Cold Regions Science and Technology 102 (2014) 8–20

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Interannual and seasonal variability in evapotranspiration and energy partitioning over the alpine riparian shrub *Myricaria squamosa* Desv. on Qinghai–Tibet Plateau

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ARTICLE INFO

Article history:
Received 9 August 2013
Accepted 14 February 2014
Available online 19 February 2014

Keywords:
Bowen ratio
Energy balance
Latent heat flux
Sensible heat flux
Freeze–thaw cycle
Qinghai Lake watershed

ABSTRACT

The Qinghai–Tibet Plateau is a sensitive area of global climate changes, and riparian ecosystems are thought as "hotspots" for climate change adaptation, but little work has been conducted regarding the alpine riparian ecosystems on the Qinghai–Tibet Plateau. We measured evapotranspiration (*ET*) and surface energy fluxes over the riparian shrub *Myricaria squamosa* Desv., which is widely distributed on the Qinghai–Tibet Plateau but has not been studied until now. The results indicated that annual *ET* was 390 mm and 503 mm for the period of 2010 to 2011 and 2011 to 2012, respectively, which was higher than the amount of precipitation during the same period. Cumulative *ET* was lower than the cumulative reference evapotranspiration during the entire experimental period, whereas *ET* in August was higher than reference evapotranspiration. *ET* in the growing season occupied over 80% of annual *ET* with a maximum daily *ET* of 7.2 mm d^{-1}, and the *ET* in the non-growing season was quite low because of the frozen soil. In general, temperature and net radiation were the key variables controlling daily *ET* rates for *M. squamosa*. Annual sensible heat flux (H) consumed 60% of net radiation (R_n) and latent heat flux (*LE*) 40% during the three years of the study. *LE* occupied the main part of R_n from July to September. H was the highest in May and June, then sunk in the mid-growing season, and rebounded the other peak at late September and early October. Daily ground heat flux was positive from April to mid-September, and it was an important heat source of land surface in the winter and spring. This study highlighted that as an alpine riparian ecosystem in a semiarid region, *ET* and surface energy partitioning of the *M. squamosa* community are strongly affected by the freeze–thaw cycle, groundwater fluctuation, precipitation pulses and soil water content. We speculate that climate warming has a significant impact on *ET* process and surface energy partitioning of the *M. squamosa* community by influencing the freeze–thaw cycle and soil water content.
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1. Introduction

The Qinghai–Tibet Plateau is approximately 2.57 million km^2 in area and, with an average elevation of greater than 4000 m above sea level, is the highest plateau in the world (Zhang et al., 2002). Energy and water cycles in terrestrial ecosystems play a key role in climate change (Betts et al., 1999; Pielke et al., 1998), and in particular, those over the Qinghai–Tibet Plateau are suggested to play key roles in the progress of Asian monsoons (Tanaka et al., 2001; Zhang et al., 2003). To better understand the mechanism and dynamics of the energy cycle over the Asian Monsoon region, it is important to estimate the energy partitioning over the Qinghai–Tibet Plateau surface (Tanaka et al., 2001). As a sensitive area of global climate changes (Klein et al., 2004), recent studies have found that the Qinghai–Tibet Plateau has displayed a significant warming trend over recent decades (Kang et al., 2010; Wu et al., 2013; You et al., 2010). These climate changes will affect the energy exchange between the land surface and the atmosphere (Gu et al., 2005). Therefore, assessing the energy partitioning and evapotranspiration (*ET*) in the alpine ecosystems on the Qinghai–Tibet Plateau may provide insights into not only the energy and water cycle in the alpine ecosystems but also the local and even regional climate changes. The heat and water fluxes have been studied on the Qinghai–Tibet Plateau under the auspices of the GAME/Tibet, CAMP/Tibet and ChinaFLUX, as well as other research projects (Gu et al., 2005; Hu et al., 2009; Li et al., 2009a; Liu et al., 2009; Ma and Ma,

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http://dx.doi.org/10.1016/j.coldregions.2014.02.001
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2006; Ma et al., 2003; Tanaka et al., 2001, 2003; Zhang et al., 2003). These previous studies mostly focused on the meadow, steppe, swamp and shrub ecosystems, whereas little work has been performed on the alpine riparian shrub ecosystems.

Riparian zones are the interfaces between terrestrial and aquatic ecosystems (Gregory et al., 1991; Meehan et al., 1977; Swanson et al., 1982), and it is believed that they will become "hotspots" for climate change adaptation in the 21st century (Capon et al., 2013). Riparian zones are likely to be highly vulnerable to climate change impacts, such as higher temperatures, as well as altered hydrological and ice conditions (Capon et al., 2013; Catford et al., 2013; Nilsson et al., 2013), and can serve as early warning systems of changing environmental conditions (Johnson et al., 2006). Surface energy partitioning and water fluxes in the riparian zone varies seasonally and yearly with the fluctuation of available radiation, temperature, vapor pressure deficit, soil water content and precipitation pattern due to the high climatic variability (Dahm et al., 2002). *ET* by riparian ecosystems is an important component of the watershed water balance in semi-arid and arid regions (Goodrich et al., 2000; Lenters et al., 2011; Scott et al., 2008; Serrat-Capdevila et al., 2011), and it is easily influenced by the fluctuation of the water table (Williams et al., 2006) and freeze–thaw cycle (Zhang et al., 2003). However, observations of water and heat coupling in the field of riparian ecosystems are surprisingly limited (Yang and Chen, 2011).

Myricaria squamosa Desv. is a common but important alpine riparian shrub in the Qinghai–Tibet Plateau and widely distributed in river valleys at an altitude between 2400 and 4600 m. No known studies have been conducted on the ecohydrological processes of *M. squamosa* in any country, although it is also widely distributed in Afghanistan, India, Nepal, Pakistan and other locations throughout the world. The *M. squamosa* community takes up 303.85 km^2 and 1.22% of land area in the Qinghai Lake watershed in the northeastern of the Qinghai–Tibet Plateau. The importance of riparian zones far exceeds their minor percentage of the land base because of their outstanding geographic position within the landscape and the inseparable linkages between terrestrial plant and aquatic ecosystems (Gregory et al., 1991; Mander et al., 1997; Meehan et al., 1977). As one of the constructive shrub species, *M. squamosa* plays a critical role in reducing bank erosion and providing habitat in breeding season for an endemic migratory fish, *Gymnocypris przewalskii*, in Qinghai Lake (Chen et al., 2008; Zhang et al., 2005) but has been seriously degenerated during recent decades due to the overstocking of sheep and yak, along with other anthropogenic activities (Li et al., 2009b). *ET* by *M. squamosa* has not been measured in the region up to now, but such an analysis is very important for the water balance analysis of the Qinghai Lake watershed, just as in other riparian ecosystems in semi-arid region (Goodrich et al., 2000; Scott et al., 2008; Serrat-Capdevila et al., 2011). Qinghai Lake, a closed saline lake, is the largest lake in China. It has experienced severe water level decline during the last 50 years, although a gradual rise occurred during recent years (Li et al., 2007b; Zhang et al., 2011a). The causes of the decline of lake level are believed to mostly be climatic factors (Li et al., 2007b), whereas water consumption by human beings, animals and crop production, industry, along with other human activities, accounts for only 3% of the available fresh water resources in the Qinghai Lake watershed (Yi, 2011), but the role of water consumption in land ecosystems in lake water level fluctuation is not clear, especially for riparian water resources, which are in great demand for use in agriculture, urban development and ecosystem services.

The objectives of this study were (a) to measure surface energy partitioning over *M. squamosa* community, (b) to evaluate temporal variability in *ET* and (c) to analyze the influence of freeze–thaw cycle, soil water content, and groundwater table fluctuation on energy partitioning and *ET*. This study provides valuable information regarding water consumption by the *M. squamosa* community that elucidates the hydrological behavior of alpine riparian ecosystems.

2. Materials and methods

2.1. Site description

This study was conducted in a valley in the lower reaches of the Shaliuhe River, the second largest river in Qinghai Lake watershed, in the northeast region of the Qinghai–Tibet Plateau, China (37°14′N, 100°12′E, 3216 m *a.s.l.*, Fig. 1), which is situated in a semiarid, cold and high-altitude climate zone. The mean annual temperature and precipitation between 1957 and 2006 were −3.3 °C and 378.2 mm, respectively. The winter is clear, dry, and cold, whereas the summer is warm and wet. Approximately, 70–80% of the annual precipitation occurs in summer and autumn.

The experimental site is approximately 8 km away from the Qinghai Lake. The site is 1.4 km^2 in area with a width of approximately 0.7 km, a length of 2 km, and has a flat topography. The soil texture is coarse sand at 0–20 cm, pebble bed with some coarse sand at 20–50 cm, and pebble bed with little coarse sand under 50 cm. The groundwater level fluctuates from 1.5 to 0.5 m within a year. Local wind direction is significantly controlled by lake–land breeze, and the wind mostly blows from lake to land during the day and reverses at night. Seasonal change of wind direction is not distinguished. Wind speed is less than 4 m s^{-1} most of the time. *M. squamosa* shrub is the only dominant overstory species with 60% coverage, approximately 1 m height, and has a leaf area index of 5.78 m^2 m^{-2} in the mid-growing season. Understory vegetation are *Potentilla anserina*, *Logotis brachystachya*, *Lancea tibetica*, and other herbs, with a height of approximately 0.5 m, coverage of 77% and a leaf area index of 5.45 m^2 m^{-2} in the mid-growing season.

2.2. Estimation of ET and energy fluxes using the Bowen ratio energy balance method

The Bowen ratio energy balance (BREB) method was used to estimate actual *ET* by calculating the partition of convective fluxes between latent and sensible heat (Bowen, 1926). The BREB is a micrometeorological method often used to estimate latent and sensible heat flux because of its simplicity, robustness, and low cost (Todd et al., 2000). It is considered to be a fairly robust method and favorably compares with other methods such as weighing lysimeters (e.g., Prueger et al., 1997), eddy covariance (e.g., Alfieri et al., 2009) or water balance (e.g., Malek and Bingham, 1993). Its advantages include straight-forward, simple measurements. It requires no information about the aerodynamic characteristics of the surface of interest. It can integrate latent heat fluxes over large areas of hectares. It can estimate fluxes on fine time scales of minutes and provide continuous, unattended measurements (Todd et al., 2000). The BREB method does have a few well documented limitations, including sensitivity to the accuracy of instruments that measure the air temperature and humidity gradients and energy balance terms, the possibility of discontinuous data when the Bowen ratio approaches −1, the possibility of inconsistency of flux–gradient relationships, and the requirement, common to micrometeorological methods, of adequate fetch to ensure adherence to the assumptions of the method (Perez et al., 1999; Todd et al., 2000). All the same, the BREB method has been applied successfully in wetlands with a homogeneous canopy (Drexler et al., 2004) and many other ecosystems (e.g., Daamen et al., 1999; Dawson, 1996; Domingo et al., 1999; Frank, 2003; Peacock and Hess, 2004; Rohli et al., 2004; Si et al., 2005; Xing et al., 2008; Zhang et al., 2008), including semi-arid steppe (Qiu et al., 2011) and farmland (Todd et al., 2000), as well as a vineyard in an arid desert (Zhang et al., 2008), etc. The BREB method has also been applied successfully to plateau systems (Savage et al., 2009; Staudinger and Rott, 1981; Wang et al., 1996). It is based on the energy balance equation:

$$R_n - G = H + LE \quad (1)$$

where R_n is net radiation; G is ground heat flux; H is sensible heat flux and LE is latent heat flux. The Bowen ratio (β) is the ratio of sensible heat flux

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