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Carbon fluxes, evapotranspiration, and water use efficiency of terrestrial ecosystems in China

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ABSTRACT

The magnitude, spatial patterns, and controlling factors of the carbon and water fluxes of terrestrial ecosystems in China are not well understood due to the lack of ecosystem-level flux observations. We synthesized flux and micrometeorological observations from 22 eddy covariance flux sites across China, and examined the carbon fluxes, evapotranspiration (ET), and water use efficiency (WUE) of terrestrial ecosystems at the annual scale. Our results show that annual carbon and water fluxes exhibited clear latitudinal patterns across sites. Both annual gross primary productivity (GPP) and ecosystem respiration (ER) declined with increasing latitude, leading to a declining pattern in net ecosystem productivity (NEP) with increasing latitude. Annual ET also generally declined with increasing latitude. The spatial patterns of annual carbon and water fluxes were mainly driven by annual temperature, precipitation, and growing season length. Carbon fluxes, ET, and water use efficiency (WUE) varied with vegetation type. Overall, forest and cropland sites had higher annual fluxes than grassland sites, and the annual fluxes of coastal wetland sites were similar to or slightly higher than those of forest sites. Annual WUE was associated with annual precipitation, GPP, and growing season length. Higher-productivity ecosystems (forests and coastal wetlands) also had higher WUE than lower-productivity ecosystems (grasslands and croplands). The strong relationships between annual GPP and ET demonstrated the coupling of the carbon and water cycles. Our results show that forest plantations had high annual NEP and WUE, and could provide larger carbon sequestration capacity than natural forests. The coastal salt marsh and mangrove ecosystems also had high carbon sequestration capacity. Efforts to strengthen China's terrestrial carbon sink should focus on ecosystems such as forest plantations in southern China where heat and water are ideal for maintaining high productivity. This strategy is especially important because efforts to increase carbon sequestration in areas of limited water may inadvertently contribute to the ongoing water crisis in northern China.

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1. Introduction

China's terrestrial ecosystems play an important role in regulating the terrestrial carbon and water cycles. China is now one of the world's top emitters of greenhouse gases that directly contribute to global warming (IPCC, 2007). The carbon sequestration potential of terrestrial ecosystems is increasingly recognized as one of the strategies for slowing down the buildup of carbon dioxide (CO_2) in the atmosphere and mitigating climate change in China (Lu et al., 2012). There is general agreement that as a whole, terrestrial ecosystems in China provide a significant carbon sink (Fang et al., 2001; Piao et al., 2009; Xiao et al., 2009; Pan et al., 2011; Tian et al., 2011) and regulate the hydrological cycle (Wei et al., 2005; Sun et al., 2006; Gao et al., 2007). However, the magnitude, spatial patterns, and controlling factors of the carbon and water fluxes of terrestrial ecosystems across China are not well understood due to the lack of ecosystem-level flux observations.

The eddy covariance (EC) technique provides a valuable approach for measuring carbon and water fluxes at the ecosystem level. The EC flux towers have provided continuous measurements of net ecosystem exchange (NEE) and evapotranspiration (ET, or latent heat flux) since the early 1990s (Wofsy et al., 1993; Baldocchi et al., 2001). NEE is equal to net ecosystem productivity (NEP) but has the opposite sign (NEP = −NEE). The NEE measurements are routinely partitioned into its two components: gross primary productivity (GPP) and ecosystem respiration (ER). ET represents latent heat flux, and is a key component of water and energy balance. EC flux observations have been widely used to examine ecosystem carbon fluxes (Baldocchi, 2008; Amiro et al., 2010; Schwalm et al., 2010), ET (Ryu et al., 2008; Khatun et al., 2011), and water use efficiency (WUE) (Ponton et al., 2006; Yu et al., 2008a) worldwide. Flux observations have also been upscaled to assess terrestrial carbon and water dynamics at regional, continental, and global scales (Xiao et al., 2008, 2010, 2011, 2012; Sun et al., 2011a). Previous studies have shown the close coupling of carbon and water cycles and the advantages of measuring both fluxes simultaneously in understanding the interactions of carbon and water at ecosystem to regional scale (Law et al., 2002; Niu et al., 2008; Beer et al., 2009).

There are currently over 200 EC flux sites in China. Flux observations have been used to examine carbon and water fluxes at individual sites and across multiple sites in China using observations from a very limited number (typically 1–6) of sites (Kato et al., 2004; Hu et al., 2008; Yu et al., 2008a,b; Dong et al., 2011). China has an enormous land area (~9.6 million km^2) and encompasses a large range of ecosystem and climate types. The use of observations from a number of sites across China is essential for assessing the carbon and water budgets of terrestrial ecosystems in China, particularly the variation within and across ecosystem types. A recent synthesis study of the spatial patterns and climatic controls of carbon fluxes (Yu et al., 2013) represents the most comprehensive evaluation to date in China. However, to our knowledge, no study has yet examined carbon fluxes, ET, and the coupling of carbon and water cycles (e.g., WUE) in China using observations from a number of sites encompassing a range of ecosystem and climate types.

Despite the large number of flux sites, the availability and sharing of flux data remain a major challenge for synthesis studies in China (Paw U, 2006). Unlike the United States, Europe, and Canada, China has not established a nationwide flux network that coordinates the collection, analysis, and distribution of observations from sites across the country. Most flux sites are instrumented and operated by different organizations (e.g., Chinese Academy of Forestry Sciences, the Chinese Academy of Meteorological Sciences), universities (e.g., Beijing Forestry University, Xiamen University, Fudan University), and institutes of Chinese Academy of Sciences (e.g., the Institute of Botany, Cold and Arid Regions Environmental and Engineering Research Institute, Institute of Geographical Sciences and Natural Resources, and Institute of Shenyang Applied Ecology). Unlike AmeriFlux, the official ChinaFlux (Yu et al., 2006) coordinates a relatively limited number (8–12) of sites. The lack of data sharing has hindered the progress of ecosystem-level carbon and water cycle and synthesis studies in China (Paw U, 2006).

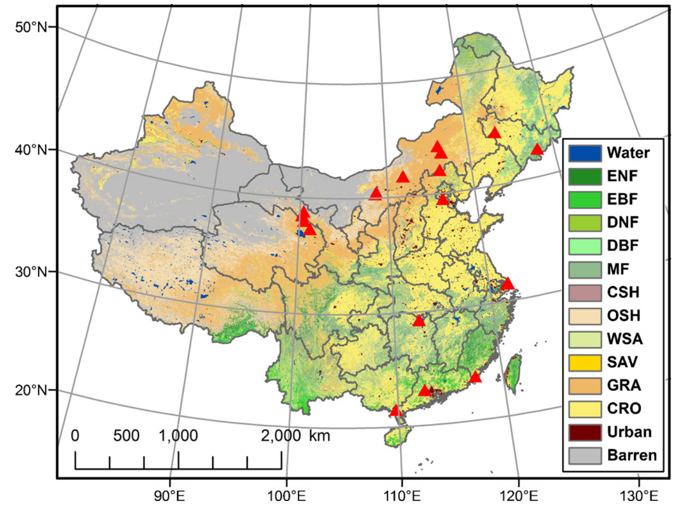

Fig. 1. Location and distribution of the eddy covariance (EC) flux sites used in this study. The base map is the 1 km land-cover map derived from the moderate resolution imaging spectroradiometer (MODIS) (Friedl et al., 2002). The land-cover types of the map are evergreen needleleaf forests (ENF), evergreen broadleaf forests (EBF), deciduous needleleaf forests (DNF), deciduous broadleaf forests (DBF), mixed forests (MF), closed shrublands (CSH), open shrublands (OSH), woody savannas (WSA), savannas (SAV), grasslands (GRA), croplands (CRO), urban, barren or sparsely vegetated (Barren), and water. The symbols represent the EC sites, and the site descriptions are provided in Tables 1 and 2.

In this study, we synthesized flux observations from 22 EC flux sites encompassing a range of climate and ecosystem types across China, and examined annual carbon fluxes, ET, and WUE of terrestrial ecosystems. This synthesis is the outcome of the initiative of the U.S.-China Carbon Consortium (USCCC) to facilitate the sharing of flux observations for synthesis studies. The USCCC is a grassroots organization that coordinates ecologists who instrument and maintain EC flux towers for ecosystem studies and scientists who are interested in synthesis studies in the U.S. and China (Sun et al., 2009). This synthesis is the first effort to examine carbon fluxes, ET, and WUE of terrestrial ecosystems in China using data from so many flux sites encompassing a range of climate and ecosystem types.

The overall goal of our study is to examine the magnitude, spatial patterns, and climate regulation of carbon fluxes, ET, and WUE of terrestrial ecosystems in China. The specific objectives of our study are to (1) synthesize flux measurements from 22 sites across China by building a database with flux and meteorology data, (2) examine the magnitude and spatial patterns of carbon fluxes, ET, and WUE and identify their key climatic controls at the national scale, and (3) better understand the interactions between GPP, ET, and WUE across ecosystems.

2. Materials and methods

We compiled flux and micrometeorological observations from a total of 22 EC flux sites across China (Tables 1 and 2; Fig. 1). These sites encompass four major vegetation types: forests, grasslands, croplands, and coastal wetlands. All 22 sites, except Dinghushan (DHS), Changbaishan (CBS), and Haibei Alpine Tibet site (HB), are affiliated with the USCCC. The 22 sites consist of 6 forest sites, 9 grassland sites, 2 cropland sites, and 5 coastal wetland sites. The site descriptions for all 22 sites including name, location, vegetation