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Energy/water budgets and productivity of the typical croplands irrigated with groundwater and surface water in the North China Plain

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ABSTRACT

Although irrigation has markedly increased agricultural productivity in the North China Plain, it has reduced groundwater levels by up to 0.8 m yr^{-1} and dried up the Yellow River for extended times since the 1970s. The objective of this study was to compare water, energy, and carbon fluxes in regions irrigated with groundwater and surface water (Yellow River) using almost four years of eddy covariance data from agricultural stations in Luancheng (water table depth: ~42 m) and Weishan (near Yellow River, water table depth: 1–3 m). Irrigation is mostly restricted to winter wheat as summer maize grows during the rainy season. Mean annual ET was 693 mm yr^{-1} for Luancheng site, which is higher than Weishan site (648 mm, ignore partial years). About ~390–480 mm of ET occurred during the wheat season (from early October to next early June, about 247 days), 230–300 mm in the maize season (from early June to late September, about 107 days). Annual crop yields were ~6864 kg/ha in the two regions. Annual water use efficiencies ranged from 4 to 6 g CO_2 kg^{-1} H_2O. Water use efficiencies were higher for maize than for wheat. Annual cropland carbon budget (CCB) was 230–280 g C m^{-2} yr^{-1} at the two sites and suggested a weak carbon sink. Irrigation compensated for seasonal and inter-annual variability in precipitation. Shifting the cropping pattern from wheat–maize double crops to a single crop of maize could significantly reduce water withdrawal and lead to a more sustainable use of water resource in this region.

1. Introduction

Irrigation plays a key role in increasing crop productivity and accounts for 20% of cropland and 40% of food production globally (Rockstrom and Falkenmark, 2000). Most irrigation is derived from either surface water or groundwater, with the fraction from groundwater increasing during the past few decades (Giordano, 2009). Siebert et al. (2010) estimate that ~40% of the areas equipped for irrigation are based on groundwater, with the remaining 60% from surface water or other sources. Although irrigation is highly beneficial for food production, there are many negative environmental impacts of irrigation, including depletion of surface water and groundwater resources and pollution (Pereira et al., 2002; Zektser et al., 2005). Irrigation derived from surface water has been responsible for flow reduction in streams and depletion in lakes (e.g. Yellow River, Tarim Basin, and Aral Sea) as well as soil salinization from rising water tables related to enhanced groundwater recharge from irrigation return flow (Singh and Singh, 1995; Khan et al., 2006; van Weert et al., 2009). Groundwater-fed irrigation has caused many of the hotspots of groundwater depletion globally (Wada et al., 2010) and indirectly impacted stream flow by reducing groundwater flow to streams.

The North China Plain (NCP, 140,000 km^2 area, Fig. 1) provides an excellent field laboratory to assess many of the issues related to irrigation. The irrigated area represented ~75% of cropland in 2008. Grain production in the NCP accounts for ~10% of total grain production in China (Fig. 1, 2010 China Statistical Yearbook). Irrigation has played an integral role in the almost eight fold increase in grain yield in the NCP from 0.64 t ha^{-1} in 1950 to ~5.00 t ha^{-1} in 2009 (Zhou et al., 2007). Grain yield relies largely on irrigation because precipitation amount (400–600 mm) and timing (mostly during summer monsoons) are insufficient to support the double cropping system of winter wheat and summer maize. Irrigation water is sourced from groundwater in most cropland in the Hebei province (~75% of the total irrigated land) and from surface water reservoirs (~25% of total irrigation land) in the Piedmont region of Taihang Moutain (Liu et al., 2010; Sun et al., 2010). In the Piedmont region,

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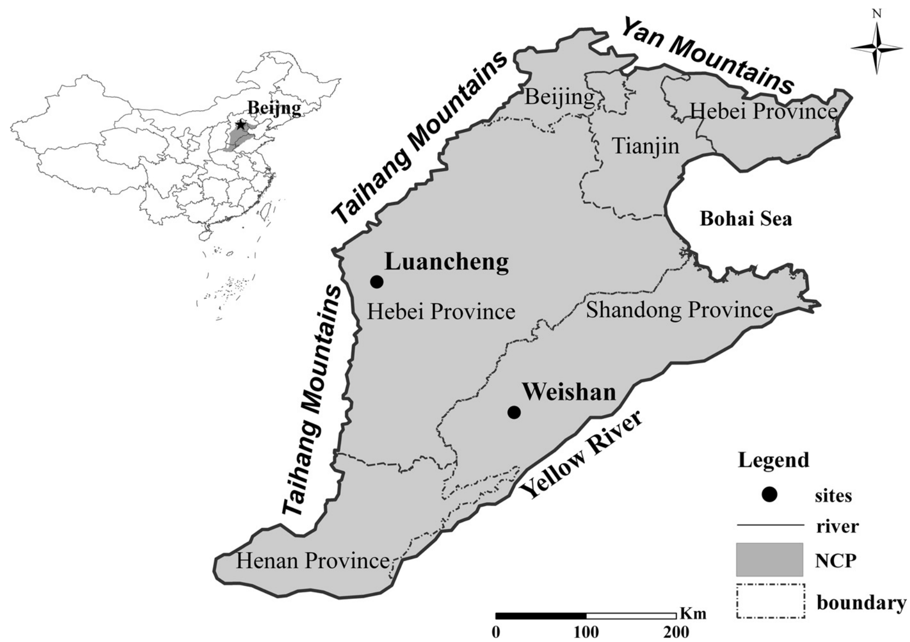

Fig. 1. Map of the North China Plain showing locations of the monitoring stations at Luancheng station (37°57′ N, 114°41′ E, altitude: 50 m) and Weishan station (36°39′ N, 116°03′ E, altitude: 30 m).

large water deficits have been offset by high levels of groundwater withdrawal, resulting in steep water table declines (~0.8 m yr^{-1} at the Luancheng station) since the 1970s, based on monitoring and modeling analyses. In addition to large scale groundwater depletion in the Piedmont region, there is rapid development of surface water irrigation along the Yellow River, annually totaling ~24.9 km^3 of water diverted from the 1950s to 1990s (Zhang et al., 2005). Irrigation water withdrawal from the Yellow River has resulted in frequent drying of the river flow since 1972 (Yang et al., 2004). From 1972 to 2000, the drying days ranged from 9 to 136 days per year. Drying generally occurred downstream extending to 680 km upstream in 1995. The Weishan irrigation district, the largest in the region, was established in 1958 at the downstream section of the Yellow River; however, salinization over a large region caused by rising water tables resulted in stopping the irrigation in 1961. After completion of the drainage system construction, soil salinity was effectively reduced and the irrigation channels were put into function again since 1970. Nowadays, flood irrigation still plays a major role in the lower reaches of the Yellow River, and agriculture in this region is facing threats from water shortages. It is necessary to evaluate the water consumption and productivity of agroecosystem in the NCP by integral of the energy, water, and carbon fluxes and processes. This kind of insight analysis could help to understand the nexus of climate, water, and agriculture, and to adjust water and agricultural management toward sustainable development.

There is rising interest in increasing crop production per unit of water (i.e. water use efficiency, WUE, kg crop per m^{-3} of water) to reduce overexploitation of water resources while maintaining crop productivity. Water consumption is generally defined as evapotranspiration (ET) over the entire crop growing season. Fang et al., 2010 reported a 10–25% increase in WUE in the wheat–maize double cropping system due to enhanced irrigation in the NCP using model simulation analyses. Reducing number of irrigation applications in a year can increase WUE, and maximum grain production can be achieved with moderate water deficits (Zhang et al., 2010) whereas excessive irrigation can reduce grain yield and WUE (Sun et al., 2006). Accurate monitoring or estimation of ET, as well as the biomass formation from cropland, are essential for estimating WUE (Todd et al., 2000; Shen et al., 2004; Shao et al., 2010).

A variety of approaches have been used to monitor ET, including weighing lysimeter (Liu et al., 2002; Castellví and Snyder, 2010), eddy covariance systems (Russell, 2010; Zhou and Zhou, 2009), and water balance modeling (Wilson et al., 2001; Sun et al., 2010). Eddy covariance (EC) systems provide information on water, energy, and carbon dioxide fluxes. Integrated analysis of these fluxes is particularly valuable for assessing controls on WUE, such as water limitations and energy limitations during different phases of crop growth. Additionally, some research has evaluated whether different types of vegetation act as carbon sources or sinks (Fan et al., 1998; Piao et al., 2009).

The objectives of this study were: (1) to compare water, energy, and carbon fluxes in irrigated agroecosystems fed by surface water and groundwater using monitoring data from the NCP; (2) to analyze the cropland water balance and productivity using field measurements to seek for a better cropping system with higher water use efficiency in the NCP. This work builds on previous separate research (Shen et al., 2002, 2004; Lei and Yang, 2010) by integrating water, energy, and carbon fluxes in heavily irrigated cropland and contrasting surface water- and groundwater-fed irrigation in areas with differing water table depths. Results of this study should provide valuable information for agricultural water management and should help assess approaches for reducing water use while maintaining crop productivity.

2. Materials and methods

2.1. Site description

The experiments and data collection were conducted at the Luancheng Agro-ecosystem Experimental Station (2008–2011) in Hebei province and at the Weishan station (2005–2006 and 2008–2009) along the Yellow River in Shandong province (Fig. 1).

The Luancheng station is located near Shijiazhuang City. The Weishan station is located in the Weishan Irrigation District (3600 km^2 area) irrigated with canals from the Yellow River that