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Synthesis on the carbon budget and cycling in a Danish, temperate deciduous forest

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ABSTRACT

A synthesis of five years (2006–2010) of data on carbon cycling in a temperate deciduous forest, Sorø (Zealand, Denmark) was performed by combining all available data from eddy covariance, chamber, suction cups, and biometric measurements. The net ecosystem exchange of CO_2 (NEE), soil respiration, tree growth, litter production and leaching of dissolved inorganic and organic carbon were independently estimated and used to calculate other unmeasured ecosystem carbon budget (ECB) components, based on mass balance equations. This provided a complete assessment of the carbon storage and allocation within the ecosystem. The results showed that this temperate deciduous forest was a moderate carbon sink (258 ± 41 g C m^{-2} yr^{-1}) with both high rates of gross primary production (GPP, 1881 ± 95 g C m^{-2} yr^{-1}) and ecosystem respiration (R_e, 1624 ± 197 g C m^{-2} yr^{-1}). Approximately 62% of the gross assimilated carbon was respired by the living plants, while 21% was contributed to the soil as litter production, the latter balancing the total heterotrophic respiration. The remaining 17% were either stored in the plants (mainly as aboveground biomass) or removed from the system as wood yield. The soil organic carbon stock was considered unchanged over the period of observation, given the high degree of uncertainty associated with the small loss detected (33 ± 85 g C m^{-2} yr^{-1}). The ECB component data were generally consistent, except for one of the derived fluxes, the aboveground autotrophic respiration, which appeared to be higher than expected. The potential causes for this, i.e. underestimation of soil respiration and/or overestimation of R_e are discussed. The plausibility analyses reported here, using multiple ECB data sets together with simple mass conservation equations and the evaluation of data consistency on the basis of the estimated residual terms is widely applicable to other experimental sites, even when some of the carbon fluxes and stock changes are not measured independently.

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1. Introduction

The net carbon budget in forest ecosystems is the difference between uptake by photosynthesis and release predominantly by respiration but also through processes such as leaching of dissolved organic carbon (DOC), soil erosion, volatilisation of organic carbon substances, and harvest (Chapin et al., 2006). Quantification of the ecosystem carbon budget (ECB), i.e. carbon allocation and storage within an ecosystem, is important for understanding both the ecosystem functioning and its interactions with changing climatic conditions and anthropogenic intervention (Heimann and Reichstein, 2008; Schimel, 1995).

In order to assess the role of the terrestrial biosphere in the mitigation of global climate change, it is necessary to investigate the fate of carbon that is assimilated through photosynthesis. This is still a major challenge at the global scale (Houghton, 2003) and has only been achieved in a few regional (Buffam et al., 2011) and site level studies (Gough et al., 2008; Granier et al., 2008; Luyssaert et al., 2007). At the plot scale, methods and protocols have been developed for the measurement of CO_2 fluxes, e.g. eddy covariance (Aubinet et al., 2000; Baldocchi, 2003) and chamber methods (Davidson et al., 2002), and the assessment of carbon storage in biomass (Clark et al., 2001) and soils (Schrumpf et al., 2011). Despite the attempts of larger research networks such as EUROFLUX (Valentini et al., 2000) and AMERIFLUX (Ocheltree and Loescher, 2007) to harmonise the methods, there are still different, equally valid methodological alternatives being applied depending on the experience of the different scientific communities.

When comparing different ECB components, an important source of uncertainty is that individual components are measured at different spatial and temporal scales (Luyssaert et al., 2009). The consistency of the ECB component estimates is potentially affected by the inherent heterogeneity of the ecosystem. Therefore, it is necessary to cross-check the individual component estimates against

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each other using e.g. a multiple constraints approach (Luyssaert et al., 2009). The consistency of the ECB datasets can in the best case be evaluated by comparing a quantity (e.g. the net ecosystem productivity) that is measured at the same temporal and spatial scale with different independent methods (Black et al., 2007; Field and Kaduk, 2004; Harmon et al., 2004; Keith et al., 2009; Miller et al., 2004). This can be (1) micrometeorological methods to assess the atmospheric fluxes, (2) inventories of stock changes in the biomass and soil, or (3) bottom up modelling of ecophysiological processes from chamber measurements (leaves, stems, roots and soil). However, such a consistency assessment requires that all ECB components are estimated for the same time interval, which is not realised in the majority of flux observation or forest inventory sites. The evaluation of data consistency, when only part of the ECB datasets is available, is therefore important.

Prior to a consistency assessment, it is important that the uncertainties of the ECB component estimates are properly characterised. This is particularly important for the development and testing of process models (Carvalhais et al., 2010; Santaren et al., 2007; Williams et al., 2009), which are simultaneously challenged by over-simplification (model structure too simple to represent the natural processes) and over-parameterisation (data availability too limited to constrain the model parameters) (Ibrom et al., 2006; Paw et al., 2000). Progress in data assimilation techniques makes it possible to incorporate the data uncertainties into the objective function of the model-data optimisation scheme (Luo et al., 2009; Raupach et al., 2005; Van Oijen et al., 2005; Wang et al., 2009; Wu et al., 2013). A prerequisite of such model data fusion exercises is that the ECB datasets are consistent and include information about their uncertainties (Raupach et al., 2005; Wang et al., 2009; Williams et al., 2009).

Data uncertainty can be expressed as the probability distribution of the true value around the measured estimate (Richardson et al., 2012). These uncertainties can be random (Ibrom et al., 2006; Richardson and Hollinger, 2005a) or systematic (e.g. biased sampling and calibration errors). Whereas the probability distribution of random errors can be characterised empirically from multiple measurements (Lasslop et al., 2008; Richardson and Hollinger, 2005a), systematic errors can often not be identified by statistical measures. For instance, different methods are available for the post processing of flux data (Aubinet et al., 2000; Falge et al., 2001; Moffat et al., 2007) and the choice of method can lead to different results. The resulting uncertainty can be estimated by applying all methods to the same raw data and comparing the results. Another cause of systematic error is the spatial and temporal variability of the carbon fluxes. At heterogeneous sites, flux representativeness needs careful investigation, but the tools available, the so-called flux footprint models, are themselves oversimplifications of the true flow regimes in complex terrain (Rannik et al., 2012). The small scale variability within ecosystems needs to be considered when comparing the representative flux-based net ecosystem production (NEP) data to other ECB components, e.g. soil respiration (R_s), which is usually measured at multiple points within a comparably small area of the site. The sampling scheme should be optimised towards covering the local heterogeneity in order to be representative for a larger unit (Knohl et al., 2008). Similarly, the measurement frequency should resolve the typical temporal variability of the process measured. If this is not possible, the values need to be up-scaled by modelling (e.g. Selsted et al., 2012). Again, the choice of the model and parameter estimation schemes can introduce systematic uncertainty, e.g. in the estimation of the annual R_s budget from discontinuous field campaigns (Richardson and Hollinger, 2005b).

The objective of this study is to provide a synthesis over all ECB related datasets collected since 1996 at a Danish beech forest (DK-Sor) when atmospheric CO_2 flux measurements were initiated. During this time several projects yielded additional ecological information for differing scientific purposes. In the second half of the investigation period (2006–2010) the data availability allows the estimation of the majority of the carbon fluxes and stock changes in this ecosystem. We test the hypothesis that the available data are consistent within the estimated uncertainty ranges. From this, we derive the most complete carbon budget assessment that is currently possible for the site. This enables us to; (1) investigate the fate of the carbon in the ecosystem; (2) relate the results to findings from other forests where similar assessments have been made, and; (3) provide information on the quality and consistency of the ECB datasets.

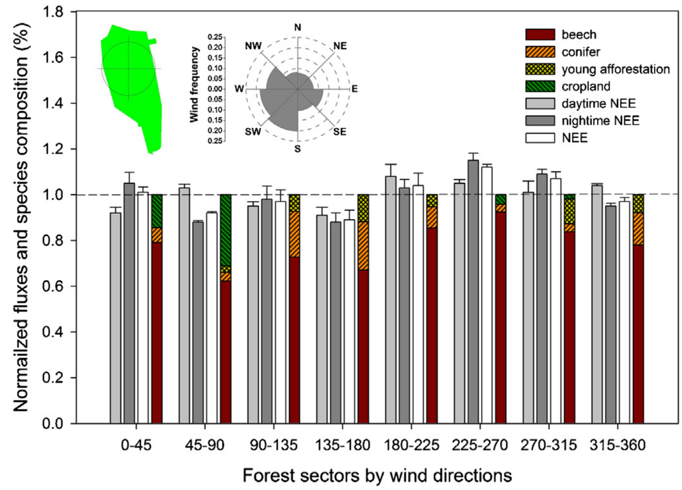

Fig. 1. Normalised average fluxes and species composition (within a 500 m radius circle) for eight forest sectors around the flux tower. For the calculation of the normalised fluxes the original NEE data of 5 years were filtered for conditions with the friction velocity > 0.25 m s^{-1} and the stability parameter ζ < 0.065. In homogeneous site conditions the values should be 1; deviations from 1 are interpreted as systematic effects from site heterogeneity (see also Section 2.2.3). The first inset subplot in the top left is the forest map (green areas), with a 500 m radius circle around the flux tower. The second inset subplot represents the frequency distribution of the wind directions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

2. Material and methods

2.1. Site description

The Danish long-term CO_2 flux investigation site is located within a beech (*Fagus sylvatica* L.) forest, near the town of Sorø on Zealand, Denmark (55°29′13′N, 11°38′45′E). The soils are classified as alfisols or mollisols (depending on the base saturation) with a 10–40 cm deep organic layer. Tree density was 288 stems ha^{-1} in 2010 and seasonal peak leaf area index varied between 4 and 5 m^2 m^{-2} (Pilegaard et al., 2011). In 2010, the stand around the flux tower was 89 years old, the average tree height was 28 m and the average diameter at breast height was 42 cm. The mean annual air temperature at the site was 8.5 °C, and the measured mean annual precipitation amounted to 564 mm (measured in the time period from 1996 to 2009). The flux tower is located in the centre of the forest. The forest fetch around the tower ranges between 425 and 1630 m (Fig. 1) depending on the direction (Pilegaard et al., 2011). Further information about the site can be found in Pilegaard et al. (2001, 2011, 2003).

2.2. Flux data processing and uncertainty estimation

The net ecosystem exchange of CO_2 (NEE, note the definitions of the sign conventions in Table 1) between the biosphere and atmosphere was measured with a closed-path eddy covariance

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