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Quantifying the link between crop production and mined groundwater irrigation in China

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HIGHLIGHTS

- We model groundwater and surface water irrigation in China, and the resulting crop production.
- Irrigation water demands can only be met by mining groundwater in excess of recharge.
- ~20% of China's agricultural production relies on groundwater mined in excess of recharge.
- There is large spatial variation in the amount of crops produced by a unit of irrigation water.

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ABSTRACT

In response to increasing demand for food, Chinese agriculture has both expanded and intensified over the past several decades. Irrigation has played a key role in increasing crop production, and groundwater is now an important source of irrigation water. Groundwater abstraction in excess of recharge (which we use here to estimate groundwater mining) has resulted in declining groundwater levels and could eventually restrict groundwater availability. In this study we used a hydrological model, WBMplus, in conjunction with a process based crop growth model, DNDC, to evaluate Chinese agriculture's recent dependence upon mined groundwater, and to quantify mined groundwater-dependent crop production across a domain that includes variation in climate, crop choice, and management practices. This methodology allowed for the direct attribution of crop production to irrigation water from rivers and reservoirs, shallow (renewable) groundwater, and mined groundwater. Simulating 20 years of weather variability and circa year 2000 crop areas, we found that mined groundwater fulfilled 20%–49% of gross irrigation water demand, assuming all demand was met. Mined groundwater accounted for 15%–27% of national total crop production. There was high spatial variability across China in irrigation water demand and crop production derived from mined groundwater. We find that climate variability and mined groundwater demand do not operate independently; rather, years in which irrigation water demand is high due to the relatively hot and dry climate also experience limited surface water supplies and therefore have less surface water with which to meet that high irrigation water demand.

1. Introduction

Increasing global demand for food over the past several decades has forced agriculture to expand into water-scarce regions and increase irrigation water use substantially (Shiklomanov and Rodda, 2003; Molden et al., 2007). With little additional land available for agricultural expansion except in tropical rainforests, future increases in crop production will likely rely on increases in irrigation and intensification, both in China and globally (Molden et al., 2007). Historically, China's agriculture was concentrated in the wetter southern half of the country, but significant expansion over the past 50 years has led to over 50% of current national crop production occurring in the dry northern regions (Ma et al., 2006). Irrigated agriculture has expanded significantly in China in the past 75 years, increasing by more than 35 million hectares since 1939 to 51 Mha of planted land and 79 Mha of harvested land in 2000 (Calow et al., 2009; Portmann et al., 2010). Groundwater exploitation has underpinned the agricultural intensification of northern China since the 1970 (Calow et al., 2009; Currell et al., 2012; Cao et al., 2013), where groundwater accounts for up to 40% of irrigation water (Wada et al., 2012). Declining groundwater levels are threatening to

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limit the irrigation water supply for China's crop production (Kang et al., 2009; Aeschbach-Hertig and Gleeson, 2012; Syed et al., 2008). There has been a 15 m drop in groundwater levels in the North China Plain since 1960 (Calow et al., 2009), and the current rate of groundwater depletion is estimated to reach up to 1 m per year regionally based on model studies (Aeschbach-Hertig and Gleeson, 2012), and up to 1.5 m per year and 3 m per year in unconfined aquifer systems and deep confined aquifer systems, respectively, based on monitoring data (Currell et al., 2012). This heavy reliance on groundwater for irrigation is driven largely by lack of sufficient surface water supplies (Wisser et al., 2008; Wada et al., 2012), and Northern China is now considered to be a region of physical water scarcity, i.e., more than 75% of river discharge is abstracted (Molden et al., 2007). Global multi-model projections of irrigation water availability show significant reduction in Northern China for irrigation potential from renewable surface water by 2100 due to climate change (using a scenario of high greenhouse gas emissions (RCP8.5)) (Elliott et al., 2014). Aquifer depletion could also significantly decrease irrigation water availability in the future. Despite the importance of groundwater and groundwater depletion for the future of Chinese agriculture, it is currently unknown how much food is produced as a direct result of irrigation with non-renewable groundwater mining.

Konikow and Leake (2014) show that groundwater depletion is a combination of decreasing aquifer storage and capture of water from subsurface storage. Over time, the relative proportion of storage reduction to water capture changes, and increases in subsurface water capture can reduce baseflow in rivers (Konikow and Leake, 2014). Previous research on groundwater in China has shown that groundwater pumping has indeed led to capture of baseflow, with implications not only for water quantity but also water quality. In the Hai River Basin in northeastern China, groundwater depletion has been identified as the cause of 40% of waterways drying up, and the disappearance of 194 natural lakes and depressions (Jiang, 2009). A multi-model study of the Baiyangdian Lake catchment in northern China shows that increased exploitation of water resources over the past 50 years has led to depletion of both groundwater and surface water levels (Moiwo et al., 2010). In the Shiyang River Basin in northwest China, localized regions have experienced groundwater level decreases of up to 14 m, and seasonal drying up of river beds (Kang et al., 2009). Downstream sections of this basin have become significantly salinized over the past 50 years, and measured total dissolved solids in well water has increased three-fold (Kang et al., 2009). Salinization due to diminished groundwater recharge has led to degradation of riparian vegetation in the Tarim River Basin in western China (Pang et al., 2010). Further examples can be found in Liu and Zheng (2004), Tang et al. (2004), and Nakayama and Shankman (2013).

Large-scale surface water balance models can simulate the use of both surface water and groundwater for irrigation. Several model-based estimates of irrigation water demand in China have been made, ranging from 220 to 850 km^3 yr^{-1}, circa 2000 (Wisser et al., 2008), with most estimates in the range of 350–500 km^3 yr^{-1} (Doll and Siebert, 2002; Siebert and Doell, 2007; Liu and Yang, 2010; Wada et al., 2012). These estimates are from a range of hydrology model studies, which used the Water Balance Model (Wisser et al., 2008), the Water-Global Assessment and Prognosis (WaterGAP) model (Doll and Siebert, 2002), the GID-based Environmental Policy Integrated Climate (GEPIC) model (Liu and Yang, 2010), the Global Crop Water Model (GCWM) (Siebert and Doell, 2010), and the PCR-Global Water Balance (PCR-GLOBWB) model (Wada et al., 2012). The proportion of irrigation water demand fulfilled by mined groundwater pumping is less well constrained. Groundwater (both renewable and mined in excess of recharge) provides up to 40% of China's irrigation water, and model results from Wada et al. (2012) show that 20 km^3 yr^{-1} (5% of irrigation demand) is drawn from non-renewable groundwater.

Water supply alone does not determine food production; cropped areas, crop choice, soil quality, and management practices all contribute (Tilman et al., 2002; Foley et al., 2011). Agriculture's vulnerability to changes in water supply will necessarily also depend on these factors, which all vary spatially across China. Crop water productivity, the crop yield gained from one unit of water, also varies spatially, even within individual watersheds (Cai et al., 2011). Global-scale studies of unsustainable water supplies and food production have used an empirical method to determine the relationship between water use and crop yields (Siebert and Doell, 2010), but this method is not suited for higher-resolution analysis (Siebert and Doell, 2010). An alternative approach is to employ a process-based crop growth model that can capture these important spatially-variable production factors (Mueller and Robertson, 2014).

In this study, we used a hydrological model in conjunction with a process based crop growth model to evaluate Chinese agriculture's dependence upon mined groundwater, and quantify mined groundwater-dependent crop production across a domain that includes variation in climate, crop choice, and management practices. We computed irrigation water demand, as well as sources of water supply, across 20 years of climate variability. Model years 1981–2000 were chosen based on the validation period of the crop growth model. Using these two models allowed us to quantify the amount of food produced as a direct result of irrigation with groundwater mined in excess of recharge. We also defined an index of vulnerability to loss of mined groundwater resources that is a function of the amount of mined groundwater required for irrigation and the productivity of a crop irrigated from that water source. The main objective of this study is to quantify how much of China's food production is directly dependent upon mined groundwater irrigation.

2. Methods

We used two models to simulate irrigation water demand, irrigated and rainfed crop yields, and crop production due to mined groundwater. A grid-based water balance model (WBMplus, Wisser et al., 2010) calculated daily fluxes and storage of water between and within different water storage pools (Fig. 1). WBMplus was used to estimate the irrigation water demand of different crop types based on weather variables, soil properties, and crop parameters, and tracked the sources of irrigation water available to meet that demand (e.g., Wisser et al., 2008). WBMplus provided an estimate of the irrigated crop area depended dependent upon mined groundwater by first calculating the total irrigation water demand, then assessing the availability of water from multiple sources. Surface water sources are used first to fully irrigate as much irrigated cropland as possible; the remaining irrigated cropland is assumed to be reliant on mined groundwater. DNDC (Li et al., 1992a, b; Li, 2007), a process-based crop growth and agroecosystem biogeochemistry model, was used to simulate fully-irrigated and rainfed crop yields for individual crops and multi-cropping systems for all counties in China. WBMplus provided an estimate of the irrigated crop area dependent upon mined groundwater. By computing DNDC's difference between irrigated crop yields and rainfed crop yields to these areas, we estimated the portion of total crop yields directly resulting from groundwater mining.

Model validation for WBMplus is discussed in Wisser et al. (2010), and for DNDC in Li et al. (1992a), Li et al. (1994), and Wang et al. (2008). In China, river discharge modeled by WBMplus is compared to station observation monthly mean river discharge from the Global Runoff Data Center (Global Runoff Data Centre, 2013) using the Nash-Sutcliffe model efficiency coefficient. WBMplus has a Nash-Sutcliffe coefficient of greater than zero (i.e., a better prediction than projection the observational mean) at 10 of the 14 observation stations, and better than 0.5 in 7 of the 14 stations. DNDC has also been validated for use in China. Wang et al. (2008) compared model soil organic carbon to six long-term (10–20 years) datasets from Northeast, North, Northwest, and Central South China, and found a high level of agreement between all study sites and model results. Qiu et al. (2009) validated DNDC's representation of fertilizer and manure treatment against three study