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Carbon balance of coniferous forests growing in contrasting climates: Model-based analysis

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Abstract

Forest carbon exchange contributes significantly to the global carbon balance and is therefore being monitored around the world, most notably using eddy covariance technology. In order to extrapolate from these measurements, we need to understand why carbon balance (or net ecosystem production, NEP) differs among forests. Here, we use a detailed model of forest carbon exchange applied to three coniferous European forests with differing NEP to pinpoint reasons for the differences among these sites. The model was parameterised using extensive ecophysiological data obtained at each site. These data gave evidence of major differences among sites in climate, leaf physiology, respiring biomass, leaf area index, and soil and biomass respiration rates. The model was compared with eddy covariance data and found to satisfactorily simulate carbon exchange by each forest. Simulations were then run which interchanged canopy structure, physiology and meteorology among sites, allowing us to quantify the contribution of each factor to the inter-site differences in gross primary productivity (GPP), ecosystem respiration (RE) and NEP. The most important factor was the difference in respiration rates, particularly soil respiration rates, among sites. Climate was also very important, with differences in incident photosynthetically active radiation (PAR) affecting GPP and differences in temperature affecting both GPP and RE. Effects of leaf area index, respiring biomass and leaf physiology on NEP were secondary, but still substantial. The work provides detailed quantitative evidence of the major factors causing differences in NEP among coniferous forests.

Keywords: Eddy correlation; Modelling; Net ecosystem exchange; Climate; Soil respiration; Forest ecosystem

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Nomenclature

A	photosynthetic rate (μmol m^{-2} s^{-1})
APAR	absorbed photosynthetically active radiation (MJ m^{-2} yr^{-1})
C_a	atmospheric CO_2 concentration (μmol mol^{-1})
C_i	intercellular CO_2 concentration (μmol mol^{-1})
D	leaf to air vapour pressure deficit (kPa)
DBH	diameter at breast height (cm)
g_s	stomatal conductance (mol m^{-2} s^{-1})
GPP	gross primary productivity (g C m^{-2} yr^{-1})
h	relative humidity
J_{max}	potential rate of electron transport (μmol m^{-2} s^{-1})
LAI	leaf area index (m^2 m^{-2})
LUE	light use efficiency (g C MJ^{-1})
ME	model efficiency
NEP	net ecosystem production (g C m^{-2} yr^{-1})
PAR	photosynthetically active radiation (MJ m^{-2} yr^{-1})
Q_{10}	proportional increase in respiration rate with a 10 °C increase in temperature
R_g	above-ground growth respiration (g C m^{-2} yr^{-1})
R_m	above-ground maintenance respiration (g C m^{-2} yr^{-1})
R_{soil}	soil respiration (g C m^{-2} yr^{-1})
RE	ecosystem respiration (g C m^{-2} yr^{-1})
V_{cmax}	maximum rate of Rubisco activity (μmol m^{-2} s^{-1})

Greek letters

α	quantum yield of electron transport (mol mol^{-1})
θ	curvature of the light response of electron transport
θ_s	soil water content in the rooting zone (kg m^{-2})

1. Introduction

It is recognised that the world's forests contribute significantly to the global carbon (C) balance, and that changes in forest C uptake may act as an important feedback to the current increase in atmospheric carbon dioxide (Malhi et al., 1999). A large research effort is therefore currently being directed at monitoring forest C balance around the world (e.g. Sellers et al., 1997; Baldocchi et al., 2001; Andreae et al., 2002). An important component of this research effort is the use of eddy covariance methodology to measure C balance of forest patches; this methodology has been applied at over 100 forest sites (Baldocchi et al., 2001). Extrapolation of these data to forests globally is now a priority for researchers. A key problem is identifying the major controls on C balance, in order to allow results for individual forest patches to be generalised (IPCC, 2003).

Forest C balance is known to be affected by a wide range of different factors. A seminal paper comparing eddy covariance measurements of forest C exchange in European forests showed that net ecosystem production of C (NEP) was linearly related to latitude (Valentini et al., 2000). However, this relationship was shown not to hold in North America (Law et al., 2002). It is argued that in Europe, latitude integrates a number of factors influencing C uptake such as radiation and precipitation, whereas these factors do not vary with latitude in the same way across North America (Barr et al., 2002). Law et al. (2002) suggested that an index combining temperature and water balance would be better able to explain variation in forest C exchange across both continents. The index explained 64% of variation in gross ecosystem productivity (GPP) in all forests and grasslands studied, but it was less successful in explaining variability in NEP. The difference between GPP and NEP is the ecosystem respiration (RE). Several authors have calculated that RE varies more than GPP and hence have suggested that RE is the main determinant of NEP (Valentini et al., 2000; Pilegaard et al., 2001; Arain et al., 2002). It is known that respiration is strongly affected by temperature on a short-term basis but when compared across sites, respiration is more strongly related to productivity than to temperature (Janssens et al., 2001). There is evidence that both autotrophic and heterotrophic respiration acclimate to temperature (Luo et al., 2001; Gifford, 2003) and it is thought that substrate limitation may determine respiration in the long term (Dewar et al., 1999; Gifford, 2003). There is also evidence that disturbance, such as ploughing or drainage, may have