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Research paper

Mission Impossible? Maintaining regional grain production level and recovering local groundwater table by cropping system adaptation across the North China Plain

Honglin Zhong[a], Laixiang Sun[a,b,c,*], Günther Fischer[b], Zhan Tian[d], Harrij van Velthuizen[b], Zhuoran Liang[e]

[a] Department of Geographical Sciences, University of Maryland, College Park, United States
[b] International Institute for Applied Systems Analysis, Laxenburg, Austria
[c] School of Finance & Management, SOAS, University of London, London, UK
[d] Shanghai Climate Center, Shanghai Meteorological Service, Shanghai, China
[e] Meteorological Service Center of Zhejiang Province, Hangzhou, China

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ABSTRACT

Insufficient precipitation and continuous over-exploitation of groundwater for agricultural irrigation led to rapid drop of groundwater table in a large part of the North China Plain (NCP), the bread basket of China. It has become widely acknowledged that current practice of winter wheat-summer maize sequential cropping system (WM-S) in the NCP will have to come to an end as soon as possible. Great research efforts have been made at the local level via both field experiments and model simulations to construct groundwater neutral cropping systems but virtually all such constructs show a substantial penalty on total output per unit of land per year. In this research, we propose a strategy to meet the double challenge of maintaining regional grain production level and recovering local groundwater table: 1) Widely adopt winter fallow and early-sowing summer maize monocropping (E-M) in water scarce part of the region to enable groundwater recovery; 2) replace WM-S by wheat-maize relay intercropping system (WM-R) in the water richer part of the NCP to increase grain production so as to compensate yield losses in the water scarce part of the region. Our simulations using DSSAT 4.6 at the site level show that both yield and water productivity of E-M are 33.7% and 41.8% higher than those of existing summer maize, with less than 20% of increase in water requirement. In comparison with spring maize, E-M requires 62.4% less irrigation water, with a yield penalty of only 4.52%. At the regional scale, the simulations targeting at maximizing groundwater saving in water scarce area subject to maintaining the current level of regional total output indicate that about 20.45% of the wheat planting area can be put on fallow in winter, most of which is located in the driest regions of the NCP. This can result in a large amount of groundwater saving at 5.62×10^9 m^3 and a substitution of wheat by maize at 24.3% of the total wheat output. These findings provide new rooms for the relevant policy makers and stakeholders to address the urgent groundwater recovering issues in the northern NCP without compromising the level of food grain production of the region.

1. Introduction

The North China Plain (NCP) is the bread basket of China. It produces about one-fourth of total food grains and two-thirds of total wheat output of the country. Such achievement has heavily depended on continuous overexploitation of groundwater for irrigation to meet the big water gaps between heavy water requirement of the prevailing wheat-maize cropping system and insufficient precipitation in large parts of the NCP (Fang et al., 2010a, 2010b; van Oort et al., 2016). Crop irrigation consumes about 70% of the total water use in the region. Continuous groundwater overexploitation has led to alarming drop of groundwater table during the last three decades, with many piedmont areas even suffering a drop rate of more than 1 m per year for 40 years (Jia and Liu, 2002; Li et al., 2005; van Oort et al., 2016). The rapid drop of

* Corresponding author at: Department of Geographical Sciences, University of Maryland, College Park, United States.
E-mail addresses: LSun123@umd.edu, LS28@soas.ac.uk (L. Sun).

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groundwater table also caused other environmental problems such as dried up rivers and lakes, seawater intrusion, land subsidence and ground fissures (Xue et al., 2000; Zhang et al., 2009). Health problems may increase as well when pumping reaches deep layers with water containing toxic levels of fluoride and arsenic (Currell et al., 2012). As forcefully pointed out in van Oort et al. (2016), the current practice of groundwater overexploitation in the region will have to come to an end in the foreseeable future so that groundwater extraction can be drastically reduced to conserve the aquifers.

Great research efforts have been made at the local level to reduce irrigation water consumption and thus groundwater overexploitation. These efforts include both the applications of water conservation technologies and the adoptions of alternative cropping strategies, with a focus on winter wheat because of its heavy irrigation requirement (Li et al., 2005). A number of water saving measurements, such as optimizing irrigation scheduling (Yao et al., 2000; Zhang and Deng, 2002), introducing limited and deficit irrigation (Wang et al., 2001; Kang et al., 2002; Li et al., 2005; Mei et al., 2013), and plastic mulching (Xu et al., 2015), are carefully evaluated based on both field experiments and crop model simulations, with the objective of maximizing irrigation water savings subject to minimum yield loss. Nevertheless, because precipitation can only meet 25–40% of the water requirement for achieving average wheat production in a large part of the region (Li et al., 2005), to support the prevailing winter wheat-summer maize sequential cropping (WM-S) system, great amounts of groundwater are still needed for irrigation use even with such water saving technologies.

The adoptions of alternative cropping strategies has been characterized by replacing current WM-S with groundwater neutral cropping systems (Yang and Zehnder, 2001; Zhang et al., 2004; Yang et al., 2015; van Oort et al., 2016).[1] Many field studies suggest spring maize monoculture as an alternative cropping system because it is much less irrigation demanding and has higher yield potential than the prevailing summer maize (Pei et al., 2015). Other major alternative cropping systems suggested include three harvests in two years (1 st year: WM-S; 2nd year: spring maize) (Meng et al., 2012) and winter wheat-spring maize strip intercropping (Gao et al., 2009). However, the literature shows that the adoptions of groundwater neutral cropping systems in the water deficit parts of the NCP face the substantial penalty of total grain output per unit of land per year (total grain yield, hereafter). Limiting wheat irrigation with groundwater will cause a great reduction of wheat yield potential from 9.7 t/ha to 3 t/ha (Wu et al., 2006). Compared with WM-S under optimal irrigation strategy, total grain yield of the three harvests in two years as suggested in Meng et al. (2012) and spring maize monoculture as suggested in Pei et al. (2015) will decrease by 19.9% and 33.8% respectively.

van Oort et al. (2016) evaluated the performance of 11 groundwater neutral combinations of alternative cropping systems and water saving technologies based on simulations with APSIM cropping systems model and the SOILWAT water balance module. The calibration and validation of the APSIM model was based on experiments at the university farm of the Agricultural University of Hebei in Xinji County (37.54°N, 115.12°E), which is located in the alluvial plain of the Taihang Mountain in the northwest of the Hebei plain, an area with the most serious water shortage in the NCP. The evaluation concludes that the total grain yield of the WM-S under groundwater neutral constraint will drop by 44% in comparison with that of the WM-S under the current practice; and water conservation by plastic film could limit this reduction to 21–33% but possible environmental impacts of plastic film need additional attention.

The literature suggests that the two policy goals of maintaining grain production level and recovering local groundwater table seem irreconcilable in the NCP. However, the existing studies focus on reconciling the two goals either at the site level or a locality. In this research, we promote a macro-perspective and argue that we can better utilize richer agro-climatic resources (temperature and precipitation) available in the southern NCP to reconcile the two policy goals at the regional level. In more detail, we propose a cropping system adaptation strategy across the North China Plain and evaluate the performance of this regional strategy with reference to the prevailing WM-S system. The strategy consists of (1) widely adopting winter wheat fallow and early-sowing summer maize mono-cropping (E-M) in water scarce part of the region to enable groundwater recovery, and (2) replacing WM-S by wheat-maize relay intercropping system (WM-R) in the water richer part of the NCP to increase grain production and compensate yield losses in the water scarce part of the region. We employ DSSAT 4.6 to evaluate the relative performances of the prevailing WM-S system and the alternative E-M, WM-R and spring maize in terms of yield and irrigation water demand at the three sites and across all grid-cells of cropland in the NCP. Based on these results, we develop a procedure to allocate the above four cropping regimes to each grid-cell with the objective of maximizing groundwater saving in water scarce area under the constraint to maintain the current level of regional total output. A successful implementation of this procedure would demonstrate that it is feasible to reconcile the two policy goals of maintaining grain production level and recovering local groundwater table at the regional level of the NCP, thus providing a scientific basis for regional cropping system adaptation design.

2. Study area

The North China Plain (112.18°E–120.25°E, 32.19°N–40.18°N), also called Huang-Huai-Hai Plain, is a large alluvial plain built up along the shore of the Yellow Sea by deposits of the Huang He (Yellow River) and the Huai, Hai, and a few other minor rivers of northern China. The plain is bordered on the north by the Yanshan Mountains, on the west by the Taihang Mountains and the Henan highlands, and on the southwest by the Tongbai and Dabie Mountains. To the south it merges into the Yangtze Plain in northern Jiangsu and Anhui provinces. From northeast to southeast it fronts the Bo Hai (Gulf of Chihli), the hills of Shandong Peninsula, and the Yellow Sea (www.britannica.com/place/North-China-Plain). It covers a total area of 4.4×10^5 km^2 (Fig. 1), with a temperate semi-arid monsoon climate. About 60% of the precipitation occurs in summer (June–September), while less than 20% happens in winter and spring. Precipitation decreases from south to north and east to west.

Local climate resources can support the cropping systems of double harvests per year or triple harvests in two sequential years. The WM-S is currently the dominant cropping system in the NCP. Winter wheat is usually sown in early or middle October and harvested in early or middle June in the following year, while summer maize is sown right after the harvest of winter wheat and harvested in late-September. Under the WM-R, summer maize is sown in a single straight line between every two rows of wheat during mid to late May, about 7–15 days before the harvest of winter wheat. Spring maize is usually planted in late April. Please note that the Yimeng Mountain of the Shandong Province takes a large part of the central-east NCP, where the shares of both planting and irrigation areas for wheat and maize in its limited hilly and mountainous cropland are very small although annual precipitation is higher compared to the northern NCP. The far southern part of the NCP is in the transit zone between wheat-maize cropping system and

[1] Groundwater neutral cropping systems refer to cropping systems with sustainable pumping rates. The evapotranspiration (ET) differs between each cropping system, therefore each ground-water neutral cropping system has its own and different sustainable pumping rate (van Oort et al., 2016).