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Farmland shift due to climate warming and impacts on temporal-spatial distributions of water resources in a middle-high latitude agricultural watershed

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ABSTRACT

Climate warming increases the active accumulated temperature (AAT) of crops and may change crop structures and patterns. Climate warming along with farmland responses has combined consequences for watershed hydrological indicators, which would be expected to exhibit different temporal-spatial patterns. In our study we investigate the combined impacts of increased temperature and shifted farmland on the hydrological features in middle-high latitude agricultural watersheds. The AAT responses in latitudinal and altitudinal directions were revealed by using an agro-climate model under different warming scenarios (△T = 0.1 °C is applied to the interval from 0.7 °C to 1.5 °C). Then, the spatial distributions of dryland shifting to paddy land were determined considering △AAT. For every 1 °C increase in average annual temperature, the boundary for planting paddy fields will shift northward by approximately 160 km and upward in the altitudinal direction by 180 m. Increasing temperature values and the new crop distributions were imported into the SWAT model, which quantified the temporal (monthly and yearly) and spatial changes of runoff and actual evapotranspiration (ET). Annual runoff decreased at a rate of 9.5 mm/°C, and annual ET increased at a rate of 7 mm/°C under climate warming combined with shifted farmlands. Combined impacts increased runoff in February, March and September, and decreased runoff from April to July. ET increased from March to July and decreased in August and September. The comparison of spatial water resource responses indicated that lower altitude and lower latitude areas experienced larger changes in runoff and ET than was the case for higher altitude and higher latitude areas.

1. Introduction

Meteorological conditions play an important role in determining crop types due to flux of mass and energy balance, both of which are sensitive to climate change, especially to rising temperature (Dunn et al., 2012; Calzadilla et al., 2013). The potential contribution of climate change in the expansion of planting areas to higher latitudes and altitudes has been long hypothesized and is implied in many studies of agro-climatic indices (e.g., active accumulated temperature) (Toshichika and Ramankutty, 2015). Previous reports have indicated that the suitable growing area of many vegetation types could shift northward or be replaced by others due to climate warming in the northern hemisphere (Meza et al., 2008; Tchebakova et al., 2011). Yang et al. (2011) claimed that the suitable planting boundary for double rice-cropping systems has shifted northward by 50 km from 1951 to 2010. These shifts could be attributed primarily to increases in air temperature. Warming has been observed in high-middle latitude areas (45–60°N) in recent years and is more significant than in the low-middle latitudes (IPCC, 2013). Thus, climate warming will affect agro-climate resources in the higher latitude and higher altitude regions and alter crop structures and patterns.

Runoff and evapotranspiration (ET) are major components of the hydrological cycle (Katul et al., 2012; Liu et al., 2013). Climate warming is expected to lead to changes of the hydrological cycle, with implications for the recycling of snowfall, precipitation, generation of runoff and ET (Dunn et al., 2012), exerting direct impacts on water resource availability for agricultural irrigation (Neupane and Kumar, 2015). There is a large amount of snow accumulation due to cold conditions in high-middle latitude and high altitude

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regions. Climate warming will cause an earlier onset of snowmelt and a decrease in snow accumulation (Stewart, 2009; López-Moreno et al., 2014). In addition, warming has been predicted in high-middle latitude areas (2.66 °C/100 year) and is more significant than in the low-middle latitudes (2.13 °C/100 year) under Representative Concentration Pathway RCP 4.5 (RCP 4.5) in China (Sun et al., 2015), and hydrological processes will be increasingly impacted by climate change in the high-middle latitude region.

Land use is considered an important component of terrestrial environmental systems. Change in land use affects runoff, stream discharge, and pollution diffusion by changing canopy interception, surface roughness, soil properties, albedo, evapotranspiration, and surface soil hydraulic conductivity (Scheffler et al., 2011; Munoz-Villers and McDonnell, 2013; Neupane and Kumar, 2015). Shifts or transformations of farmland will have particularly large effects on hydrological processes and water resources due to irrigation and tillage. Especially in high-middle latitude area, this significant farmland conversion caused by warming will have serious effects on local hydrology and water resources.

Changes in water resources caused by climate change have become critical issues affecting terrestrial hydrological processes and water resource functions (Eugenio et al., 2014) and may lead to political problems at both local, national and international levels. An example of the latter is the Mekong River Basin in Southeast Asia (Keskinen et al., 2010). However, these environmental effects caused by climate change vary with hydrologic processes and seasonality under land use changes (Gupta et al., 2015). With climate warming, the period of snowmelt, runoff and ET volume will change in high-middle latitude agricultural watersheds. At the same time, climate warming will affect planting structure and patterns in this region, and climate-induced farmland changes will change this hydrologic response. Climate warming combined with climate-induced farmland change will result in changes in temporal (monthly and yearly) and spatial hydrologic indicators (runoff and ET). The effects of these changes require further investigation to facilitate suitable adaptation measures of climate change. While rainfall is known to be greatly affected by a warming climate, for the purposes of analysis in this study, it is assumed in the analysis to remain unchanged. The effects of climate warming on precipitation, and effects of slope, soil water content, runoff on crops will be studied in a later investigation and they could mitigate or exaggerate the warming effects estimated here.

The effects of climate and land use changes on hydrologic processes have been reported in recent years (van Roosmalen et al., 2009; Eugenio et al., 2014; El-Khoury et al., 2015). According to a report by Krysanova and White (2015), 210 papers studying climate change and 109 papers studying land use change were published between 2005 and 2014. They also report that in the same time period fewer than 30 papers have been published on topics related to the combined impacts of climate change and land use where the Soil and Water Assessment Tool (SWAT) model was used as an analytical tool. Although these studies claimed that they presented the combined impacts of climate and land use change on hydrology, climate and land use factors were generally considered independent of each other. Land use projection methods used in these studies included generalized assumptions (van Roosmalen et al., 2009; Eugenio et al., 2014) and detailed land use allocation modeling (Kim et al., 2013; Fan and Shibata, 2015; El-Khoury et al., 2015). However, the importance of climate-induced land use change was not emphasized, especially farmland shifts in high-middle latitude regions. There is a general lack of knowledge concerning the combined impacts of climate change and climate-induced farmland shifts on water resources in high-middle latitude agricultural watersheds.

To bridge this gap, in this study we propose a modeling framework based on climate warming scenarios, a simple agro-climate model and the SWAT model. In this study, climate warming scenarios were established by perturbing daily changes in maximum (T_{max}) and minimum (T_{min}) air temperatures, a technique which has been used in previous studies (Vano et al., 2012, 2015; Das et al., 2011). Warming-induced farmland shifts can be predicted based on an agro-climate model. Increasing temperature values and the corresponding farmland patterns were imported into the SWAT model to assess the combined impacts of climate warming and farmland shifts on water resources. The merit of using perturbed temperature is that this method could assess and analyze simply how the farmland shifts respond to temperature warming and how the hydrology responds to warming combined with farmland shifts. This study provides insights into how the combined impacts of temperature warming and farmland shifts on water resources, and contributes to the understanding of future hydrological changes in high-middle latitude regions. The major goals of this study are: (1) to assess farmland responses to different temperature increments; (2) to model the responses of temporal (monthly and yearly) and spatial hydrological indicators to the combined impacts; (3) to assess the combined impacts on the temporal-spatial distribution of future water availability in a high-middle latitude agricultural watershed in northeastern China.

2. Materials and methods

2.1. Study area description

The Naoli River watershed is a key part of the Sangjiang Plain in northeastern China which is located in a region with a continental monsoon climate (the latitude ranges from 45°42′12″ to 47°25′18″N) (Fig. 1). Its total watershed area is 220,500 ha which consists of 78.4% plains area, 4.8% hills area, and 16.8% mountainous area. The elevation of the watershed ranges from 35 to 836 m. Based on meteorological data from 1995 to 2011, the average annual temperature was 1.91 °C and the mean annual precipitation was 518 mm in the entire watershed. Precipitation during the growing season (May to October) accounted for the major proportion (76%) of the annual amount; in addition, the watershed receives considerable snowfall from November to February. Based on the effective drainage, plentiful water resources and fertile soils, agricultural land (paddy fields and upland) has expanded in this region over the last 30 years (Ouyang et al., 2012).

2.2. Climate change scenarios

Output from Global Climate Models (GCMs) has been commonly used to study the impact of climate change (Delpla and Rodriguez, 2014; Fan and Shibata, 2015; El-Khoury et al., 2015). An alternative way to estimate the hydrologic sensitivity to climate warming is to use the perturbed temperature, which increases by uniform amounts each day of the year throughout the period of record (Das et al., 2011; Vano et al., 2012, 2015). In this study, we perturbed T_{max} and T_{min} of one climate station (grid point) of lowest elevation by uniform amounts (e.g., $\triangle T = 0.1$ °C) for the period of 1993–2011, and calculated the $\triangle T$ of the other 15 grid points based on the latitudinal (R_L) and altitude (R_H) temperature gradient. These temperatures were employed for different warming scenarios in the SWAT model. We created the $\triangle T$ by using additive perturbations in T (0.7–1.5 °C at an interval of 0.1 °C). These warming temperature scenarios were also reported in Gao et al. (2016).

2.3. Farmland response prediction

Warming temperatures in agricultural areas can increase the accumulated temperature for crops, so planting areas for crops