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How do climatic and management factors affect agricultural ecosystem services? A case study in the agro-pastoral transitional zone of northern China

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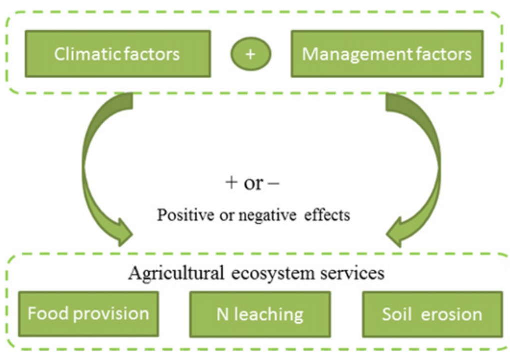
HIGHLIGHTS

- Management factors had larger effects on AES than climatic factors.
- Daily minimum temperature was the main climatic factor affecting changes in AES.
- Tradeoffs existed between crop production and negative environmental effects.
- Agro-ecosystem can be more sustainable through adaptive management practices.

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural ecosystem management needs to ensure food production and minimize soil erosion and nitrogen (N) leaching under climate change and increasingly intensive human activity. Thus, the mechanisms through which climatic and management factors affect crop production, soil erosion, and N leaching must be understood in order to ensure food security and sustainable agricultural development. In this study, we adopted the GIS-based Environmental Policy Integrated Climate (EPIC) model to simulate crop production, soil erosion, and N leaching, and used a partial least squares regression model to evaluate the contributions of climate variables (solar radiation, precipitation, wind speed, relative humidity, and maximum and minimum temperature) and management factors (irrigation, fertilization, and crop cultivation area) on agricultural ecosystem services (AES) in the agro-pastoral transitional zone (APTZ) of northern China. The results indicated that crop production and N leaching markedly increased, whereas soil erosion declined from 1980 to 2010 in the APTZ. Management factors had larger effects on the AES than climate change. Among the climatic variables, daily minimum temperature was the most important contributor to the variations in ecosystem services of wheat, maize, and rice. Spatial changes in the cultivated area most affected crop production, soil erosion, and N leaching for majority of the cultivated areas of the three crops, except for the wheat-cultivated area, where the dominant factor for N leaching was fertilization. Although a tradeoff existed between crop production and negative

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environmental effects, compromises were possible. These findings provide new insights into the effects of climatic and management factors on AES, and have practical implications for improving crop production while minimizing negative environmental impacts.

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1. Introduction

The global agricultural ecosystem, representing humankind's largest engineered ecosystem, occupies about 38% of the earth's terrestrial surface (FAOSTAT, 2011). This ecosystem can supply multiple ecosystem services, such as provision (i.e., food and fiber), support (i.e., nutrient cycling), culture (i.e., recreation and spiritual), and regulation (pollination), which are essential for human well-being and sustainable development (MA, 2005; Wu, 2013).

Among the different agricultural ecosystem services, food provision usually receives special attention due to the need to maintain regional food security (FAO, 2015). Although global food production has increased rapidly in the past decades, and food security status has improved, approximately 795 million people were still undernourished worldwide in 2015 according to the Food and Agriculture Organization (FAO) report (FAO, 2015). By the middle of the current century, the global population is expected to increase to 9 billion (Godfray et al., 2010), and this rapid population growth will present new challenges for food production.

This urgent requirement for food production will increase agricultural land-use intensity and have non-negligible effects on the environment (Basche et al., 2016; Foley et al., 2005; Liu et al., 2016). Agricultural practices may have negative environmental effects, such as soil erosion (Montgomery, 2007), N leaching (Valkama et al., 2016), and habitat degradation, and thus, present a threat to sustainable agricultural ecosystem management. Agricultural production is sensitive to climate change, which may further intensify the negative environmental effects of soil erosion and N leaching. Therefore, there is an urgent need to characterize the spatial and temporal variation in crop production, soil erosion, and N leaching in order to target measures of adaptation to climate change.

Human-induced changes in management practices (i.e., fertilization, irrigation, and adjustment of crop cultivation structure) are prominent factors leading to variation in agricultural ecosystem services (AES) (Berzsenyi et al., 2000; Zhang et al., 2017; Zhu and Chen, 2002). Numerous studies have evaluated the effects of fertilization, irrigation, and climate change on AES using control variable methods. Gheysari et al. (2009) evaluated the effects of different irrigation and nitrogen fertilizer levels on N leaching, and found that N leaching could be controlled with an appropriate combination of fertilizer and irrigation management. Liu et al. (2007) analyzed the effects of irrigation on crop production and found it to play an important role in increasing food production in China. Yin et al. (2015) projected the potential yield of major crops under climate change, in which the crop distribution was held as static.

However, few studies have evaluated the contributions of both climatic and management factors on variations in AES. In particular, the contribution of changes in crop distribution to variation in AES is rarely been considered. In practice, the driving factors of climatic change and management factors were combined together to play role in the variation in AES. Therefore, understanding the integrated contributions of driving factors to the variation in AES and quantifying the predominant factors are necessary to optimize the AES under climate change conditions.

It is necessary to understand the mechanisms of interactions among multifaceted AES. Therefore, we selected the arid and semiarid agro-pastoral transitional zone (APTZ) of northern China as the study area and integrated the GIS-based Environmental Policy Integrated Climate (EPIC) model and partial least square regression model to identify how climate change and human management factors affect AES. Our objectives were to 1) analyze trends in driving factors, including the climatic variables of solar radiation, precipitation, minimum temperature (T_{min}), maximum temperature (T_{max}), wind speed, and relative humidity, and human management measures, including fertilization, irrigation, and adjustment of cultivated area of wheat, maize, and rice from 1980 to 2010; 2) simulate crop production, soil erosion, and N leaching in wheat, maize, and rice from 1980 to 2010; and 3) evaluate the respective contributions of these driving factors to the variation in AES, and to select the factor with the largest effect on the AES.

2. Study area

The APTZ is located between the 34°46′–48°32′N and 100°55′–124°41′E and covers an area of approximately 7.26×10^5 km^2 (Fig. 1). Although the cropland area has changed significantly since the implementation of the Grain for Green project in 1999 (i.e., returning the farmland to forest or grassland), the APTZ remains an important area for food provision, and accounted for 7.7% of China's total food production in 2010 (China Agricultural Statistical Yearbook, 2010). The APTZ is located in the arid and semiarid region, which has a temperate continental monsoon climate with strong winds, cold weather, and little rain. From 1980 to 2010, the average annual temperature was unevenly distributed and varied from 3.0 to 9.9 °C (Fig. 1a). The spatial distribution of precipitation is extremely uneven across the whole region. The areas with the most precipitation are concentrated in the northeast and southwest, where the average annual precipitation is over 500 mm, whereas the average annual precipitation in the dry areas is <250 mm (Fig. 1b). Limited irrigation facilities have been developed to ensure local agricultural production, which is mainly distributed in the northeast and southwest regions (Fig. 1c). The terrain slope in this region ranges from 0 to 38% (Fig. 1d). The main soil types are loam and sand, accounting for 74.9% of the whole study area (Fig. 1e).

3. Materials and methods

3.1. Model description

EPIC is a cropping system model that has been widely used since 1990 (Sharpley and Williams, 1990), and is an effective tool for assessing the effect of agricultural management measures on crop yield and associated biophysical processes (Benson et al., 1992; Chavas et al., 2009; Thomson et al., 2006). The EPIC model consists of a crop growth module, a soil erosion module, a nutrient cycling module, and other modules. In the present study, the EPIC model (version 0509) was combined with ArcGIS 10.1 to simulate the AES of crop production, soil erosion, and N leaching for wheat, maize, and rice in the crop-cultivated areas. In the calibration process, the simulated yield of each grid within a municipal area was averaged to match the statistical yield recorded at the municipal scale. The linear root mean square error (RMSE) and relative RMSE (RRMSE) indicators were used to evaluate the performance of EPIC in simulating crop yield.

3.1.1. Crop growth module

In the EPIC model, the daily increase in potential biomass is calculated using the algorithm described by Monteith (1977):

$$\Delta B_{p,i} = 0.001 \times WA \times PAR_i \tag{1}$$

where $\Delta B_{p,i}$ represents the increased potential biomass in day i, WA is the efficiency of light energy utilization, and PAR_i is the intercepted

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