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Implications of ice storm damages on the water and carbon cycle of bamboo forests in southeastern China

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ABSTRACT

Extreme climate events have significant impacts on carbon and water exchanges between forest ecosystems and the atmosphere. Quantification of extreme climate event effects on carbon and water exchanges of forests can improve our understanding of the feedbacks between the terrestrial ecosystem and the atmosphere in the context of global change. This study analyzes the impacts of the early 2008 ice storm that occurred in southeastern China. The impacts on the Gross Primary Production (GPP) and Evapotranspiration (ET) of Moso bamboo forests were analyzed using ecosystem models, MODerate resolution Imaging Spectroradiometer (MODIS) data, and Eddy Covariance flux tower measurements. Interannual differences in GPP and ET were divided into three parts: (1) environmental-dependent, (2) biophysical-dependent, and (3) ice storm damage-dependent. Our results showed that the GPP and ET of Moso bamboo forests were accurately predicted using the remote sensing-driven Penman-Monteith (RS-PM) and Eddy Covariance Light Use Efficiency (EC-LUE) models, respectively. The early 2008 ice storm caused a slight decrease in annual ET and GPP, mainly during the ice storm. Plant transpiration had a slight decrease, but soil (background) evaporation increased because of the reduction in Leaf Area Index (LAI) caused by ice storm effects. This ice storm decreased annual mean GPP by 0.17 $g\,C\,m^{-2}\,d^{-1}$ (roughly 3% of average GPP in 2008) since the fraction of photosynthetically active radiation (FPAR) approached to zero because of ice and snow cover effects. Ice storm damage effects on ET and GPP for the off-year (the year with few new shoot production) were slightly greater than those for the on-year (the year with many new shoot production) due to their different growth characteristics. The time for bamboo forest recovery (1–2 years) from ice storm damage was quite short.

1. Introduction

Forests influence climate through physical, chemical, and biological processes that affect planetary energetics, the hydrologic cycle, and atmospheric composition; furthermore, these complex and nonlinear forest–atmosphere interactions can dampen or amplify anthropogenic climate change (Bonan, 2008). Conversely, climate change also influences physical, chemical, and biological processes of forests (Gu et al., 2003). Extreme climate events can cause pronounced change in environmental conditions that lead to a change in forest structure and carbon and water exchanges between forest ecosystems and the atmosphere, e.g. drought, ice storms, and hurricanes (Irland, 2000; Xiao et al., 2011; Zhao and Running, 2010). In past decades, ice storms have frequently occurred in the north-eastern United States (Irland, 2000). The ice storm that occurred in early 2008 in southeastern China was exceptional, both in duration and in its large distribution across China. According to weather station records, it lasted from January 10 to February 6 and the deepest ice accumulation was 160 mm (Sun et al., 2012). During this 28-day period, the number of freezing days was about 13 days in northwestern Zhejiang province (Sun et al., 2012). Like the 1998 ice storm that occurred in Canada and the United States (Beaudet et al., 2007; Hooper et al., 2001; Irland, 2000; Likens et al., 2004; Olthof et al., 2003, 2004; Parker, 2003; Weeks et al., 2009), several studies on the early 2008 ice storm effects on forests showed that the ice storm caused a large-scale ecological disturbance to the natural and managed ecosystems (Ma et al., 2010; Stone, 2008; Zhou et al., 2011a; Zhu et al., 2011). The impact of the 2008 ice storm on Moso bamboo plantations was

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also investigated (Zhou et al., 2011a), but to our knowledge no study has estimated changes in Gross Primary Production (GPP) and Evapotranspiration (ET) caused by ice storm damage.

A set of powerful and effective approaches for quantifying spatio-temporal variations in ecosystem carbon and water exchanges at large scales have emerged based on the integration of remote sensing data, Eddy Covariance (EC) measurements, and ecosystem models (Cleugh et al., 2007; Mahadevan et al., 2008; Mu et al., 2007, 2011; Running et al., 1999a; Xiao et al., 2008, 2011; Yuan et al., 2007, 2010). Compared with other ecosystem models, the Light Use Efficiency (LUE) model and Penman-Monteith (PM) model may have the most potential to adequately address the spatial and temporal dynamics of GPP and ET because of their strong theoretical basis and practicality (McCallum et al., 2009; Mu et al., 2011; Yuan et al., 2010). Besides, an attractive feature of the LUE and PM models is their suitability for use with remotely sensed observations. An LUE model for simulating daily GPP, called the Eddy Covariance Light Use Efficiency (EC-LUE) model, has been developed (Yuan et al., 2007). A satellite-based evaporation algorithm that uses the well-known PM equation (hereafter RS-PM) was proposed (Cleugh et al., 2007; Mu et al., 2007). The EC-LUE model and the RS-PM model were applied in this study to estimate GPP and ET of Moso bamboo forests, respectively, because of their simplicity, with few inputs and inclusion of good indicators of forest response to ice storm damage (Leaf Area Index (LAI), Normalized Difference Vegetation Index (NDVI)) (Millward and Kraft, 2004; Olthof et al., 2003, 2004; Weeks et al., 2009). Although the relationship between photosynthesis and irradiance at the canopy level is still unclear for most plant functional types, LUE modeling should consider the need to account for GPP saturation (McCallum et al., 2009). In this study, we include light saturation in the EC-LUE model and compare it with the original EC-LUE model, which did not describe this effect (Yuan et al., 2007).

Bamboo forests are one of the most important and special forest types in China and are extensively distributed in tropical and subtropical parts of the country (Lobovikov et al., 2006). Regarding growth characteristics and management measures, bamboo forests are distinct from other forest types. First, the growth rate of a newly emerged Moso bamboo shoot is very high; a bamboo shoot can reach crown height within two months (Zhou et al., 2009). The developed rhizome system connecting culms under the ground enables carbohydrate and nutrient transport from mature culms to bamboo shoots (Li et al., 1998; Lin et al., 2004) and bamboo shoots can generate a large amount of energy by the regulation of anaerobic and aerobic modes of respiration (Cui et al., 2012). Second, about one-third of bamboo culms in a stand are replaced by new bamboo culms every two years, with the new shoot production year known as on-year and the following year as off-year (Zhou et al., 2011a). The majority (more than 90%) of new shoots are produced in the on-year. Additionally, leaves of old bamboo turn yellow after flushing of new shoots during the on-year, but during the off-year old bamboo keep their leaves green all year (Qiu, 1984). These phenomena are rare in other forests. Third, intensive management is applied to bamboo forests, such as intensive fertilization and one thinning during the on-year. Because of bamboo's rapid growth rate and its strong capacity for storing carbon, carbon sequestration research on bamboo forests is important (Chen et al., 2009; Du et al., 2010a; Xu et al., 2011; Zhou et al., 2011b). A series of studies on stand-scale transpiration and canopy conductance on the basis of sap-flux measurements showed transpiration and canopy conductance for bamboo forests were higher than those for coniferous forests (Komatsu et al., 2010, 2012; Kume et al., 2010). Research on the GPP of bamboo forests has been investigated less frequently than water flux regulation.

Quantifying ice storm effects on ET and GPP of Moso bamboo forests is important for accurately evaluating their responses to global climate change. The objectives of this study were to (1) determine the parameter values in the EC-LUE and RS-PM models based on daily GPP and ET estimates from EC measurements, respectively, (2) estimate GPP and ET at large scales based on the MODerate resolution Imaging Spectroradiometer (MODIS) and Modern Era Retrospective- Analysis for Research and Applications (MERRA) dataset over the period 2004–2011, and (3) evaluate the early 2008 ice storm effects on GPP and ET of Moso bamboo forests, and relate these to changes in biophysical factors.

2. Materials and methods

2.1. Study area and EC tower

Anji County was selected as the study area because of the availability of data from an EC tower, which was built in 2010, and its large distribution of bamboo forest (Fig. S1 [Supplemental]). Anji County is located in the northwestern part of Zhejiang province, China. The study area covers 1886.45 km^2, of which 71.10% is covered by forests. Bamboo forests account for 56.47% of the forested areas (79.30% is Moso bamboo) with needle-leaf and broad-leaf forests accounting for the remaining area. The needle-leaf forest is mainly dominated by *Pinus massoniana* and *Cunninghamia lanceolata*, while the broadleaf forest mainly consists of *Cyclobalanopsis glauca*, *Castanopsis sclerophylla*, *Castanopsis eyrei*, *Schima superba*, and *Quercus fabri*. The terrain is undulating with elevation ranging from 4 m to 1587 m above sea level. The annual precipitation average is between 1100 mm and 1900 mm, and the annual temperature average is between 12.20 °C and 15.60 °C.

According to the 55 sample plots, each covering 30 m by 30 m, sampled within the study area in August, 2008, the continuous canopy layer in the forest is at approximately 11 m. The mean Diameter at Breast Height (DBH) for the 55 samples was 9.30 cm and the range was between 6.90 cm and 11.30 cm. The bamboo density was approximately 3235 bamboos ha^{-1}. The growth characteristics of the bamboo forest between the eastern and western parts of the study area were different. The odd-numbered years (for example, 2005, 2007) were on-years and the even-numbered years (for example, 2004, 2008) were off-years for the eastern area (Qiu, 1984). However, this trend was the opposite for the western area.

The 1000 m × 1000 m square around the flux tower site is a Moso bamboo forest with small proportion of mixed forests, cropland, and buildings (Fig. S1 [Supplemental]). The site is surrounded by relatively complex terrain, ranging in elevation from 288 m to 525 m above sea level. The southern and southeastern region of the site is flat, whereas the northern and northwestern region is slightly steep. EC measurements were collected using a Campbell Scientific CSAT3 sonic anemometer (Campbell Inc., USA) and an open-path LICOR-7500 gas analyzer (LiCor Inc., USA) at 38 m above ground (or about three times the canopy height). Additional measurements included vertical profiles of air temperature and relative humidity using a HMP45C (Vaisala, Helsinki, Finland) with inlets at 1, 7, 11, 17, 23, 30, and 38 m above ground and solar radiation using a CNR4 radiometer at 15 m above ground. Vertical profiles of CO_2 were collected using a LI-840 gas analyzer with inlets at 1, 5, 7, 9, 13, 17, and 19 m above ground. The data analyzed here were collected during 2011.

2.2. Models

In this study, the revised RS-PM (hereafter RS-PMr) model (Mu et al., 2007; Yuan et al., 2010) and the EC-LUE model (Yuan et al., 2010) were used to estimate ET and GPP, respectively. A brief introduction of both models is shown in Section 1 [Supplemental]. The applicability of parameters from Yuan et al. (2010) was tested.