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Energy and water vapor exchange over a young plantation in northern China

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ABSTRACT

Northern China's plantations have long played a role in providing ecological services to the people of China. Reliable detection and attribution of ecosystem water and energy exchange is a precondition to the development of strategies for the sustainable management of these plantations. Here, the seasonal and interannual variability in surface energy exchange and evapotranspiration (*ET*) over a young pine plantation was investigated using eddy-covariance measurements collected over a four-year period (2012–2015). Seasonal patterns in net radiation (R_n), latent (*LE*) and sensible heat fluxes (*H*) were largely similar over the four years. *H* was the dominant energy component, with *LE* exceeding *H* only during the mid-growing season. A significant share of R_n was allocated to *H* during the 2014 summer drought. Energy exchange for the young pine plantation was characterized by high Bowen ratios ($\beta = H/LE$; 6.28, 6.42, 5.65, and 5.34 for the four years), high H/R_n (0.37, 0.36, 0.36, and 0.30), and low LE/R_n (0.15, 0.17, 0.17, and 0.16), with mean annual values of 5.92, 0.35, and 0.16 for β, H/R_n, and LE/R_n, respectively. Daily maximum and annual *ET* were 4.8, 4.5, 4.1, and 3.3 mm day^{-1} and 328, 371, 290, and 326 mm for the four years, with a mean annual value of 329 mm. Seasonal variation in *ET* was strongly controlled by biological factors (i.e., bulk surface conductance and vegetation greenness and density, as characterized by the normalized difference vegetation index) regulated by soil water availability and water vapor pressure deficit (VPD). Evapotranspiration varied interannually and the evapotranspiration-to-precipitation ratio (*ET/P*) ranged from 0.79 to 1.62. Soil water replenishment through precipitation during the non-growing period of the previous year and mid-growing season of the current year was responsible for the interannual variation observed in *ET*. These results clearly indicate the importance of precipitation timing and soil moisture carry-over from previous years in controlling ecosystem energy and water vapor exchange. Irrigation during the spring and dry periods of the year is highly favorable for growth of plantation trees in northern China.

1. Introduction

The terrestrial surface energy balance is affected by vegetation (Raupach, 1998; Zeng and Neelin, 2000). Forests play an important role in the exchange of energy and water vapor between the biosphere and the atmosphere, as forests cover approximately 30% of the total global land surface (Kazuho et al., 2008; FAO, 2009). Level of reforestation in China has been rapidly increasing in recent years (Gao et al., 2014). Plantations account for 33% of forestland in China (Chen et al., 2014). Large plantations can affect the surface albedo and radiation exchange, leading to local temperature changes and subsequent changes in ecosystem functioning (Mykleby et al., 2017). However, many aspects of the energy and water vapor dynamics in plantations, especially in young plantations of northern China's drylands remain poorly understood. Therefore, understanding the basic characteristics of energy and water vapor exchange in young plantations is important for defining better forest and water management practices in afforestation regions of northern China.

Energy and water vapor exchange processes between the land surface and atmosphere is controlled by complex interactions of environmental and biological factors (e.g., solar radiation, air and soil temperature, soil water content, atmospheric water vapor pressure deficit, plant functional type, phenology, and stomatal regulation; Ding et al., 2013; Jia et al., 2016; Zhang et al., 2016). Previous studies have

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Nomenclature

Abbreviations/Symbols

H_2O_v	Water vapor
CO_2	In-air carbon dioxide gas
R_n	Net radiation ($W\,m^{-2}$)
H	Sensible heat flux ($W\,m^{-2}$)
G	Soil heat flux ($W\,m^{-2}$)
LE	Latent heat flux ($W\,m^{-2}$)
LE_{eq}	Equilibrium LE ($W\,m^{-2}$)
ET	Evapotranspiration (mm)
P	Precipitation (mm)
VWC	Soil volumetric water content (%)
VPD	Vapor pressure deficit (kPa)
T_a	Air temperature (°C)
T_s	Soil temperature (°C)
PAR	Photosynthetically active radiation ($mol\,m^{-2}\,day^{-1}$)
β	Bowen ratio (H/LE)
α	Priestley-Taylor coefficient (LE/LE_{eq})
g_s	Bulk surface conductance ($m\,s^{-1}$)
Ω	Decoupling coefficient
ρ_w	Water density ($1\,g\,cm^{-3}$)
λ	Latent heat of vaporization of water ($kJ\,g^{-1}$)
γ	Psychrometric constant ($kPa\,K^{-1}$)
$\triangle$	Slope of the saturation vapor pressure versus T_a
ρ	Air density ($kg\,m^{-3}$)
C_p	Specific heat capacity of air ($J\,kg^{-1}K^{-1}$)
g_a	Aerodynamic conductance ($m\,s^{-1}$)
U	Wind velocity ($m\,s^{-1}$)
U_*	Friction velocity ($m\,s^{-1}$)
NDVI	Normalized difference vegetation index (non-dimensional)

reported that energy partitioning and evapotranspiration (*ET*) in forest ecosystems have considerable seasonal, interannual, and regional variation (Wilson et al., 2002a; Restrepo and Arain, 2005). Climatic conditions, vegetation growth, tree species composition, and soil moisture content are some of the more important controlling factors (Baldocchi et al., 2000; Restrepo and Arain, 2005; Gu et al., 2006; Launiainen, 2010; Hirano et al., 2017). However, as energy and water vapor exchange is influenced by human activity, landuse change associated with reforestation and afforestation may play a role in controlling these fluxes (Naudts et al., 2016). Better understanding of seasonal and interannual variability in energy and water vapor exchange and their controlling mechanisms is vital with accurately predicting future hydrological cycling in plantations and/or addressing the consequences of management decisions on large plantations in northern China.

Plantations in northern China are critical for ecological protection as they help to reduce wind and sand damage. Native tree species are widely used in this vast region for land restoration. Successful land-degradation reversal coincides with clear increases in vegetation cover and biodiversity and reductions in sand buildup (Cao et al., 2011). However, planting trees in regions inherently deficient of water resources can lead to over-exploitation of soil water as trees continue to grow, requiring widespread irrigation (Cao, 2011; Cao et al., 2011; Wang and Cao, 2011). Irrigation of plantations in Beijing has recently led to severe water shortages (Zhai et al., 2010). Due to this problem, scientists and policy makers have focused their attention on various ecosystem-management programs in order to augment plantation functioning, while diminishing the need for irrigation.

In this study, we analyzed a 4-year record (2012–2015) of continuous biospheric-atmospheric flux data from a young pine plantation in Badaling Tree Farm, north Beijing, China. The measurement period covered climatic events with extreme high daily precipitation (2012) and high annual mean air temperature (2014 and 2015), with 2015 having normal levels of precipitation and the years 2012 to 2014 being drier than the average of the past 30 years. The objectives of this investigation were to examine (1) the characteristics of energy flux partitioning over a young plantation, and (2) the biophysical controls on seasonal and interannual variation in *ET*. We hypothesized that seasonal and interannual change in *ET* for the plantation was mostly controlled by biological factors that may have undergone modification because of seasonal changes in soil water availability.

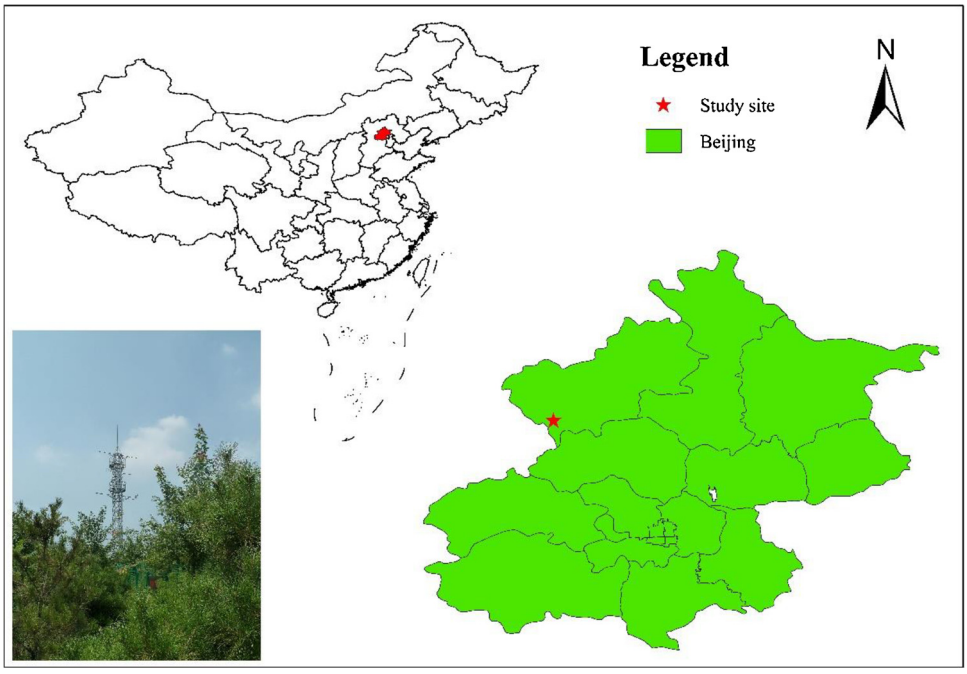

Fig. 1. Location of the study area and the Beijing Badaling research site, at which the eddy covariance system was installed.