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Comparative evaluation of crop water use efficiency, economic analysis and net household profit simulation in arid Northwest China

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ABSTRACT

Decreasing water availability for agricultural production has prompted researchers to focus on comparing and evaluating water use efficiency (*WUE*) of different crops in various water management strategies. A field survey was conducted to investigate the amount of irrigation water, inputs and yields of eight crops (spring wheat, maize, onion, cotton, hot pepper, sunflower, melons and fennel) grown under furrow irrigation systems in an arid region, Minqin county, Northwestern China (NWC). Previous publications reporting crop *WUE* were identified and major statistics of evapotranspiration (*ET*), yield (*Y*) and *WUE* were calculated for each crop. By comparing with literature reporting, the mean *WUE* of onion (8.71 kg m^{-3}), cotton (0.56 kg m^{-3}), sunflower seed (0.78 kg m^{-3}) and fennel (0.51 kg m^{-3}) grown in NWC were at the same high levels; while *WUE* of wheat (0.87 kg m^{-3}) and maize (1.17 kg m^{-3}) were slightly lower and *WUE* of hot pepper (2.68 kg m^{-3}) and melons (3.27 kg m^{-3}) were extremely low. Great potential of saving water could be achieved to realize increased or ideal *WUE* values for crops in NWC. The total net profit per household of cotton (1606.62 $ hh^{-1}) was significantly larger and of onion (−3132.30 $ hh^{-1}) significantly lower than that of other crops. Cotton, sunflower seed, melons and hot pepper had significantly higher crop production values per unit water than other crops, 0.39 $ m^{-3}, 0.36 $ m^{-3}, 0.32 $ m^{-3} and 0.31 $ m^{-3}, respectively. The net household profits were significantly higher when excluding onion production for its extremely low price in 2011. With simulation based on different combinations of onion production and increase of migrant workers, the average net household profit could be optimized to provide benefits to local farmers and policy makers regarding income increase and rural policy design.

1. Introduction

In the arid and semi-arid regions of Northwestern China (NWC), the most commonly irrigated grain crops include spring wheat (*Triticum*) and maize (*Zea mays*), and the main irrigated cash crops include cotton (*Gossypium* spp.), hot pepper (*Capsicum annuum*), and sunflower (*Helianthus annuus*). These irrigated crops constitute the main income source of the region's rural households. During the past decades, the substantial increase of crop yield was mainly supported by the increasing application of irrigation water in these regions.

Grain crops take the major part concerning the consumption of irrigation water in arid and semi-arid regions (Xie et al., 2005). Inefficient irrigation methods and soil management hinder achievement of high crop yield and increase of water use efficiency (*WUE*) (Kang et al., 2002; Li et al., 2005). In most arid and semi-arid regions throughout the world, lack of rainfall limits growth and yield of crops. Water allocation and management has become a hot topic to researchers worldwide because of increasing water scarcity in agriculture. Controlled irrigation systems and soil management methods are taking important roles for yield increase of many crops (Cossani et al., 2012). A range of *WUE* values of different crops have been reported at various locations (Chakraborty et al., 2008; Kang et al., 2000; Liu et al., 2010, 2011; Sezen and Yazar, 2006; Wang et al., 2010; Zhou et al., 2011). Different irrigation systems can, to a large extent, influence water consumption and crop yields, thus *WUE* can vary significantly in different locations or even within the same experimental area. According to the field

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research conducted in Turkey by Cetin and Bilgel (2002), for cotton production, the *WUE* ranges for furrow, drip and sprinkler irrigation were 0.19–0.42, 0.35–0.61 and 0.17–0.66 kg m^{-3}, respectively. Other studies of comparing *WUE* using different irrigation methods were carried out by Mo et al. (2005), Onder et al. (2005), Unlü et al. (2006) and Sezen and Yazar (2006). Generally, micro irrigation systems (drip emitters, drip tape, spray, and sprinkler) are more efficient than furrow irrigation (Cetin and Bilgel, 2002; Tanwar et al., 2014), while Tayel et al. (2006) reported surface irrigation was more efficient than surface drip and subsurface drip irrigation on potato production in Egypt. Deficit irrigation, which can achieve the goal of low water application and high *WUE* for crops, is becoming a practical and well-acceptable method in arid and semiarid regions (Nagaz et al., 2012; Schneider and Howell, 2001). Soil management, such as film plastic mulching and crop straw mulching, can greatly contribute to decreasing the soil evaporation and increasing crop yields and *WUE* significantly (Chakraborty et al., 2008; Zhao et al., 2012). Usually, one or more management strategies can be jointly applied in experiments or farm production. For instance, an experiment on the combination of early sowing and irrigation to increase grain yield and *WUE* under Mediterranean conditions was reported by Yau et al. (2011). Moreover, Li et al. (2005) conducted a three-year experiment in North China Plain (NCP) and optimized the irrigation scheduling for winter wheat to make wheat yield and *WUE* achieve their maximum values of 7423 kg ha^{-1} and 1.645 kg m^{-3} at the evapotranspiration (*ET*) rate of 509 mm and 382 mm, respectively. Thus, the wheat management model, pre-sowing irrigation + irrigations at jointing and flowering stages, was identified and recommended for practical winter wheat production in the NCP.

In order to improve water use efficiency, it is useful to comparatively evaluate a crop's *WUE* in different parts of the world and explore effective crop water management strategies increasing crop yield and market values. A comparison of crop *WUE* has been implemented on a global scale by Zwart and Bastiaanssen (2004). The average *WUE* values were 1.09, 1.09, 0.23 and 1.80 kg m^{-3} for wheat, rice, cotton (lint) and maize, respectively, with very large ranges. The climate conditions, irrigation water management and soil (nutrient) management were responsible for the variability of *WUE* and this could be improved significantly by reducing irrigation and inducing crop water deficit.

Minqin county is located in Northwestern China; its climate is classified as arid continental. Rainfall is rare and the average precipitation is 110 mm per year, a majority of which comes from June to August. The annual mean evaporation of 2650 mm greatly exceeds the annual precipitation (Ma et al., 2008; Zhang et al., 2012). In order to offset the water deficit and maintain a high crop yield, irrigation is a critical constraint to agricultural production in this region. Increasingly intensive use of irrigation water for crops makes agriculture the largest water consuming sector and the proportion of irrigation water accounts for more than 80% of Minqin's water supply (Sun et al., 2006b).

In the arid and semiarid regions of NWC, few studies have comparatively evaluated crop water demand, evapotranspiration and *WUE* under different climate conditions. Such information can contribute to improvement of water distribution and application systems, so as to achieve sustainable agricultural production and ecological restoration in these regions (Kang et al., 2003). Prior to this study, investigations of survey-based major crops' yield, irrigation and *WUE* under furrow irrigation systems in Minqin county were not conducted or reported. Comparisons with studies conducted in other regions of China and other countries allow us to understand whether there can be improvements in *WUE* in relation to irrigation management under water conditions in arid and semi-arid NWC. The main objectives of this study were (i) to estimate *WUE* and *IWUE* of eight crops, namely spring wheat, maize, onion (*Allium cepa*), cotton, hot pepper, sunflower, melons (*Cucumis melo*) and fennel (*Foeniculum vulgare*), at regional level based on an agricultural water utilization survey conducted in Minqin county; (ii) to identify results of various field and experimental literature reporting *WUE* and comparatively evaluate *WUE* values for the above eight crops, (iii) to conduct economic analysis of crops and local households including water cost, total input cost, agricultural revenue, other revenue, total revenue and net profits, as well as crop production market values per m^3 water use, and (iv) to optimize the total net household profit with a simulation of potential increase of migrant workers and reduction of agricultural production area, and provide recommendations for the local farming households and policy makers in arid and semiarid NWC.

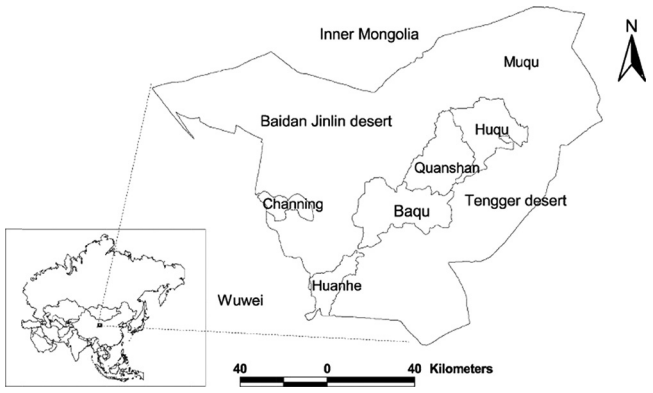

Fig. 1. Location of the study area—Minqin county, Northwestern China (Sun et al., 2006a).

2. Survey and methods

2.1. Study area

Located in Gansu province of Northwest China (ranging from 101°49′ to 104°12′E and from 38°03′ to 39°28′N), Minqin county has an area of 15,870 km^2 and it is surrounded by hills and deserts, and slopes downward from southwest to northeast (Fig. 1). The climate is characterized by low precipitation, high potential evaporation, intense sunshine, and strong wind. Table 1 shows the climate details of Minqin county in the year of 2011 (Minqin, 2012). Under influence of an arid continental climate, the average annual temperature for the year 2011 was 8.8 °C (maximum temperature 38.0 °C in August and minimum temperature −23.1 °C in January). Total evaporation was 2623 mm, that is 19 times the total precipitation of 139 mm. The main soil type is silty clay; cultivated land occupies 6.78 × 10^4 hm^2 and people are mainly living from agricultural production (Sun et al., 2006a, 2009). The principal field crops include cereals (spring wheat, summer maize) and economic crops (onion, cotton, melon, and fennel) (Fang et al., 2005). The water resources used by crops are constituted of rainfall and irrigation water (surface water and groundwater) during crop growing seasons.

2.2. The survey

A survey on crop production was conducted in three irrigation districts: Baqu, Quanshan and Huqu of Minqin county (Fig. 1) in January 2012. Stratified random sampling was employed in this study for its appropriateness of representing the aforementioned irrigation districts samples and estimating reliable irrigation water application and crop yield values for the entire region. A direct face-to-face survey method was applied because it is more likely to