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Simulation of the irrigation requirements for improving carbon sequestration in a rainfed cropping system under long-term fertilization on the Loess Plateau of China

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ABSTRACT

The nutrients and water supplied to rainfed agroecosystems need to be properly managed to meet food security and global warming challenges in the coming decades. A revised CENTURY model was adopted to evaluate the effects of long-term fertilization and supplemental irrigation (SI) on carbon (C) sequestration in a conventional 3-year rotation on the Loess Plateau of China (CWWM): spring corn in the first year, followed by 2 years of winter wheat, and fallow millet was sown in June of the third year. The simulation showed that grain C and soil organic C (SOC) benefited from long-term synthetic nitrogen (N) application. The contribution of this treatment to SOC accumulation was less than that of manure, but the concomitant increase in grain C was greater than that under manure treatment. Fertilization coupled with SI exerted a positive effect on grain C and SOC accumulation for both corn and wheat. The supply of 142 mm of irrigation water when the soil moisture status fell below 80% of the soil available water content (SAWC) in April for spring corn improved grain C accumulation by 33.7% compared with the control (CK); similarly, supplying 83 mm of irrigation water to winter wheat in October increased its grain C by 16.8%. Simulated SOC at the end of a 30-year period in which SI was applied once per month was higher than that obtained under SI in a single month. The highest SOC of 2256.5 g m^{-2}, 4% higher than in CK, was obtained when SI was applied during corn growing season when the soil moisture fell below 50% of the SAWC. These findings implied that irrigation should be seriously considered for improving C sequestration in rainfed agroecosystems.

1. Introduction

Carbon (C) sequestration in plants and soils not only improves soil quality due to the significant function of soil organic C (SOC) in the formation of soil structure and maintenance of microbial activity but also alleviates the greenhouse effect by reducing net anthropogenic CO_2 emissions to the atmosphere (Lal, 2004, 2011,2015). Croplands play an important role in the global C cycle and have the potential to sequester more C in the future (Van Oost et al., 2007). Thus, pursuing sustainable C sequestration strategies in an agroecosystem is essential for long-term soil sustainability and meeting ever-increasing food demands as well as mitigating CO_2-induced global warming.

Sustaining higher C sequestration in an agroecosystem is possible by increasing C inputs and reducing C losses through cropland management (Amado et al., 2006). Chemical fertilizers has been reported to provide essential nutrients for crops and to sustain higher crop productivity, thereby favoring the buildup of SOC because of enhanced belowground biomass (Blanco-Canqui and Lal, 2004; Liu and Greaver, 2009; Ren et al., 2014; Qin et al., 2015). Moreover, significant SOC increases have been observed in fields where manure is added compared to fields that receive only chemical fertilizers (Liang et al., 2012; Ren et al., 2014). However, the C benefits from crop growth and SOC accumulation may be largely offset by the emission of N_2O and CH_4 after fertilization (Liu and Greaver, 2009; Qin et al., 2015). Therefore, due to the intrinsically complex interactions among the components of an agroecosystem, it is still debated how much organic C can be stored in the soil and how well a fertilizer can be utilized to meet the demands of the crop growing season.

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Rainfed agriculture covers approximately 80% of the arable land in the world and is a major source of global food production (Oweis and Hachum, 2009). However, rainfed agriculture is often characterized by low productivity mainly due to erratic precipitation, poor soil fertility and low agricultural inputs, such as water and nutrients (Rockstrom et al., 2010; Mueller et al., 2012). The Loess Plateau (LP) is considered the cradle of agriculture in China, and rainfed agriculture remains the most widespread cropping system in the region, occupying 80% of the arable land (Huang et al., 2011). This region exhibits low soil fertility due to deep loess deposits (Xu et al., 2016; Yuan et al., 2016), and the mode of agricultural production management in the region (characterized by small-scale production, low inputs and poor water management) is not efficient (An et al., 2014). The LP has a typical continental monsoon climate, and the average annual precipitation ranges from 200 mm to 750 mm (with approximately 70% occurring from June to September) (Sun et al., 2015). Corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) are the major local food crops; however, the yields of these crops are far below the average levels of China, even though fertilizer is widely applied (Fan et al., 2005; Zhang et al., 2014b, 2016a). The shortage of plant-available soil moisture is the main reason for the low yields, due to the uneven intra-annual distribution of precipitation (Zhang et al., 2004; Guo et al., 2012). For example, winter wheat is cultivated from October to May, whereas the main rainy season on the LP is from June to September; thus, the majority of the rainfall cannot be effectively utilized by winter wheat. However, the growth of spring maize, which occurs during the rainy season, has been hampered in recent years by drought during key growth stages (Zhang et al., 2013; Wang et al., 2015). Hence, exploration of the potential benefits of water management on the LP is an emerging scientific issue.

Over the past several decades, the influences of cultivation practices and fertilization on the crop yields and water use efficiency (WUE) under various agroecological conditions on the LP have been determined (Hao et al., 2007; Zhang et al., 2014b; He et al., 2015; Eldoma et al., 2016). However, most of this knowledge was established over short periods. Although some long-term field studies have also been conducted on the LP, they were designed using similar treatments over time in terms of fertilization, rotation and conservation tillage, which limits the ability to conduct a multiple factor assessment for decision making. Ecological models allow exploratory research that can determine the sensitive responses of an ecosystem to various management strategies and optimize resource utilization. These studies can be conducted at a low costs, with quick responses. Here, the CENTURY model was selected to simulate a 3-year long-term rotation on the LP: spring corn the first year, followed by 2 years of winter wheat and fallow millet was sown in June of the third year (CWWM). The impacts of fertilization and supplemental irrigation (SI) on C sequestration of this cropping system were evaluated. The specific objectives were to (1) quantify crop C accumulation and SOC buildup in the CWWM copping system under various amounts of synthetic nitrogen (N) application and manure addition; (2) evaluate tentative SI strategies and estimate water requirements in the crop growing season; and (3) explore the optimal fertilization and SI management practices for improving the C sequestration of spring corn and winter wheat on the LP of China.

2. Materials and methods

2.1. Study site, field experiment and datasets

The long-term field experiment involving the CWWM rotation system was conducted at the State Key Agro-Ecological Experimental Station of the Chinese Academy of Sciences (35°12′N, 107°40′E) in Shilipu, Changwu County, Shaanxi Province, China. This region is a typical tableland area in the central southern part of the LP, where the elevation is 1220 m, and it is a traditional farming area with rainfed winter wheat and spring maize grain production. The climate is semi-humid with a continental monsoon. Based on the meteorological records from the Changwu station, the 59-year (1957–2015) average annual precipitation is 587.7 mm, approximately 65% of which occurs from June to September. The average annual minimum temperature varies between 3.4 °C and 5.3 °C, and the average annual maximum temperature ranges from 13.8 °C to 17.5 °C, with 59-year mean values of 4.3 °C and 15.7 °C, respectively. Historically, this region has played an important role in food production for the LP, due to its unique landform and climate. The dominant cropping system in this region is the double-crop rotation of spring maize and winter wheat with autumn forage crops.

The field experiment began in 1984 in Shilipu and was conducted by the Institute of Soil and Water Conservation of the Chinese Academy of Sciences to investigate the responses of grain production to long-term rotation and fertilization application. The original land use of the study site was spring corn and winter wheat with low-input management. The CWWM rotation was used for the long-term experimental study. In the first rotation year, spring corn was grown from April to September, and winter wheat was sown in early October and harvested in late June in the second rotation year; then, winter wheat was planted again in October and harvested in June of the third rotation year; finally, millet was planted as a fallow crop in early July and harvested in October of the third year. This experiment was replicated three times in plots with sizes of 66.95 m^{-2} (10.3 m × 6.5 m). All three plots were plowed to a depth of 20 cm after each crop harvest and left as fallow before seeding the next crop. Synthetic fertilizer in the forms of urea and calcium superphosphate was applied once at rates of 12 g m^{-2} N and 6 g m^{-2} P_2O_5-P, respectively, for each experimental plot before sowing. At the same time, organic fertilizer (cattle manure) was applied at a rate of 7.5 kg m^{-2}, with average N, P_2O_5, and K_2O concentrations of 0.26 g kg^{-1}, 0.11 g kg^{-1} and 3.6 g kg^{-1}, respectively. These fertilizers were simultaneously broadcast as basal fertilizers, and the field was then plowed to distribute the fertilizers to the subsurface. Weeds were manually removed, and herbicides or pesticides were not used during the growing season. All crops were manually harvested, and all aboveground biomass except for the stubble (stubble approximately 5 cm in height remained on the ground and was tilled into the soil in the next growing season) was removed from the plots. The soils at the study site originated from loess deposits and are classified as Calcic Kastanozem according to the FAO classification system (FAO, 2014). The soil samples collected from the top 20 cm in 1984 before planting had a bulk density of 1.32 g cm^{-3}, a field capacity of 29% and a wilting point of 11% by volume, and a pH of 8.2 and contained 6.2 g kg^{-1} SOC, 0.6 g kg^{-1} total N, and 3.1 mg kg^{-1} available phosphorus.

Grain yields and biomass were measured for each crop at the end of the growing season, and the C content was determined via the dry combustion method (Nelson and Sommers, 1996). The crop yield and C data were available from 1985 to 2014. The meteorological data for the study site were acquired from the Climatic Data Center of China (http://data.cma.cn; National Meteorological Information Center, China Meteorology Administration). The N deposition data for the study site from 1985 to 2014 were obtained from Dentener (2006). These datasets had a 2° × 2° geographic grid and comprised the monthly dry deposition and wet deposition. We extracted the data from the datasets and calculated the yearly average value for the model input. The annual atmospheric CO_2 concentration data were obtained from Dlugokencky and Tans (2017).

2.2. Model description

CENTURY is a biogeochemical ecosystem model that aims to simulate plant growth, nutrient cycling, and soil organic matter (SOM) dynamics for both natural ecosystems (grasslands and forests) and agricultural systems. The model has been widely used to evaluate the effects of climate variability and management on terrestrial C storage and was well described by Parton et al. (1987,1988). In brief, CENTURY has different plant production submodels that are linked to a common