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Differences in carbon uptake and water use between a managed and an unmanaged beech forest in central Germany ☆

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ABSTRACT

Net atmospheric carbon dioxide exchange, total evapotranspiration and net primary production of two neighbouring beech (*Fagus sylvatica* L.) forests in central Germany differing in site management were measured using the eddy covariance technique and biometric methods. The unmanaged site was an old-growth forest with admixtures of ash (*Fraxinus excelsior* L.) and sycamore (*Acer pseudoplatanus* L.) trees whereas the managed site was a regularly thinned, even-aged (about 130 years old), pure beech stand. Average carbon fluxes measured over seven years did not differ significantly between the two forests. Evapotranspiration was slightly higher (and consequently water use efficiency lower) at the unmanaged site. The maximum rates as well as the interannual variability of both net ecosystem exchange and net primary production were considerably larger at the managed, even-aged stand. The lowest annual carbon sequestration rates were observed in years with high fruit production in beech combined with cold and dry spells during leaf development which affected the carbon balance of the managed forest more than that of the unmanaged forest. In contrast, an extraordinarily dry period in late summer 2003 caused a stronger reduction in net carbon uptake in the old-growth forest which can probably be attributed to the contribution of ash to the ecosystem fluxes. Ash has a different phenology which made it more susceptible to the late summer drought. The relative importance of tree and structural (age, size) diversity, leaf area index and regenerative growth as well as the temporal frame and extent of single weather extremes for the forest–atmosphere exchange is discussed and it is concluded that site management and forest structure needs to be included in soil–vegetation–atmosphere-transfer models as it can often override effects of land use or plant functional type.

1. Introduction

Changes in land cover and their biophysical and biogeochemical effects have been investigated much more thoroughly so far than differences in land management within a single land cover type (Luyssaert et al., 2014). Forest management can alter species and structural diversity as well as ecophysiological traits. Their influence on the carbon cycle and the water use efficiency of forest ecosystems and their interannual variability are as yet not well understood. This hampers any robust assessment of the impact of management practices on the greenhouse gas balance. Many recent studies about the effect of land cover type on the ecosystem carbon budget and the water use efficiency are based on the increasing number of canopy gas exchange measurements by means of the eddy covariance technique (Luyssaert et al., 2007; Keenan et al., 2013). However, it has also been noted that a large variability in gas exchange is caused by species-specific traits within one land use type (Groenendijk et al., 2011; Law, 2014) which can make it difficult to transfer general trends to specific sites. Inhomogeneous instrumentation and data analysis often amplifies the problem.

Therefore we present a case study of paired measurements of ecosystem carbon and water fluxes in two neighbouring forests that are characterised by the same site conditions and are dominated by European beech (*Fagus sylvatica*), and where identical instrumentation and data analysis were used, to investigate the effect of structural diversity and the admixture of other tree species, caused by different historical and recent forest management, on canopy gas exchange. In terms of recent trends in forest management, beech is considered as "pillar of close-to-nature forestry in the central European lowland" (Pretzsch, 2014). Understanding

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its responses to natural and anthropogenic changes and disturbances is thus of high relevance and significance. With this study, which combines eddy covariance measurements with more traditional biometric methods to assess the forests' primary production, we try to test the following two hypotheses:

(1) Forest management in terms of establishing and maintaining an even-aged, mono-specific stand improves the carbon gain and the water use efficiency compared to an unmanaged forest.
(2) Structural diversity as encountered in the unmanaged forest decreases the interannual variability of growth and water use as well as the susceptibility to disturbances.

2. Material and methods

2.1. Sites

The two forests sites are located in Thuringia in central Germany, ca. 30 km apart from each other. Both stands grow at an altitude of 450 m a.s.l. and face similar soil conditions (Triassic limestone covered with variable Pleistocene loess deposits) and climatic conditions (*suboceanic–submontane climate* with long-term means of about 8 °C for annual air temperature and 750 mm precipitation). Annual air temperature and precipitation sums during the study period are given in Table 1.

The Hainich site is an unmanaged stand in the central part of Hainich National Park. The area was never clear-cut but used as a coppice-with-standards system until the end of the 19th century and then for selective cutting by the local population until 1965. From 1965 to 1997 it was part of a military training area and only single, very valuable trees were cut. Since December 1997 no management activities at all have taken place. Regarding to its highly diverse horizontal and vertical structure the forest can be characterised as an old-growth forest with tree ages varying between 0 and 250 years (Fig. 1, Knohl et al., 2003; Mund, 2004). Beech (*F. sylvatica* L.) is the dominating tree species, accounting for ca. 64% of tree biomass, and ash (*Fraxinus excelsior* L.) and sycamore (*Acer pseudoplatanus* L.) make up most of the remaining biomass with a share of 28% and 7%, respectively (Table 2). Single trees of *Carpinus betulus* (L.), *Ulmus glabra* (L.), *Acer platanoides* (L.) and *A. campestre* (L.) are admixed as remnants of the historical forest management regime (Mund et al., 2010).

The Leinefelde site is an even-aged, pure beech stand managed as a shelterwood system for maximum wood production. Thinning was carried out regularly every 10–20 years (Anthoni et al., 2004). The measurement site consists of a 130 year-old stand which is surrounded by other even-aged beech stands. The site at Leinefelde is characterised by a slightly thicker loess cover, associated with a dominance of Luvisols, than the Hainich site where Cambisols are the dominant soil type (Mund, 2004). The herbaceous ground vegetation differs in species composition between the two forests (Anthoni et al., 2004).

Table 1
Mean annual air temperature (t_a) and annual precipitation (P) during the study period.

Year	t_a (°C)	P (mm)
2003	8.50	544
2004	7.83	763
2005	8.13	736
2006	8.66	660
2010	6.71	756
2011	8.85	544
2012	8.27	701

The maximum annual effective leaf area index as measured with an LAI-2000 plant canopy analyser (LI-COR Inc., Lincoln, NE, USA) was on average 5.1 at the unmanaged site and 4.2 at the managed site (Table 2). The latter had a lower stand density (224 m^{-2} vs. 323 m^{-2}) but a higher wood biomass (above- and belowground; 237 t C ha^{-1} vs. 212 t C ha^{-1}). The leaf area was concentrated more towards the canopy top than it was the case at the unmanaged site. The maximum canopy height as determined by visual inspection from the respective tower was about 35 m at both sites.

2.2. Eddy covariance data

The eddy covariance measurements at the two sites were carried out at 44 m above the ground with identical instrumentation and data acquisition techniques. Each measurement system consisted of a three-dimensional sonic anemometer (Solent R3, Gill Instruments Ltd., Lymington, UK) and a closed-path CO_2/H_2O infrared gas analyser (LI-6262, LI-COR Inc., Lincoln, NE, USA) placed at the bottom of the instrument tower and connected to the gas inlet close to the anemometer by a 50 m long tube. Technical details about the installation can be found in Knohl et al. (2003). Data were synchronised and stored on a field computer using the "EddySoft" data acquisition software by O. Kolle (Max-Planck-Institute for Biogeochemistry, Jena, Germany). The turbulent fluxes were recalculated in 2013 with version 4.1 of the "EddyPro" software (LI-COR Inc., Lincoln, NE, USA).

The data collection and quality control followed the methodology of Aubinet et al. (2000) and Foken et al. (2004). The gap filling and the partitioning of the net ecosystem CO_2 exchange (NEE) into gross primary production (GPP) and ecosystem respiration (R_{eco}) was carried out using the "Fluxnet" online-tool based on Reichstein et al. (2005). Evapotranspiration was calculated as the residual of net radiation and sensible heat flux (Gash et al., 1999) in terms of the annual totals. Direct eddy covariance measurements of ET based on the water vapour concentrations recorded by the LI-6262 were rejected because of a large underestimation of the flux caused by attenuation of the water vapour fluctuations in the long tubing. For details about standard meteorological variables recorded at the sites we refer once again to earlier descriptions of the two measurements stations (Knohl et al., 2003; Anthoni et al., 2004). Due to a lack of funding, no flux data could be obtained at the managed site from 2007 to 2009.

2.3. Biometric data

The estimates for annual wood NPP of the study sites resulted from continuous measurements of stem diameter at breast height (1.3 m above ground level) in combination with stand inventories. At the tree scale stem diameter increment was measured with dendrometers distributed over different diameter size classes and at Hainich also over different tree species. At the homogenous stand Leinefelde up to 22 trees were equipped with a dendrometer and at the unmanaged stand Hainich up to 96 trees. The exact number of measurement trees in each year of the study period varied because of damages to single dendrometers, and at Hainich also because of the natural dieback of individual trees that had to be replaced with new trees. For 2003 and 2004 also data from stem increment cores taken at the Hainich site were available (Kahl et al., 2012; M. Bryukhanova, Institute of Forest SB RAS, Akademgorodok, Krasnoyarsk, Russia, unpublished) and included in this study.

To scale up stem growth from the tree level to the stand level site- and species-specific regression functions describing the annual relationship between initial basal area (cross-sectional area of a stem at breast height) and basal area increment were developed and applied to stand inventories of the study sites. The extent