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Research paper

Turbulent energy and carbon dioxide exchange along an early-successional windthrow chronosequence in the European Alps

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ABSTRACT

Intensifying natural disturbance regimes are driving changes in turbulent forest-atmosphere exchange of energy and carbon dioxide (CO_2), which are affecting the atmosphere at local to global scales. In the European Alps, windthrow and bark beetle infestations have been increasing in severity and intensity; however, studies employing eddy covariance to investigate net ecosystem-atmosphere exchange of sensible (*H*) and latent heat (*LE*), and CO_2 (*NEE*) along forest disturbance chronosequences in this ecoregion have yet to emerge. This paper presents the first eddy covariance measurements at windthrow sites in the European Alps. Despite the complex terrain, turbulent flux data quality at the sites was high, as indicated by the near-100% energy balance closures and the large proportion of data satisfying strict quality criteria. Seasonal datasets (15th May–15th October) from the two sites (disturbed in 2009 and 2007, respectively) were subsequently combined in a time series-chronosequence approach to investigate *H*, *LE*, and *NEE* over the 2nd to 8th growing seasons post-windthrow. While varying weather conditions strongly influenced energy partitioning, post-disturbance vegetation recovery coincided with a general decrease in median summer Bowen ratios (*H*/*LE*), although the decline was most pronounced between the 2nd and 3rd summers. Net CO_2 emissions on the other hand demonstrated a clear and consistent post-disturbance decline, though the seasonal fluxes point toward large losses of ecosystem carbon (C) after disturbance. In the 3rd season post-windthrow, a net total of $405 \pm 15\,g\,C\,m^{-2}$ was lost to the atmosphere, while the seasonal net ecosystem production of $-4 \pm 16\,g\,C\,m^{-2}$ observed at the 2007 windthrow site indicates that 8 years after disturbance the site remains an annual net C source. This study therefore demonstrates that eddy covariance can provide robust and valuable insights into forest disturbance impacts on *H*, *LE*, and *NEE* in the European Alps.

1. Introduction

Natural forest disturbance regimes have been intensifying (becoming more frequent and/or more severe) (Hicke et al., 2012; Schelhaas et al., 2003; Seidl et al., 2014; Westerling et al., 2006), questioning the role of forests within climate change mitigation strategies (Canadell and Raupach, 2008). Natural stand-replacing disturbance by wind, fire and insect infestation initiate abrupt-, and subsequent successional changes in ecosystem composition, structure and function (Dale et al., 2001), which influence *inter alia* forest-atmosphere exchange of turbulent energy (Amiro et al., 2006b; Liu et al., 2005) and carbon dioxide (CO_2) (Amiro et al., 2010; Goulden et al., 2011). These are important fluxes which influence weather and climate (Pielke et al., 1998). Disturbance related changes in energy partitioning between the sensible (*H*) and latent heat fluxes (*LE*) for example can cause local summer surface temperatures to increase by 1 °C (Maness et al., 2013), while studies have recently demonstrated the potential of natural disturbance-driven reductions in carbon (C) sink strength to offset (Seidl et al., 2014) or overwhelm (Kurz et al., 2008) forest management strategies aiming to increase regional C sequestration. A comprehensive understanding of natural disturbance impacts on these and other forest-atmosphere fluxes is therefore crucial if forest management is to be successfully incorporated into climate change mitigation strategies (Anderson et al., 2011; Bonan, 2008; Le Page et al., 2013).

The need for data on natural disturbance impacts on *H*, *LE*, and net ecosystem exchange of CO_2 (*NEE*), saw the emergence

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of in situ micrometeorological measurement campaigns along a variety of forest disturbance chronosequences (forest sites in different stages of post-disturbance succession) (Amiro et al., 2006a, 2010, 2006b; Dore et al., 2008; Goulden et al., 2011, 2006; Liu et al., 2005). A general paradigm of initial stand-replacing disturbance impacts can be drawn from the above studies. Following abrupt tree mortality and canopy loss over large areas, transpiration and gross ecosystem photosynthesis decline substantially, causing shifts in energy partitioning from *LE* to *H*, and a shift from annual net C uptake to net C release. The C sink-source shift can be further enhanced (though not always e.g. Moore et al. (2013)) by accelerated heterotrophic respiration (decomposition), due to increased soil temperatures following canopy loss, and the sudden pulse of above-, and below-ground dead organic material. Typically, post-disturbance successional vegetation recovery (associated increase in leaf area index (LAI)) leads to a quick recovery of evapotranspiration (*ET*), and increased turbulent energy partitioning into *LE*, similar to/above pre-disturbance levels. Gross ecosystem production and autotrophic respiration concurrently increase, though recovery to net ecosystem production (*NEP*) at/above pre-disturbance levels is slower than for *LE*. After the initial post-disturbance pulse, heterotrophic respiration begins to decline also leading to increases in *NEP*. However, the decline is not always monotonic, with secondary pulses occurring later in the succession as more recalcitrant disturbance detritus legacies (e.g. coarse roots, stumps, fallen and/or standing stems) become mobilised (Harmon et al., 2011).

Despite the above generalisations, the magnitude of disturbance impacts and rates of recovering vary substantially between forest and disturbance types, and due to local factors (e.g. management) influencing secondary succession. Synthesizing the observations along North-American chronosequences (which included harvest disturbances), Amiro et al. (2010) report maximum post-disturbance C losses via *NEE* ranging between 200 and 1270 $g\,C\,m^{-2}\,yr^{-1}$. The small number of such studies in Europe is thus a concern, especially given the trend of increasing frequency and severity of windthrow and bark beetle infestations (Schelhaas et al., 2003; Seidl et al., 2011). To date, such investigations have been confined to two studies employing short measurement campaigns at boreal windthrow sites (Knohl et al., 2002; Lindroth et al., 2009), and a 5 year campaign at a temperate upland windthrow site in Bavaria, Germany (Lindauer et al., 2014). Many important European forest ecoregions have thus so far been ignored, with the Alps particularly conspicuous by their absence. While this represents a glaring omission considering that this region is forecast to be a hot spot of future windthrow and bark beetle activity (Seidl et al., 2014), the challenges of performing such experiments in the Alps are substantial. Eddy covariance, now the standard in situ method for measuring turbulent fluxes, works best when the surrounding surface conditions are flat and homogenous (Baldocchi et al., 2001; Baldocchi, 2003; Foken et al., 2012), where criteria underlying successful application (stationarity of covariances, flux-variance similarity, zero mean vertical wind speeds; see Foken et al. (2004))) are more often observed. Due to the inherent topographical complexity and spatial ecosystem heterogeneity, satisfying these criteria is more difficult in mountainous areas (Turnipseed et al., 2003, 2004), while flux-variance similarity (used to assess development of turbulence (Foken and Wichura, 1996)), may demonstrate different scaling relationships in complex terrain (Stiperski and Rotach, 2015). Furthermore, the application of common one-dimensional eddy covariance systems assumes that the integral exchange over soil-atmosphere/canopy-atmosphere interfaces are in quasi-equilibrium with the turbulent exchange measured above the ecosystem in the surface layer i.e. the vertical and horizontal advection of scalars (heat, water vapor, CO_2) is negligible. However, with the onset of stable nighttime boundary layer conditions, the advection of scalars via drainage flows typical of sloping terrain become significant (Aubinet, 2008; Etzold et al., 2010; Turnipseed et al., 2003).

Although sites in complex terrain remain underrepresented within the global flux research network, FLUXNET (Rotach et al., 2014), eddy covariance, with stringent data quality control, has nonetheless provided important insights into surface-atmosphere exchange of mountain ecosystems (Etzold et al., 2011; Hammerle et al., 2007; Hiller et al., 2008; Wohlfahrt et al., 2008). With this encouragement, eddy covariance measurement campaigns were commenced at two neighbouring montane windthrow sites (disturbed in 2007 and 2009) located in the Austrian part of the European Alps. Considering the aforementioned methodological challenges, the initial objective of this study was to test whether eddy covariance provides defensible measurements of *H*, *LE*, and *NEE* at the two naturally disturbed sites. Assuming validity of the working hypothesis that with strict quality control, robust measurements of turbulent fluxes can be made, the second objective was to describe the development of growing season turbulent exchange over the initial post-disturbance period. Given the observed vegetation recovery at the two sites (Mayer et al., 2014), it is hypothesised that daytime *LE* will generally increase at the expense of *H*, and that net CO_2 uptake, when integrated over days and growing seasons, demonstrates a successional increase.

2. Materials and methods

2.1. Site description

The investigation took place at a disturbed montane mixed forest within the Höllengebirge mountain range. The range belongs to the Northern Calcareous Alps and is located in the Salzkammergut region of Upper Austria (47°47′19″ N, 13°38′21″ E). Between 1999 and 2010, an average annual precipitation and air temperature of 1654 mm and 8.5 °C, respectively, were recorded by a nearby (480 m a.s.l., 3.8 km distance from the test sites) hydrological station, which is operated by the Austrian federal ministry of agriculture, forestry, environment and water management (BMLFUW). Much of the Höllengebirge is managed by the Austrian federal forestry agency (ÖBf AG) as protection forest; however, significant revenue is generated from deer and chamois hunting in the area. In 2007, the storm "Kyrill" caused considerable forest damage in the area. This storm, together with several local storms in 2009 opened up a 29 ha gap in a >200 year old montane forest on a south exposed slope (mean inclination of ~25°, elevation 700 to 1200 m a.s.l.) in the western part of the range (Fig. 1). While much of the blown-over stem material was removed during post-disturbance management operations, ca. 15% of the stem fraction, together with branches and stumps, were left on site. With the bedrock dominated by karstified limestone and dolomite, well-developed Chromic Cambisols, shallow Rendzic Leptosols and Folic Histosols (IUSS Working Group WRB, 2006) are found within metres of one another at the sites. Moder and Tangel (Zanella et al., 2011) constitute the prevailing humus forms. Originally, the forest was dominated by European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*), and Silver fir (*Abies alba*). However, following windthrows in 2007 and 2009, the initially sparse ground vegetation cover has increased, with pioneer herbaceous plants (e.g. *Adenostyles glabra*, *Eupatorium cannabinum, Cirsium arvense*, *Senecio ovatus*, *Urtica dioica*) and grasses (e.g. *Calamagrostis varia, Carex alba*) dominating (Fig. 2). While forest regeneration has been inhibited at the site disturbed in 2007 (hereafter abbreviated as HW07) and the site disturbed in 2009 (hereafter abbreviated as HW09), comparatively stronger tree regeneration has been observed at HW07, due to some