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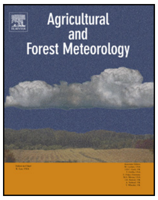

Energy balance and evapotranspiration changes in a larch forest caused by severe disturbance during an early secondary succession

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ABSTRACT

Larch, a deciduous needle-leaf gymnosperm, is widely distributed in cool temperate and boreal forests of the Northern Hemisphere. Thus, evaluating evapotranspiration (ET) in larch forests is important to elucidate energy and water cycles on a global scale. In addition, severe forest disturbance is expected to change ET and energy balance through a drastic change in the canopy structure. However, knowledge related to the environmental functions of larch forests in cool temperate regions remains lacking compared with Siberian larch forests. Furthermore, few reports describe quantified changes in ET and energy balance before and after forest disturbance. Therefore, for more than a decade, we measured sensible and latent heat fluxes using the eddy covariance technique above a larch forest in northern Japan and its succeeding ex-forest after a stand-replacing disturbance caused by windthrow. In general, the larch forest's ET was not limited by water in contrast to that of a Siberian larch forest. Although the aboveground biomass decreased by 97% through the disturbance, both cumulative ET and latent heat flux normalized by incident solar radiation (lE/R_g) during the snow-free period of about seven months were decreased by only 24% in the second year after disturbance. The 24% decrease was caused by 17% decrease in the partition of incident solar radiation to net radiation (R_g/R_n) and 9% decrease in the partition of net radiation to ET (lE/R_n). The former resulted from increased albedo and decreased net longwave radiation, and the latter was mainly due to decrease in surface conductance. According to the vegetation recovery of shrubs and herbaceous plants, cumulative ET during the snow-free period increased gradually and almost reached pre-disturbance levels in six years. However, normalized ET by solar radiation (lE/R_g) decreased in the 11th and 12th years after reaching the pre-disturbance level. Positive relationship between cumulative ET and vegetation indices indicates that the ET recovery was due to vegetation recovery.

1. Introduction

Forest evapotranspiration (ET) plays a key role in planetary hydrologic and energetic cycles (Oki and Kanae, 2006). How biotic and abiotic mechanisms controlling ET will be altered in the future remains a central research issue for ecosystem service assessment, water resource management and climate prediction (Katul et al., 2012). Teuling et al. (2010) reported that forests can mitigate the impact of extreme and/or long-lasting heat events through ET because of their root systems, which can access deep soil water. However, the global forest area has diminished substantially, as quickly as 5.2 million ha per year during 2000–2010 (FAO, 2010) because of land-use conversion into farmland and natural disasters such as wildfires, severe drought and strong winds (van Lierop et al., 2015). Change in the vegetation composition of ecosystems through succession after such disturbances is a global phenomenon that potentially changes the mass and energy exchange between the land and atmosphere (Scott et al., 2014). Amiro et al. (2006) reported the effect of wildfire on the boreal forest energy balance and implied that increased albedo after a disturbance engenders changes in energy partitioning and causes cooling feedback on climate. Yang et al. (2015) reported that climate variation explains 76% of interannual ET variation across the North American East Coast, whereas considerable degrees of land conversion dramatically affected long-term change in ET on a watershed scale. Therefore, identifying potential changes in ecosystem functions, including ET and energy partitioning, is necessary to ascertain their

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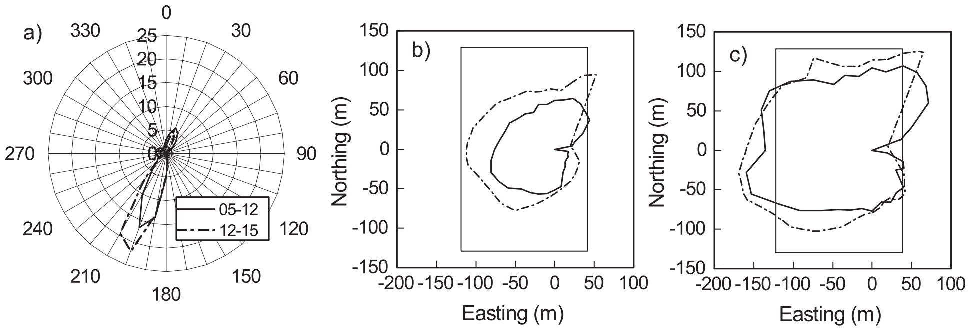

Fig. 1. Relative distribution (%) of wind directions (wind speed >0.2 m s^{-1}) at intervals of 10° (a), and distributions of 80% footprint distances of eddy fluxes (Kormann and Meixner, 2001) from the mast position before the movement (the origin) in the daytime (PPFD > 10 µmol m^{-2} s^{-1}) (b) and the nighttime (PPFD ≤ 10 µmol m^{-2} s^{-1}) (c). Solid and dashed lines denote before and after the mast/tower movement in August 2012, respectively. Rectangles denote the study plot.

feedbacks on climate and to project critical transitions of climate on a global and on a local scale (Barnosky et al., 2012).

There are several studies on the effect of disturbance, including thinning, clear cutting and fire, on energy balance and ET of temperate or boreal conifer forest chiefly using the combination of the eddy covariance technique and a chronosequence approach. Moderate disturbance due to thinning by 25–30% decrease in basal area or leaf area index (LAI) did not decrease ET (Vesala et al., 2005), whereas ET was once decreased by thinning, and then recovered in four years to the pre-disturbance level (Dore et al., 2012). In contrast, ET increased by 40% in the second year after thinning because of biotic stimulation (Lagergren et al., 2008). These results suggest that decrease in ET by thinning is limited. As for stand-replacing disturbance, summertime ET was still lower in cutover five years after harvesting, in which shrub and natural regeneration of Scots pine seedlings were dominant, than a neighboring mature pine forest (Rannik et al., 2002). In a Douglas fir plantation, annual ET dropped by about 30% after clear cutting and fully recovered when stand age was about 12 years (Jassal et al., 2009). During the first three years after clear cutting of a temperate mixed forest, ET was increasing gradually through the progress of secondary succession, whereas net radiation (R_n) did not change (Williams et al., 2014). Land conversion from a pine forest to sparse grassland by an intense wildfire consistently decreased annual ET by 12–30% for at least 15 years after burning (Dore et al., 2012). Also, ET of three-year-old grassland, which emerged after forest fire, was lower by 33% than that of a 15-year-old regenerating broadleaf forest after burning in interior Alaska (Liu et al., 2005). A synthesis analysis using chronosequence data after fire from across the western boreal zone of North America showed summer R_n normalized by global solar radiation (R_n/R_g) was lower in forests under succession than in more mature forests by about 10% (Amiro et al., 2006). Thus, in comparison with thinning, the stand-replacing disturbances decrease ET considerably and probably continue the decrease for at least several years, depending on biotic (natural regeneration or planting) and abiotic (disturbance severity, climate, soil etc.) conditions. However, the recovery process of ET through vegetation succession is complex, because the initial condition of regeneration is site-specific. Further studies are still necessary to evaluate how important initial damage is and how long the damage lasts. In particular, long-term flux monitoring starting before disturbance and lasting during the early stage of succession is valuable to understand the dynamic change of ecosystem processes due to severe disturbance and the subsequent gradual change in response to vegetation recovery.

Larch forests are distributed extensively in northeastern Asia (Gower and Richards, 1990) and strongly affect high-latitude and global water cycles because of their vast area (Ueyama et al., 2010). Thus, to quantify the ET of larch forests and understand its response to disturbances are important. Although there are several studies on the ET and energy balance of larch forests in eastern Siberia and Mongolia, which have characteristics of low precipitation, low temperature, the short growing season and permafrost (Miyazaki et al., 2014; Ohta et al., 2008, 2014). In contrast, knowledge about the ET and energy balance of larch forests in coastal climates is scarce (Hirano et al., 2003). Therefore, flux measurement began above a larch plantation in northern Japan in 2000. Larch has been one of the most important plantation species in Japan (Takahashi et al., 2015). Hirano et al. (2003) reported the energy balance and ET of the larch plantation using the first year's data measured at height of 42 m, about 27 m higher than the canopy. The height probably resulted in the underestimation of eddy flux because of insufficient fetch and low energy balance closure (Hirano et al., 2003). The larch forest was disturbed severely by a typhoon in September 2004. About 90% of its trees fell down. The trunks were taken from the study site for timber use within several months. Consequently, the flux measurement was suspended, and the site was left with uprooted stumps and little vegetation (Sano et al., 2010). Through secondary succession, the aboveground biomass has increased gradually. Some deciduous tree species emerged in three years after the disturbance (Yazaki et al., submitted). The flux measurement was recommenced at the ex-larch forest in August 2005. Using flux data for more than 10 years from 2002, this study was conducted (1) to clarify the characteristics of ET of a larch forest in northern Japan, (2) to quantify the impact of a severe disturbance on ET and energy partitioning, and (3) to assess the change of ET according to vegetation recovery at the early stage of secondary succession.

2. Materials and methods

2.1. Site description

The study site was located in southern Hokkaido, northern Japan (42°44′N, 141°31′E; 125 m above sea level). The site terrain was generally flat, with a slope of 1–2° on average. Flux and meteorological measurements began on a 42-m-tall tower in a Japanese larch (*Larix kaempferi*) forest (Hirano et al., 2003; Hirata et al., 2007). However, measurements were suspended in September 2004 because typhoon Songda struck widely (Sano et al., 2010).

The larch forest, which was afforested in 1957–1959, had an area of about 100 ha and the canopy height of about 15 m (Hirano et al., 2003). Deciduous broadleaf trees (*Betula ermanii*, *Betula platyphylla* and *Ulmus japonica*) were scattered and spruce trees (*Picea jezoensis*) were sparsely distributed in the forest. The stand densities of trees with diameters at breast height (DBH) greater than 5 cm were 673, 459, 18 and 1150 stems ha^{-1}, respectively, for larch, broadleaf trees, spruce and all species in 1999 (Hirano et al., 2003). The basal area densities at DBH of larch, broadleaf trees, spruce and all species