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Net ecosystem exchange over a non-cleared wind-throw-disturbed upland spruce forest—Measurements and simulations

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ABSTRACT

Net ecosystem exchange (NEE) was measured in a wind-throw-disturbed upland spruce forest in the Bavarian Forest National Park (Germany) continuously over four years from 2009 to 2013 by the eddy-covariance method. Estimated annual NEE (positive values stand for a net carbon source) of the non-cleared wind-throw resulted in 347 ± 104, 255 ± 77, 221 ± 66, 240 ± 52, and 167 ± 50 gC m^{-2}. However, two to six years after the storm event (windstorm Kyrill, January 2007) GEP was already strong, increasing from 393 (2009) to 649 gC m^{-2} yr^{-1} (2013). Ecosystem respiration showed a high inter-annual variability during the measurement period, ranging from 656 to 816 gC m^{-2}. Carbon dioxide (CO_2) fluxes during snow-covered periods averaged about 0.8 μmol m^{-2} s^{-1} with only little variation.

The contributions of spruces and grasses to the overall carbon exchange, and the differentiation into autotrophic and heterotrophic respiration were estimated by the biogeochemical model LandscapeDNDC (formerly MoBiLE). Comparisons with observations indicate that the model represents gross primary productivity very well, but underestimates ecosystem respiration during early spring and late autumn, and thus tends to diverge from measurements over multi-year simulation periods.

These results show that (1) low productivity mountain forest sites may switch from a carbon source to a carbon sink within relatively few years after disturbance, and (2) model uncertainties are most prominently related to soil respiration, decomposition of coarse woody debris, and succession of ground cover species.

1. Introduction

Forests, especially those of mid-latitudes are generally reported to serve as strong carbon sinks (Ciais et al., 2008; Dixon et al., 1994; Dragoni et al., 2011; Gough et al., 2008; Gruenwald and Bernhofer, 2007; Janssens et al., 2003; Knohl et al., 2003; Liski et al., 2002, 2003; Ueyama et al., 2011; Valentini et al., 2000, 2003). However, their contribution to the global carbon budget is still uncertain (Luyssaert et al., 2010; Nabuurs et al., 2003; Pan et al., 2011; Thornton et al., 2002; Wharton et al., 2012; Whitehead, 2011). For instance, FLUXNET, a network of eddy-covariance flux-towers, aims at collecting information about the magnitude of carbon exchange in different types of ecosystems all over the world (Baldocchi et al., 2001). Most of these flux-towers are located in more or less intact forest ecosystems. However, severe disturbances such as fire (Amiro et al., 2006; Dore et al., 2012), harvest (Schmid et al., 2006; Yanai et al., 2003), insect outbreaks (Seidl et al., 2008) or strong storms (Amiro et al., 2010; Knohl et al., 2002; Lindroth et al., 2009; Thürig et al., 2005) can switch an ecosystem from a carbon sink to carbon source within only short time period. Large-scale disturbances can thus change not only the magnitude but also the sign of currently observed carbon fluxes in the future (Canadell et al., 2000). In addition, disturbance-caused damage of forest ecosystems, in particular from storms, insects, and fires is expected to increase due to climate change (Donat et al., 2011; Liu et al., 2011; Luyssaert et al., 2008; Running, 2008; Schelhaas et al., 2010; Seidl et al., 2011b; Spathelf et al., 2013).

Thus, to accurately determine the contribution of forests to the global carbon budget, disturbances have to be considered (Lindroth et al., 2009; Reichstein et al., 2013). Unfortunately, most CO_2 flux (and other) measurements in wind-throw disturbed ecosystems are conducted during only a few months (e.g., Knohl et al., 2002;

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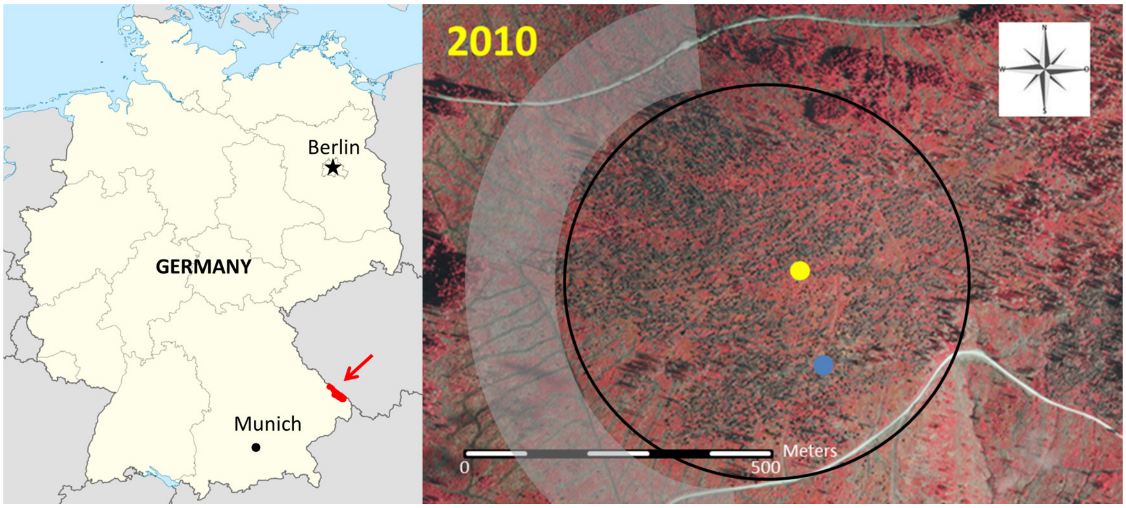

Fig. 1. Left: the study site in the Bavarian Forest National Park on the border between Germany and the Czech Republic (red arrow) (modified, based on www.weltkarte.com). Right: aerial false-color photograph of the study site provided by BFNP; red color represents near-infrared radiation and indicates live vegetation; the yellow point marks the main measurement tower, blue dot the satellite tower; the black circle roughly includes the wind-throw area; the shaded area in the west indicates a clear-cut bark-beetle-protection-zone which had no influence on the measurements. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Lindroth et al., 2009). The C-exchange effects of other disturbance types (e.g., harvesting, fire) have been studied year-round in some cases (e.g., Amiro et al., 2003; Humphreys et al., 2005; Zha et al., 2009).

Due to the scarcity of data, the multitude of different and sometimes interacting impacts, and the relative shortage of process understanding, it is still challenging to model carbon exchange in disturbed ecosystems (Seidl et al., 2011a). For example the dynamic interaction between microclimate, nutrient availability and ecosystem succession after disturbances is usually not accounted for in models designed for intact forest ecosystems or grassland (such as Chen et al., 2004; Royo and Carson, 2006). Current approaches thus simplify the task, excluding competition by ground vegetation, assuming that physical conditions remain unchanged or that dead trees are completely removed by management directly after the event. Furthermore, secondary stresses such as ungulate browsing (Rammig et al., 2007) at cleared sites or insect attacks on storm-damaged trees are very seldom addressed.

An opportunity to study the carbon cycling within a wind-throw disturbed forest offered itself in the Bavarian Forest National Park (BFNP) in 2007. Partially this area had been heavily damaged by the severe winter storm Kyrill that swept over large parts of Europe with gusts up to 60 m s^{-1} and left a trail of devastation on January 18th/19th in 2007. The silvicultural damage was disastrous. An amount of almost 60 million m^3 of wood all over Western Europe was uprooted – from these, 37 million m^3 where thrown in Germany. Within the BFNP, Kyrill caused some large contiguous wind-throw areas. Due to a policy of conservative hands-off forest management, the administration of the National Park decided not to clear most of these areas. All dead-wood remained at the site, thereby creating an almost unique opportunity to investigate and observe an ecosystem that was recently affected by severe disturbance during ecological succession without anthropogenic intervention.

The overall objective of the study is to examine how the disturbance and the recovery from it affect the carbon cycling of this forest ecosystem. To this end CO_2 exchange (net ecosystem exchange – NEE) was measured by eddy-covariance and combined with an ecosystem exchange model, including a dynamic vegetation module.

2. Materials and methods

2.1. Site description

The study site is located in the Bavarian Forest National Park, in the eastern part of Bavaria, Germany, close to the border of the Czech Republic (Fig. 1). Micrometeorological instruments were installed at the beginning of 2009 (two years after Kyrill) on the Lackenberg hill, in the middle of a large (30 ha) wind-throw area (49.100° N, 13.305° E; 1308 m a.s.l.). The terrain slopes from north to south (≈9°). The pre-storm forest was about 150 years old (BFNP Administration, personal communication) with a tree density of approximately 1000 trees ha^{-1}. Average height was about 18 m and average girth was about 1.5 m (estimated from aerial photography and a survey of fallen trees). The number of new seedlings after the storm was estimated at about 2500 seedlings ha^{-1} (stem count in July 2010). The present vegetation mainly consists of Norway spruce (*Picea abies* (L.) H. Karst) even though at the Lackenberg site only few individuals of this species have survived the storm Kyrill. However, many new seedlings have since emerged almost everywhere between the fallen trees. The other live vegetation is dominated by grasses (*Deschampsia flexuosa* (L.) Trin, *Luzula sylvatica* (Huds.) Gaudin, *Juncus effuses* L.), fern (*Athyrium distentifolium* Tausch ex Opiz), few blue berries (*Vaccinium myrtillus* L.), and very few rowan berries (*Sorbus aucuparia* L.). The vegetation period roughly lasts from May to August. The snow cover period usually extends from November to March but can also last from September to May in some years. Diameter of the root-plates from the uprooted trees, which is 2 m on average, was taken as the typical height of roughness elements, because most remaining and new emerging vegetation does not exceed this height yet. Predominant soil types in this region are Typic Dystrudepts (Dystric Cambisols), Andic Dystrudepts (Dystric Cambisols with low bulk density), and Entic Haplorthods (Entic Podzols) (Späth, 2010; Spielvogel et al., 2006). These soils are well drained and not very deep, with the available root zone rarely exceeding 50–100 cm depth.

2.2. Climate

Climate in this region can be quite variable and mainly depends on the altitude. Daily mean air temperature roughly ranges