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Farmland–atmosphere feedbacks amplify decreases in diffuse nitrogen pollution in a freeze-thaw agricultural area under climate warming conditions

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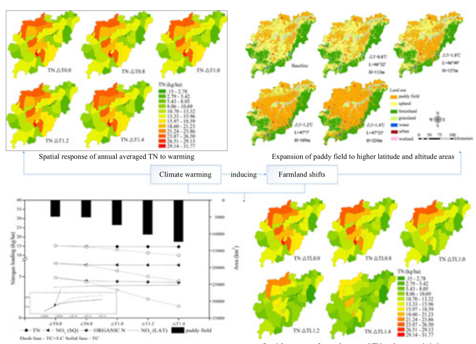
HIGHLIGHTS

- The synergistic impacts of climate warming and farmland shifts were assessed.
- Farmland shifts amplified the total nitrogen loading decrease caused by warming.
- Synergistic impacts enlarged nitrate increase in lateral flow caused by warming.
- Low altitude or latitude areas showed greatest decrease in total nitrogen loading.

GRAPHICAL ABSTRACT



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ABSTRACT

Although climate warming and agricultural land use changes are two of the primary instigators of increased diffuse pollution, they are usually considered separately or additively. This likely lead to poor decisions regarding climate adaptation. Climate warming and farmland responses have synergistic consequences for diffuse nitrogen pollution, which are hypothesized to present different spatio-temporal patterns. In this study, we propose a modeling framework to simulate the synergistic impacts of climate warming and warming-induced farmland shifts on diffuse pollution. Active accumulated temperature response for latitudinal and altitudinal directions was predicted based on a simple agro-climate model under different temperature increments ($\triangle T_0$ is from 0.8 °C to 1.4 °C at an interval of 0.2 °C). Spatial distributions of dryland shift to paddy land were determined by considering accumulated temperature. Different temperature increments and crop distributions were inserted into Soil and Water Assessment Tool model, which quantified the spatio-temporal changes of nitrogen. Warming led to a decrease of the annual total nitrogen loading (2.6%–14.2%) in the low latitudes compared with baseline, which was larger than the decrease (0.8%–6.2%) in the high latitudes. The synergistic impacts amplified the decrease of the loading in the low and high latitudes at the sub-basin scale. Warming led to a decrease of the loading at a rate of 0.35 kg/ha/°C, which was lower than the synergistic impacts (3.67 kg/ha/°C) at the watershed level. However, warming led to the slight increase of the annual averaged NO3 (LAT) (0.16 kg/ha/°C), which was amplified by the synergistic impacts (0.22 kg/ha/°C). Expansion of paddy fields led to a decrease in the monthly total nitrogen loading throughout the year, but amplified an increase in the loading in August and September. The decreased response in spatio-temporal nitrogen patterns is substantially amplified by farmland–atmosphere feedbacks associated with farmland shifts in response to warming.

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1. Introduction

In China, the high-middle latitude regions will experience more warming (2.66 °C 100 year^{-1}) than low-middle latitude regions (2.13 °C 100 year^{-1}) under RCP 4.5 (Representative Concentration Pathway 4.5) (Sun et al., 2015). Climate warming has significant effects on the agro-ecosystem, and changing heat conditions in high-middle latitude areas leads to the expansion of planting area to higher latitudes and altitudes (IPCC, 2013; Brodie, 2016), which has been documented in China (Zhang et al., 2013; Ye et al., 2015) and Europe (Olesen and Bindi, 2002; Tchebakova et al., 2011). In addition, climate warming will cause a decrease (in both volume and duration) of the snowpack in winter, which often amplifies freeze-thaw cycles (Shibata, 2016). This phenomenon may lead to either higher or lower diffuse nitrogen pollution loading, which could directly impact water quality in the freeze-thaw areas (Shibata et al., 2013; Urakawa et al., 2014). Shifts or transformations of farmland caused by warming will have particularly large effects on nitrogen diffusion due to changing tillage and fertilizer application during the crop growing season (Fan and Shibata, 2014; Neupane and Kumar, 2015). The synergistic impacts of climate warming and warming-induced farmland shifts will lead to changes in diffuse nitrogen pollution loading. The synergistic impacts require further investigation to facilitate suitable adaptation measures for climate warming in freeze-thaw areas.

The impacts of climate and land use changes on diffuse pollution have been discussed in recent years (Gassman et al., 2014; Molina-Navarro et al., 2014; El-Khoury et al., 2015). Recent reviews of the Soil and Water Assessment Tool model (SWAT) literature confirm that over 70 combined impact studies have now been documented (Teshager et al., 2016; CARD, 2016). Such studies include applications focused on the impact of historical land use change (Zuo et al., 2016) and land use projection methods, which include generalized assumptions (Guse et al., 2015; Goldstein and Tarhule, 2015; Teshager et al., 2016) and explicitly-spatial modeling (Guimberteau et al., 2016; Fan and Shibata, 2015; Mehdia et al., 2015). These studies claimed to present the combined impacts of climate and land use changes, but the "combined impacts" mostly means independent or additive combination, which did not emphasize the importance of climate-induced land use change (Brodie, 2016). The potential contribution of climate warming to the expansion of planting area has been hypothesized and is suggested by many studies exploring agro-climatic indices (e.g., active accumulated temperature) (Zhang et al., 2013; Ye et al., 2015; Toshichika and Ramankutty, 2015). Synergistic impacts, whereby agriculture expansion caused by warming either exacerbates or ameliorates the impact of climate on diffuse nitrogen pollution, have been insufficiently explored, especially in high-middle latitude regions that will experience more warming than low-middle latitude regions.

The selected study area is a large agricultural watershed located in a freeze-thaw areas of the high-middle latitude regions, which results in a large temperature gradient in the horizontal and vertical directions. The synergistic impacts of changes to climate warming and farmland shifts as well as their spatial gradients in the freeze-thaw area should follow different patterns than discussed in previous studies in different regions. Given this background, this study uses models to assess the synergistic impacts of climate warming and farmland shifts on diffuse nitrogen pollution. This study will provide insights into how climate warming might influence future cropping pattern and how the diffuse nitrogen load response to the synergistic impacts. The major objectives of this study are: (1) to model the responses of temporally (monthly and yearly) and spatially diffuse nitrogen pollution loading to different temperature increments; (2) to simulate the responses of temporal (monthly and yearly) and spatial diffuse nitrogen pollution loading to the synergistic impacts of climate and land use change; and (3) to analyze and assess the synergistic impacts of warming and farmland shifts on diffuse nitrogen pollution loading in freeze-thaw area.

2. Modeling framework

Mathematical programming models, such as agro-climate models, can capture the decision-making processes and interactions that drive farmland shifts (Zhang et al., 2013) under climate change. These models are also able to link climate elements with hydrological and biophysical elements and can be used to represent the synergistic impacts of climate warming and land use change (Brodie, 2016).

The framework proposed (Fig. 1) is a bottom-up approach focusing on the synergistic impacts of climate warming and land use change on the hydrology and diffuse pollution at the sub-basin and watershed levels. This bottom-up approach can reveal the most relevant stakeholders and elements of agricultural land use (Lescot et al., 2013). This proposed framework is composed of climate models or scenarios, an agro-climate model and the SWAT model. Climate change scenarios can be developed using Global Climate Models (GCMs), Reginal Climate Models (RCMs) (Delpla and Rodriguez, 2014; Guimberteau et al., 2016) or 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; Vano et al., 2015). Climate-induced farmland shifts can be obtained using an agro-climate model (Section 4.2). Climate warming scenarios and new crop distributions were imported into the SWAT model to simulate the synergistic impacts of climate warming and its induced farmland shifts on diffuse nitrogen pollution at the sub-basin and watershed levels.

3. Case study watershed

The watershed is a key part of the Sanjiang Plain in northeastern China and has a continental monsoon climate (Fig. 2). Its total drainage area is 220,500 ha, including 78.4% plains area, 4.8% hills area and 16.8% mountainous area. The elevation of this watershed ranges from 45 to

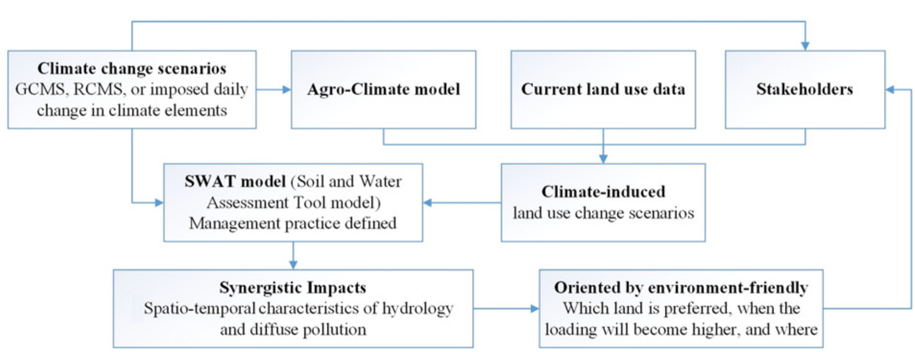

Fig. 1. Synergistic impacts analysis framework. Climate warming scenarios can be developed using this way: the information is incorporated in the study by dividing the increase of temperature (from RCMs or GCMs) into several change scenarios. The created warming scenarios were inserted into the Agro-Climate model and SWAT model to simulate the synergistic impacts of climate warming and warming-induced farmland change on the hydrology and diffuse pollution at the sub-basin and watershed levels.