Research article

Increase in economic efficiency of water use caused by crop structure adjustment in arid areas

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A B S T R A C T

The Heihe River is located in the arid zone of northwestern China. In its middle-reach region, irrigation agriculture is well developed. With rapid population growth and expansion of the cultivated land in this region, effective water resource use is vital for the sustainable development of the river basin and the increase of incomes from farming practices. In this study, based on farmer survey data, the input parameters of the CROPWAT model were modified, the water use amount was simulated after deducting the influences of climate, seeds, and irrigation systems, and the variation of economic efficiency of water use (EEWU) induced by crop structure adjustment from 2001 to 2012 was analyzed. The results show that simulations for evapotranspiration of maize based on the CROPWAT model are in accord with the observed data. From 2001 to 2012, due to changes in the regional crop structure, EEWU in the study area increased by about 40%. In the arid areas in northwest China, crop structure adjustment has a huge potential for improving EEWU and increasing incomes from farming practices.

1. Introduction

Water shortage is a global problem. The increase of water consumption per capita, accompanied with rapid population growth, has significantly increased the demand for water resources (Sauer et al., 2010). According to a report of the United Nations (2006), in the 1900s, water use has been increasing at a more rapid rate (about twice as fast) than population growth. It has been estimated that by 2025, 60% of the world's population is likely to face water resource scarcity (Qadir et al., 2006). On a global basis, agricultural water use accounts for 70–90% of the total freshwater consumption (Sauer et al., 2010; Calzadilla et al., 2011; Maeda et al., 2011; Zhang and Vesselinov, 2017).

In China, along with the rapid economic and agricultural development, the shortage of water resources is currently becoming more serious (Wang et al., 2015). In 2010, the renewable water resources per capita in China consisted of $2100 \, m^3$, which was close to the lower threshold of water resource pressure ($2000 \, m^3$ per capita) (Tang et al., 2014). Agricultural production in China relies heavily on irrigation (Yang et al., 2003), and in 2015, 50% of the total cultivated area in the country were irrigated land (NBSPRC, 2016). Especially in the arid areas of northwestern China, there is little rainfall and high evaporation, which means that crop production is highly dependent on water

resources (Tanji and Kielen, 2002). In some arid areas, agricultural water use accounts for more than 90% of the total water consumption (Li et al., 2017).

In recent years, due to the rapid population increase and significant economic development, the agricultural land area has expanded into arid areas of northwestern China, thereby further increasing the demands for water. Due to the excessive use of surface water and groundwater for irrigation, the hydrologic cycle of river basins has been greatly changed, resulting in a variety of environmental problems (Azad and Ancev, 2014), such as downstream cutoff, lake shrinking, groundwater decline, natural vegetation reduction, salinization, and sandstorm area expansion (Tanji and Kielen, 2002; Wang et al., 1999; Huang et al., 2017; Lu et al., 2015; Zhang et al., 2015; Kang et al., 2007). At the same time, the income of farmers in northwestern China was still relatively low. In 2014, the disposable income per capita from farming in western China was RMB 7437 (Chinese currency), which was 63% of the average income in the eastern regions and 83% of that in the central regions (NBSPRC, 2016). Therefore, in the course of the development of rural areas, it is crucial to increase both incomes of farmers and EEWU in China's northwestern regions.

Improving water resource use efficiencies includes two main aspects: 1) implementing the use of water-saving technologies, such as
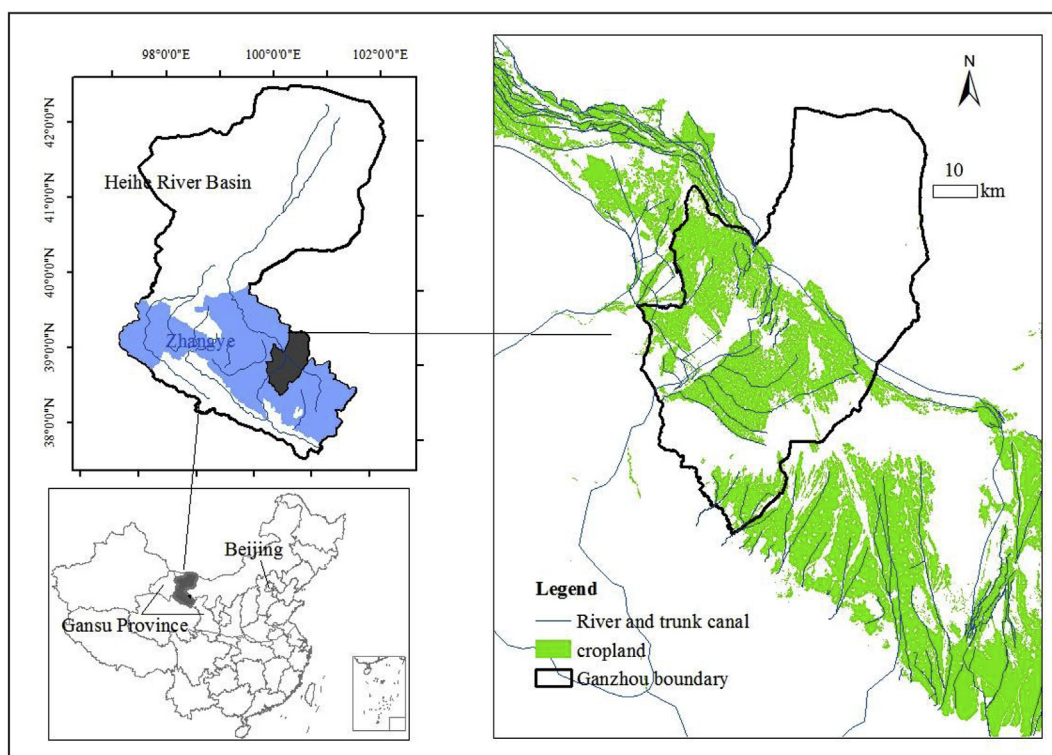
Fig. 1. Location of Ganzhou district, Zhangye, China.

furrow irrigation, border irrigation, spray irrigation and drop irrigation, and GPS-based precision irrigation (Gao et al., 2002; Evans and Sadler, 2008; Miriti et al., 2012; Shao et al., 2016; Huang et al., 2017); 2) developing policies and regimes (Tanji and Kielen, 2002; Syme et al., 2008; Tang et al., 2014) to control the used water quantity by measures such as implementing staggered water prices, water tickets, and by closing wells (Zhang et al., 2014; Zhou et al., 2015; Chang et al., 2016). For instances, higher water prices can prompt farmers to use water-saving technologies, thus improving water resource use efficiencies (Zhang et al., 2014; Cai et al., 2003). Recently, the comparison of water use efficiencies of different crops has attracted considerable attention (Zwart and Bastiaanssen, 2004; Fan et al., 2014). For instance, Zwart and Bastiaanssen (2004) examined water resource use efficiencies of wheat, rice, cotton, and maize on a basis of a review of 84 literature sources not older than 25 years. However, studies on this aspect are not sufficient, esp. in terms of research about the influences of changes in crop structure on EEWU, after deducting the influences of climate, seeds, and the irrigation regime.

In the literature, there are various definitions of water use efficiency. A widely used definition is the ratio of agricultural yield to the seasonal evaporation (Miriti et al., 2012; Zhang et al., 2014). It should be noted, however, that investigations on water use efficiency in agricultural systems have mainly focused on one or two crops. It is difficult to compare the water use efficiencies of various crops using this definition, because the yields of different crops vary largely. For example, the yield of wheat is a grain yield, while that of the potato is a tuber yield. In view of this, it has been proposed that the yield of different crops can be converted into a uniform currency value, i.e., EEWU can be represented by the economic value of the crop per unit of water amount (Duan, 2005). If we use the economic value to represent water use efficiency, the influences of different crop structures on this factor can be studied.

In calculations of water use efficiency, evapotranspiration (ET) is a frequently used key indicator (Maeda et al., 2011; Miriti et al., 2012; Zhang et al., 2014). The measurement of ET includes two methods: ground experiment or observation and model estimation (Li et al.,

2016a). Ground experiment or observation methods of ET include the Bowen ratio method and the eddy covariance method (Zheng et al., 2012; Uddin et al., 2013). The model estimation of ET includes a variety of methods such as the FAIDS model, the CERES model, the SWAT model, the SEBAL model, and the CROPWAT model (Eichinger et al., 2006; Jhorar et al., 2009; Zhao et al., 2010; Li and Zhao, 2010; Li et al. 2012, 2016b; Luo et al., 2012; Miriti et al., 2012; Xiong et al., 2015). Of these, the CROPWAT model is considered to be a reliable model (Zheng et al., 2012; Ismail and Depeweg, 2005) and is provided by the Food and Agriculture Organization (FAO) of the United Nations; it is used to calculate crop water requirement (CWR) (LWD-FAO, 2009). In the CROPWAT model, CWR and crop evapotranspiration (ET_c) are identical, although they have different connotations. The former refers to the amount of water needs to be supplied, while the latter is used for evapotranspiration (Allen et al., 2006).

The Heihe River is the second largest river in the arid areas of China, with an area of $0.24 \times 10^6 \, \text{km}^2$ (Zang and Liu, 2013). Its middle-reach oasis is an important food base of the arid zone of northwestern China and located in China's Gansu Province. The annual grain output of Zhangye Prefecture (an administrative unit ranking between a county/district and a province) in the middle-reach is about 800,000 t, which accounts for about 17% of the total grain output of the Gansu Province and provides 35% of the commodity grain of the Gansu Province (Ning et al., 2008). It is worth mentioning that the seed maize yield of the Ganzhou District in Zhangye accounts for 20% of the total seed maize yield in China (STDGS, 2016). In Zhangye, the low rainfall conditions mean that the regional agricultural development largely relies on surface water or groundwater for irrigation (Zhao et al., 2011). Water used for irrigation accounts for 83% of the river basin water resources, leading to an annual decline rate of 0.5–1.8 m of the groundwater depth in the Heihe River Valley (Zhou et al., 2009; Chai et al., 2014).

Based on the CROPWAT model and taking the Ganzhou District in Zhangye Prefecture as an example, this study employed field survey data to calibrate the model parameters, simulated regional ET_c values and grain production using day as the time step. First, the ET in 2012 was estimated, using input parameters of 2012, covering climate factors