Agricultural and Forest Meteorology 233 (2017) 235–241

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Groundwater facilitated water-use efficiency along a gradient of groundwater depth in arid northwestern China

Bing Liu[a,*], Huade Guan[b], Wenzhi Zhao[a], Yuting Yang[c], Shoubo Li[d]

[a] Linze Inland River Basin Research Station, Laboratory of Heihe River Eco-Hydrology and Basin Science, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000
[b] School of the Environment and National Centre for Groundwater Research and Training, Flinders University, Adelaide, SA 5001, Australia
[c] CSIRO Land and Water, Canberra, ACT 2601, Australia
[d] School of Geography and Remote Sensing, Nanjing University of Information Science and Technology, Nanjing, 210044, China

ARTICLE INFO

Article history:
Received 28 September 2016
Received in revised form
29 November 2016
Accepted 4 December 2016

Keywords:
Groundwater
Rainfall
Aboveground net primary production
Water-use efficiency
Groundwater use efficiency
Rain use efficiency

ABSTRACT

Groundwater strongly impacts ecosystem performance in arid regions by driving vegetation structure and species distribution. It is unknown how water use efficiency varies along a gradient of depth to groundwater (*DWT*). In this study, we developed a framework to estimate water use efficiency (*WUE*), groundwater use efficiency (*GUE*), and rain use efficiency (*RUE*), and to examine the contribution of rainfall to transpiration in groundwater-dependent ecosystems (GDEs). The method was applied to an arid region in northwest China with a gradient of groundwater depth from 0.5 to 12 m. The results indicate that the above-ground primary production, evapotranspiration, plant transpiration, *WUE*, and *GUE* decreased significantly from riparian forest, wetland, oasis edge, desert-oasis ecotone, and to sandy desert along a gradient of increasing *DWT*. *RUE* is found to be 0.26 g m^{-2} mm^{-1} at the sandy desert without groundwater contribution where 21% of rainfall is used for transpiration. Water use efficiency increases to 0.85 g m^{-2} mm^{-1} at the riparian site where groundwater is about 0.5 m depth. The fraction of rainfall consumed by plants increases with a decreasing *DWT* from a threshold of 6.3 m, suggesting groundwater enhances rain use efficiency in GDEs.

1. Introduction

Ecosystems are controlled by water availability in semi-arid and arid regions (Rodriguez-Iturbe and Rinaldo, 2001; Hickler et al., 2009; Yang et al., 2014), which occupy approximately 40% of the global land area (Parsons and Abrahams, 1994). In arid regions, annual rainfall is much less than annual potential evapotranspiration (E_p) (Parsons and Abrahams, 1994; Guswa et al., 2004; Newman et al., 2006; Yang et al., 2016a). In addition, the water supply for vegetation from surface flows (e.g., runoff, rivers) is generally very limited. Groundwater therefore becomes an important source of water that greatly affects the spatial and temporal distributions of soil moisture, which in turn affects the distribution of vegetation (Lowry et al., 2011; Naumburg et al., 2005; De Paola and Ranucci, 2012; Dai et al., 2014; Zhu et al., 2015). Along the gradient of groundwater depth, the vegetation community undergoes succession from phreatophytes, which obtain a large fraction of water from near-surface groundwater or the capillary fringe, perennial shrubs, xerophytic species, which depend mostly on rainfall, and to annuals and ephemerals) (Steed and DeWald, 2003; Dwire et al., 2004; Liu et al., 2010, 2011, 2013; Zhao and Liu, 2010; Fan et al., 2014). These ecosystems are highly sensitive to changes in water table, which are characterized as groundwater-dependent ecosystems (*GDEs*) (Eamus et al., 2006; Lowry and Loheide, 2010). The pattern of vegetation cover is primarily controlled by groundwater which determines ecosystem stability and evolvement between oasisization and desertification.

Water availability is a key control of aboveground net primary production (*ANPP*) worldwide (Yahdjian and Sala, 2006; Yang et al., 2015). *ANPP* increases linearly along spatial precipitation gradients from deserts to steppes and grasslands in China, North America, South America, and Africa (Webb et al., 1978; Lauenroth, 1979; Liang et al., 2015; Sala et al., 1989; McNaughton et al., 1993; Paruelo et al., 1998; Yahdjian and Sala, 2006; Bai et al., 2008). However, the impact of groundwater on *ANPP* is seldom documented. As a critical link between water and carbon cycles in terrestrial ecosystems, water-use efficiency (*WUE*), has been identified as an effective integral trait for assessing the response of ecosystem *ANPP* to water

---

* Corresponding author.
E-mail address: liubing@lzb.ac.cn (B. Liu).

http://dx.doi.org/10.1016/j.agrformet.2016.12.003
0168-1923/© 2016 Elsevier B.V. All rights reserved.

availability (Kuglitsch et al., 2008; Beer et al., 2009; Scott et al., 2010). However, the published studies on the WUE response to precipitation variability are sometimes conflicting. For example, the *WUE* and rainfall-use efficiency (*RUE*) have been reported to decrease (Huxman et al., 2004; Scanlon and Albertson, 2004; Bai et al., 2008; Yu et al., 2008) or keep constant (Lauenroth et al., 2000; Niu et al., 2011) with increasing precipitation along a spatial precipitation gradient. For a given ecosystem, a number of studies have shown that ecosystem *WUE* decreases (Lauenroth et al., 2000; Li et al., 2008; Fay et al., 2003) or increases (Bai et al., 2008; Yang et al., 2016b) over time with increasing annual precipitation. These seemingly conflicting spatial and temporal patterns of *WUE* in different ecosystems may be associated with the different scales of the analyses (Wu and Loucks, 1995; Wu et al., 2006).

Groundwater can be a source of soil moisture for plant water uptake to support photosynthesis (York et al., 2002; Yeh and Eltahir, 2005; Fan et al., 2007; Niu et al., 2007; Maxwell and Kollet, 2008; Lowry and Loheide, 2010; Soylu et al., 2014), and increase soil evaporation and plant transpiration (Orellana et al., 2012). With accessible groundwater, ecosystems develop better vegetation coverage, which may enhance rain water use efficiency, i.e., more proportion of rain can be used for transpiration. Meanwhile, groundwater used by ecosystems may also contribute to primary production. However, no research has been done on groundwater-use efficiency (*GUE*). In the present study, we attempted to examine how *WUE*, *GUE*, and *RUE* vary along a gradient of depth to groundwater table, and investigate the contributions of rainfall and groundwater to *ANPP* of the GDEs. The objectives were to answer three questions: (1) How do *WUE* and *GUE* vary in GDEs along a gradient of groundwater table? (2) What are the relative contributions of *WUE* and *GUE* in these ecosystems? (3) What are the water sources for plant transpiration? We hypothesized that (1) both *WUE* and *GUE* would increase with decreasing depth to groundwater table, (2) *GUE* would be greater than *RUE*, and (3) groundwater would increase the proportion of rain being used for transpiration.

2. Theory and hypotheses

The normalized-difference vegetation index (*NDVI*) typically increases with decreasing depth to the water table (*DWT*), but approaches a constant background value determined by the climate when *DWT* is greater than a certain threshold (DWT_0). This relationship can be described by the following empirical equation (Lv et al., 2013):

$$NDVI = NDVI_0 + k_v(DWT - DWT_0)\mathrm{forDWT} \;<=\; \mathrm{DWT}_0 \tag{1}$$

where $NDVI_0$ is the *NDVI* of baseline vegetation supported by rainfall without any contribution of groundwater, *DWT* is the depth to the water table, DWT_0 is the threshold depth beyond which there is no groundwater contribution to ecosystem primary production, and k_v is an empirical regression coefficient. In the present study, we assumed that *NDVI* in Gobi desert, an arid region where plants are supported primarily by local rainfall, represented $NDVI_0$, in which *DWT* stabilized at a value deeper than 12 m (CV = 4.5%). As a result, desert plants can't access groundwater in this region throughout the year. We hypothesized that k_v is contributed both by high temporal availability of the groundwater supply and by an increase in the bio-consumptive fraction of rainfall with a shallower groundwater (f_0, proportion of rainfall being used for transpiration).

WUE (g m^{-2} mm^{-1}) is defined as the ratio of *ANPP* (g m^{-2}) to *ET* (mm) (Monclus et al., 2006):

$$WUE = ANPP/ET \tag{2}$$

At a site where $DWT > DWT_0$ and there is no significant surface flow, water loss through evapotranspiration is replenished only by rainfall. Thus, *RUE* (g m^{-2} mm^{-1}) can be obtained as the threshold value of *WUE* (WUE_0), and described as the ratio of the aboveground net primary production without any contribution from groundwater ($ANPP_0$) to the mean annual precipitation (P) (Huxman et al., 2004; Bai et al., 2008; Yang et al., 2010).

$$RUE = ANPP_0/P \tag{3}$$

where *P* is the mean annual precipitation.

At a site where $DWT < DWT_0$, soil moisture loss by ET is replenished by a combination of water from rainfall and groundwater. In this case, *GUE* is calculated as follows:

$$GUE = (ANPP - ANPP_0)/(ET - P) \tag{4}$$

The increase in ANPP from the climatic background value (i.e., ANPP-ANPP0) can be partly due to an increased bio-consumptive fraction of the rainfall in GDEs.

For a site where $DWT > DWT_0$,

$$f_0 = T_P/ET = (P - E)/P \tag{5}$$

where T_P is amount of precipitation being used for plant transpiration (mm) and *E* is soil evaporation (mm).

For a site where $DWT < DWT_0$, we expect to see a larger value of *f* because of increased vegetation cover.

$$f = T_P/P \tag{6}$$

It is expected that

$$f = f_0 + k_w(DWT - DWT_0) \tag{7}$$

where k_w represents the contribution groundwater to enhance *RUE*.

To calculate the ratio of T_P to *P*:

For a site where *DWT* is low («DWT_0), $T_P/P = (1 - [E/ET])$.

For a site where *DWT* is high, (>DWT_0), $T_P/P = (P - E)/P$.

3. Study sites and data collection

3.1. Study sites

Our study area (Fig. 1) is located in the middle reaches of China's Heihe River Basin (between 39°10′ N and 39°40′N, and between 100°02′E and 100°11′E). The region has been described in detail in Liu et al. (2010, 2012, 2014). The study area is dominated by groundwater-dependent ecosystems, which form a spectrum from riparian forest, wetland, oasis edge, a desert-oasis ecotone, sandy desert, and to gobi desert along a gradient of groundwater depths. (Note that in this paper, *gobi* refers to a desert in which the surface is primarily coarse particles in the gravel size categories.) The gradient covers a total length of about 15 km, over which mean precipitation is very similar. The difference in the vegetation types is driven solely by the groundwater gradient. In the riparian forest zone, vegetation is distributed on or near the banks of the Heihe River and is dominated by trees (*Populus alba*, *Elaeagnus angustifolia*, *Salix babylonica*), shrubs (*Tamarix chinensis*), and herbs (*Carex karoi*, *Juncus articulatus*, *Phragmites australis*, *Leymus secalinus*, *Sophora alopecuroides*). This ecosystem has the highest *NDVI* and species richness (Table 1). The wetland ecosystem is primarily wet meadows dominated by shrubs (*T. chinensis*) and halophytic herbs (*P. australis*, *Agropyron cristatum*, *Oxytropis glabra*, *Equisetum ramosissimum*, *Typha orientalis*, *Carex tangiana*). The oasis edge belongs to the shelter forest belt, which is a combination of agricultural land, tree, shrub and grass. It plays an important role in the control of sand dunes and protection of farmland. The soil water mainly comes from the lateral seepage from farmland irrigation and the recharge from shallow groundwater. The desert-oasis ecotone ecosystem is dominated by fixed and semi-fixed dunes that are separated by inter-dune lowlands. Its vegetation comprises desert