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Quantifying the contributions of agricultural oasis expansion, management practices and climate change to net primary production and evapotranspiration in croplands in arid northwest China

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ABSTRACT

Cropland area in north-western China has quadrupled over the past 50 years. The effects of this rapid expansion on regional carbon and water budgets have not been examined quantitatively. In this study, an enhanced Biome-BGC model including crop growth processes was used to quantify the effects on regional net primary productivity (NPP) and evapotranspiration (ET) in a representative catchment. The model results were in good agreement with biometric measurements. The catchment-scale total NPP (TNPP) and total ET (TET) increased by 81.8% and 89.4%, respectively. The increase in cropland area (LUCC) explained 40.3% and 60.5% of the increased TNPP and TET, while management practices (Mana) accounted for 46.1% and 16.8% of the increased TNPP and TET, respectively. Climate change (CLM) had the least influence on the increase in TNPP and TET (accounting for 1.8% and 4.7%). As assuming no interactions between CLM and LUCC, we detected effects of interactions between CLM and Mana (accounting for 10% and 16.8%) and between Mana and LUCC (accounting for 1.8% and 4.7%) on the increased TNPP and TET. These results implied that the rapid expansion of cropland and intensive agricultural management practices had important effects on regional carbon and water budgets.

1. Introduction

Arid and semi-arid regions cover approximately one third of the world's land area (Okin et al., 2006). In China, these regions cover approximately 22% of the land area, 2.15 × 10^6 km^2, mostly in the northwestern part of the country (Hu et al., 2010). Agricultural oases are referred to cultivated land in arid or semi-arid regions formed by human activities that are irrigated by anthropogenic means (e.g., withdrawn river water or pumped underground water; Wang, 2010a,b). Agriculture in artificial oases is necessary to maintain social development and the increased population in these arid and semi-arid regions (Chen, 2008) and plays an important role in the regional carbon and water cycle (Foley et al., 2005). First, most agricultural cropland was converted from natural vegetation in natural oases, which are generally called agricultural oases in arid and semi-arid regions of northwest China. Thus, agriculture is highly dependent on management practices such as irrigation and fertilization (Wang and Zhang, 1999), which increase crop yields and modify the carbon, water, and nitrogen budgets in the cropland (Li et al., 2005; Zhang et al., 2011). Second, the arable area of the agricultural oases in northwestern China has quadrupled from 2.5 × 10^5 km^2 to 10.4 × 10^5 km^2 over the past 50 years (Wang, 2010a,b). The expansion of agricultural oases is a type of land-use and land-cover change (LUCC), which greatly changes the vegetation distribution and surface biogeochemical and biophysical processes, leading to dramatic changes in the water cycle and ecosystem productivity (Houghton and Hackler, 2003; Tian et al., 2011). At the same time, water is the most limiting resource for sustaining crop production in agricultural oases due to high water demands of the increased cropland area and population (Jia et al., 2004). To address this concern, the effects of expansion and associated management practices in agricultural oases on regional carbon and water budgets have not been examined quantitatively.

The effects of LUCC and agriculture on the terrestrial carbon cycle can be estimated based on the process-based terrestrial ecosystem models that have been widely used in recent decades (Bondeau et al., 2007; Ciais et al., 2011; Li et al., 2011; Parton et al., 1998; Vuichard et al., 2008), or based on statistically empirical models (Aggarwal et al., 2006; Bradford et al., 2005; Field et al., 1995; Graf et al., 1990; Huang et al., 2007; Lieth, 1975; Potter et al., 1993). Terrestrial ecosystem models can be used to describe

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the effects of human activities and environmental changes on carbon balance in croplands based on geophysical and geochemical processes and, therefore, have received much more attention (Ciais et al., 2011). A large number of terrestrial ecosystem models have been developed, including the Biome-BGC (Running and Hunt, 1993), IBIS (Kucharik, 2003), ORCHIDEE (Krinner et al., 2005), and JULES (Clark et al., 2011) models. All of these models were originally designed for natural vegetation, not for crops. When the models are applied to agricultural systems, the crops are generally described as grasslands (Churkina et al., 2010; Gervois et al., 2004; Mu et al., 2008; Vetter et al., 2008; Wang et al., 2005); however, the crops differ from grasslands in both physiological processes and management practices (Gervois et al., 2004). Therefore, some terrestrial ecosystem models have been coupled with crop growth models. The Agro-IBIS model has incorporated managed agroecosystems into the IBIS model (Kucharik and Brye, 2003) and has been used to simulate the spatial patterns and impact on maize yield at the regional scale in the USA (Kucharik, 2003). Gervois et al. (2004) and De Noblet-Ducoudré et al. (2004) coupled the ORCHIDEE model with STICS, an agronomic crop-growth model, and Li et al. (2011) comprehensively assessed its performance in estimating the fluxes of CO_2 and H_2O in several European maize sites. Hoof et al. (2011) incorporated a generic crop model (SUCROS) into a land surface model (JULES) and evaluated the fluxes simulated by the coupled JULES-SUCROS model against FLUXNET measurements at six European sites. Crop-specific parameters and management practices are defined in these coupled models, and their effects on phenology, biomass allocation, and carbon and water processes are given in the ecosystem model (De Noblet-Ducoudré et al., 2004; Gervois et al., 2004; Kucharik and Brye, 2003).

The Biome-BGC (BioGeochemical Cycles) model is a common model that can be used to simulate the carbon, nitrogen and water cycles of terrestrial ecosystems (Running and Hunt, 1993). The Biome-BGC model is a multi-biome generalization of FOREST-BGC (Running and Coughlan, 1988), which was originally developed to simulate a forest's development through its life cycle. The Biome-BGC model has been widely used for various biomes, including forests (Chiesi et al., 2007), grasslands (Running and Hunt, 1993) and crops (treating them as grasslands; Wang et al., 2005) and has been used at the site (Ueyama et al., 2010), regional (Mu et al., 2008; Turner et al., 2007) continental and global scales (Churkina et al., 2010; Vetter et al., 2008). The Biome-BGC model has already been modified to simulate the carbon and water flux of agro-ecosystems. Di Vittorio et al. (2010) updated the Biome-BGC model (Agro-BGC) to investigate the carbon, nitrogen and water balance of C_4 perennial grasslands, including crops. Ma et al. (2011) used eddy flux measurements of agro-ecosystems to identify the spatially generalized ecophysiological parameters of the ANTHRO-BGC model (another modified version of the Biome-BGC) in croplands. Both versions of the modified Biome-BGC model have been used at the site scale; however, the crops were still treated as "managed grasslands", and specific features of crops' physiological processes such as phenology, biomass allocation and agricultural management practices were not described when the Biome-BGC model was used at the regional scale.

Therefore, the objectives of this study are to (1) incorporate a specific agricultural module including crop phenology, biomass allocation and agricultural management practices (irrigation and fertilization) into the Biome-BGC model; (2) evaluate the performance of the enhanced Biome-BGC in simulating crop biometric variables (leaf area index, LAI, leaf and stem biomass, grain yield) and evapotranspiration (ET); and (3) apply the modified Biome-BGC to a representatively agricultural oasis in northwest China to investigate the temporal-spatial changes in NPP and ET and to estimate the contributions of the increased area in agricultural oasis, management practices and climate change on regional NPP and ET from 1971 to 2006.

2. Material and methods

2.1. Study area

This study area was in Sangonghe Catchment, a relatively isolated in land catchment with mountains, agricultural oasis and deserts in the arid region of northwestern China (Fig. 1). The agricultural oasis is called Sangonghe Oasis and is located in the north Tianshan Mountains and southern flank of Junggar Basin, with total area of approximately 942 km^2. The upper alluvial fan, at an elevation of 500–700 m, has gravelly and sandy desert soil where corn was grown, while the lower alluvial plain, at an elevation of 450–500 m, has fine-textured clay soil in which the dominant crop is winter wheat (Luo et al., 2008). The climate is extremely dry, and precipitation during the growing season was not sufficient to meet the demands of crop growth. The mean annual solar radiation was 5650 W m^{-2}, and the annual average temperature was 6.9 °C from 1971 to 2006. The mean annual precipitation was only 226 mm, while the annual potential evaporation reached 1808 mm. The old oasis is distributed along the river edge, and the newly developed oasis is converted from the shrublands or grasslands in or around the original oasis. The water withdrawn from Sangonghe River and pumped from groundwater was used for irrigation in Sangonghe Oasis (Wang et al., 2008).

2.2. Biometric measurements

Biometric data (LAI, leaf and stem biomass, and grain yield) were collected at Wulanwusu Agrometeorological Station (WAS). WAS is located in a suburb of Shihezi city (44.3°N, 85.8°E, 468.5 m a.s.l.), 180 km from Fukang city, the center of the Sangonghe Catchment (Fig. 1). Biometric measurements were taken from 1995 to 2007. The WAS site has climatic conditions similar to those of Sangonghe Oasis. The mean annual temperature was 7.5 °C, annual precipitation was 225 mm, and annual pan evaporation was 1571 mm.

LAI and biomass (fresh and dry weights) were measured from destructive plant samples. Ten winter wheat plants were harvested at four stages including turning green, elongation, heading and milk-ripe stages; additionally, five corn plants were harvested at the three-leaf, seven-leaf, elongation, heading and milk-ripe stages. The number of winter wheat and maize was counted in each LAI measured periods in a 1 m × 1 m plot. Winter wheat had a higher plant density than corn. The maximum plant density of winter wheat and corn was 1390 plants m^{-2} and 12.5 plants m^{-2}, while the minimum value was 810 plants m^{-2} and 7.5 plants m^{-2}. The dimensions (length and width) of all the leaves of the sampled plants were measured with a scale, and the total leaf area was calculated as the product of its length along the primary vein, its maximum width and a correction coefficient (0.85 for winter wheat and 0.7 for corn). The leaf area per unit of single crop (unit: m^2 $plants^{-1}$) was converted to leaf area per unit of ground area (unit: m^2 m^{-2}) by plant density (unit: plants m^{-2}). Then, the sampled plants were divided into leaves and stems (including sheaths), and were oven-dried for 8–10 h. The dry matter of the leaves and stems were weighed separately. The mature crop plants in a 5 m × 5 m plot were harvested and oven-dried for 8–10 h, and the yield was measured by weighing the dried grains.

2.3. Management practice data

The mean dates of sowing in the Sangonghe Oasis for winter wheat and corn were 21 September and 21 April, while the mean