^{-1}$)
RE	Annual ecosystem respiration ($g\,C\,m^{-2}\,yr^{-1}$)
GEE	Annual gross ecosystem exchange ($g\,C\,m^{-2}\,yr^{-1}$)
CUP	Carbon uptake period (d)
LP	Leafed period (d)

The climate projections for Denmark (Christensen et al., 2007) imply a temperature increase at the end of this century between 2.5 and 3 °C on an annual basis with slightly higher increase (3–3.5 °C) during the winter months (December–February) and slightly lower increase (2.5–3 °C) during the summer months (July–August).

In Europe it was found that over the period 1959–1996 spring events (like leaf unfolding) have advanced on average by $-0.21\,d\,yr^{-1}$ and autumn events have been delayed by an average of $+0.15\,d\,yr^{-1}$ resulting in a prolongation of the vegetation period of $+0.36\,d\,yr^{-1}$ (Menzel, 2000). Similarly, data from the Hubbard Brook Experimental Forest (Richardson et al., 2006) suggests significant trends towards earlier springs ($-0.18\,d\,yr^{-1}$, sugar maple) and increased green canopy duration ($+0.21\,yr^{-1}$, sugar maple). The relationship between phenology and ecosystem productivity was investigated in temperate and boreal forests by analyzing data from 21 sites where carbon fluxes were measured over several years (Richardson et al., 2010). From these results it was, however, not possible to accurately predict how productivity will respond to future changes in phenology. The increased carbon assimilation in spring and autumn tends to be offset by concurrent, but smaller, increases in ecosystem respiration, and thus the effect on carbon sequestration will be positive. In contrast to this Piao et al. (2008) found that both photosynthesis and respiration increased during autumn warming in northern forests, but the increase in respiration was greater, resulting in a lower overall carbon sequestration; the warmer temperatures in autumn increased ecosystem CO_2 losses by shortening the carbon uptake period.

Recent increases in biomass was observed in North American temperate forests (McMahon et al., 2010). The recent increase in growth was unrelated to stand age and averaged $3.4\,Mg\,ha^{-1}\,yr^{-1}$. The authors listed six hypotheses that might explain the difference between expected and observed growth: increased temperature, increased growing season, increased CO_2, nutrient fertilization, community composition, and demographic stochasticity.

A recent literature review concluded that in the short term global change (increased CO_2, increased temperature, and increased N deposition and availability) is likely to increase carbon sequestration in forests (Hyvönen et al., 2007). In the longer term, however, respiration may be more affected than assimilation and the forests might turn into carbon sources. The authors also note, that most of the experimental evidence is based on single-factor responses from short-term experiments that can be misleading for long-term predictions, because of feedback and acclimation occurring over longer time scales.

Most multi-year studies of carbon dioxide exchange over forests show a large inter-annual variation, but generally no overall trend (Baldocchi, 2008). Inter-annual variability in net ecosystem CO_2 exchange in temperate deciduous forests is believed to be caused by a number of factors, such as summer drought, solar radiation and leaf area. CO_2 exchange measurements exceeding a decade are still scarce. Measurements over 1992–2004 from the Harvard forest (a mixed forest with mainly deciduous trees; Urbanski et al., 2007) showed a systematic increase in carbon sequestration which leads to increases in tree biomass. This increase was associated with successional change in forest composition, increased leaf area, and canopy photosynthetic capacity.

The above findings show that forests are exposed to a changing environment and responses to recent climate change start to become visible if observation periods become long enough. We here present the results of continuous CO_2 flux measurements above a mature Danish beech forest over the years 1996–2009. In this paper we describe the long-term changes and relate them to possible causes such as climate change and ecosystem internal factors.

2. Materials and methods

2.1. The site

The station is located in the forest "Lille Bøgeskov" near Sorø on the island of Zealand at 55°29′13″N, 11°38′45″E 40 m above mean sea level. The forest is privately owned by the foundation Sorø Akademi.

The climate is temperate maritime and is dominated by westerly winds and frequent passes of frontal systems. Normally, the weather is characterized by cool summers and mild windy winters. Occasionally easterly winds dominate, resulting in severe winters and hot summers. The average annual temperature during the measurement period was 8.5 °C and the measured annual precipitation was 564 mm.

The soils are brown soils classified as either Alfisols or Mollisols (depending on a base saturation under or over 50%) with a 10–40 cm deep organic layer. The carbon pool in the soil (down to 1 m depth) is $20\,kg\,m^{-2}$. The C/N ratio is about 20 in the upper organic soil layers falling to about 10 in the lower mineral layers. The parent material is relatively rich in lime (25–50%). However most of this is leached from the upper horizons of the forest soil, resulting in a low pH (4–5) and a lower base-saturation (Østergård, 2000). The ground water table fluctuates between 0.2 m in winter and at least 2 m below the surface during summer (Ladekarl, 2001).

The forest is dominated by European beech (*Fagus sylvatica* L.) and the trees immediately around the station were planted in 1921. The forest is managed and the different beech sections are thinned about 20% every 10th year, resulting in an average thinning of 2% per year. The average tree height in the forest part where the mast is located was 23.8 m in 1995 increasing to 25.8 m in 2007 (Sorø Akademi, personal communication); the main rooting depth is 1 m. The roughness length was 1.8 ± 0.7 m and the displacement height 20.6 ± 4 m (Dellwik and Jensen, 2005). The average tree diameter in 1995 was 38 cm, the stand density 283 stems ha^{-1}, and the wood volume increment calculated by yield tables (Møller, 1933) was approximately $11\,m^3\,ha^{-1}\,yr^{-1}$. The average increase in tree diameter at breast height in 25 sample trees amounted to $0.52\,cm\,yr^{-1}$ (difference between 2008 and 2007 measurement in March). The peak leaf area index of the canopy is $4–5\,m^2\,m^{-2}$ at mid summer. The main part of the surrounding forest consists of beech trees of