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Modeling impacts of film mulching on rainfed crop yield in Northern China with DNDC

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ABSTRACT

Water stress is a major factor threatening agricultural production across a wide range of rainfed croplands in China. Drought threats would become worse along with climate change, especially in Northern China where the projected climate change scenarios indicated decreases in precipitation in the arid or semi-arid agricultural areas. Pilot experiments have been launched to search alternative farming management practices for adaptation of the climate change in China. Plastic film mulching (FM) has recently been tested at a number of sites in China with encouraging results although no any regional assessment has been done yet. This paper reports how we met the gap by testing a process-based, biogeochemical model, Denitrification-Decomposition or DNDC, against observations and then utilizing the model to upscale the simulations to a large region in China. DNDC was first modified by including a new module, which tracked variations of soil climate under the film mulching conditions. Two new input parameters, i.e., FM-covering fraction and duration, worked in conjunction with daily weather data to define the daily soil temperature and moisture profiles. By varying the FM coverage or duration, we could simulate a variety of FM settings and their impacts on the soil climate. A 3-year dataset of soil climate as well as crop yield measured at a rainfed corn field in Shaanxi Province in Northwestern China were used to serve the model validation tests. The measured and modeled results were in agreement with each other and both indicated that the FM practice substantially improved the soil moisture as well as the crop yield. Sensitivity tests were conducted with the revised DNDC by varying each of four factors, i.e., precipitation, temperature, soil texture and fertilizer application rate, in its range commonly observed in Northern China while keeping other input factors constant. Results from the sensitivity tests indicated that the effectiveness of FM was mainly related to precipitation. Efficiency of FM increased with decrease of precipitation. The FM effectiveness was evaluated at regional scale by linking DNDC to the databases holding spatially differentiated climate, soil and management data for all the 1.17 million ha of rainfed corn fields in the entire province of Shaanxi, across which the annual average precipitation decreased from 940 mm in the south to 390 mm in the north. Results from the regional simulation indicated that (1) corn production increased by 1.79 million tons or 16% with FM applications in the domain of Shaanxi; (2) the FM-induced increases in corn yield mainly occurred in the northern counties of the province where precipitation was lower than 700 mm; and (3) the effectiveness of FM decreased with increase in precipitation from the northern to the southern areas in the domain. The study concluded that film mulching practice could play an important role in elevating rainfed crop yields in the arid or semi-arid regions in China.

1. Introduction

Food security is one of the top priority issues for China with population more than 1.4 billion (Pingali, 2007; Khan et al., 2009). Northern China possesses 1 billion ha of arable land and produces 46% and 61% of grain and cotton, respectively, for the nation (Luo, 1994; Shangguan et al., 2001). However, a large portion of the croplands in Northern China are located within the arid or semi-arid

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climatic zones, where the annual precipitations vary between 250 and 600 mm. Only approximately 35% of the croplands have access to irrigation facilities with 65% left as rainfed lands in Northern China. Driven by the inter-annual or seasonal variations of precipitation, the upland agricultural productivity is constantly under the threat of droughts across the region (Deng et al., 2006).

Climate changes over China have been projected based on regional climate models developed by the National Climate Center/China Meteorological Administration (NCC/CMA) and the Institute of Atmospheric Physics/Chinese Academy of Sciences (IAP/CAS). The modeled results indicated that significant warming would occur in the 21st century in China, with the largest warming occurring in winter and in the northern portions of China (Joint Global Change Research Institute and Battelle Memorial Institute, 2009). Over the past 50 years, a drying trend with decrease in precipitation has been observed in the North China Plains as well the Yellow River Basin. Some of the projected climate change scenarios indicated a great variability in precipitation in Northern China (Piao et al., 2010). Faced by the possible change in climate, China has launched campaigns to investigate alternative farming management practices to maintain the crop production.

Affected by the East Asian monsoon climate, the agriculture in Northern China has long been suffering from damages caused frequent droughts. Most of the soil water received from precipitation is lost through evaporation or runoff in most upland agroecosystems in Northern China (Li and Gong, 2002). Alternative efforts have been focused on the conservation of soil water. During the past decades, a variety of water-saving measures have been tested for rainfed cropland in China, which included plastic film mulching, straw mulching, gravel mulching, conservation bench terraces, contour furrowing, strip tillage etc. Among the tested approaches, the film mulching method showed a wide range of applicability for reducing the soil evaporation to maintain optimum crop yields (Li et al., 2000b; Tian et al., 2003; Jia et al., 2006; Li et al., 2007; Wang et al., 2008). However, based on nationwide observations, the effectiveness of film mulching varied greatly in space and time (Li and Gong, 2002; Anikwe et al., 2007; Araya and Stroosnijder, 2010; Li et al., 2012). The researchers indicated that a number of factors such as climate, soil or management conditions had effects on the mulching effectiveness (Li et al., 2001; Ren et al., 2008; Zhang et al., 2011). Apparently, it is hard to tackle the complex interactions between film mulching and soil biogeochemistry at regional scale only relying on a limited number of field experiments. Process-based models are considered to be a useful tool for interpreting, integrating and extrapolating field observations gained at site scale for agroecosystems (Oron and Enthoven, 1987; Sanchez-Cohen et al., 1997; Young et al., 2002).

Upon reviewing a number of published agroecosystem models, we realized that none of the existing models was capable of simulating film mulching practice yet. However, through model comparisons, we adopted the Denitrification-Decomposition or DNDC model for our studies as it possessed a relatively complete set of soil thermo-hydraulic and biogeochemical processes, which could be used as a basis to build up the film mulching algorithms. This paper reports how we modified the DNDC model by adding the film mulching practice and linking it to the soil hydrological and biogeochemical processes and then conducted validation test and regional epscaling with the revised model.

2. Materials and methods

2.1. Field experiments

Field experiments for measuring impacts of film mulching on soil moisture and crop yield were conducted at a corn field in the Upland Experimental Station of Northwest Agricultural and Forestry University (34°10′N, 106°20′E) located in Heyang County, Shaanxi Province, China in 2008–2010. The area has an annual mean precipitation of 538.2 mm and a mean temperature of 11.5 °C with frequent droughts during 1976–2006. The local soil is classified as loam with pH 8.2, bulk density of 1.37 g cm^{-3}, field capacity of 22.5% in volume, and organic matter content of 0.007 kg C kg^{-1}.

During the 3-year experimental period, three replicate fields were planted with corn. The seasons for the single-season corn were April 25-September 8, April 24-September 12 and April 22-September 17 for 2008, 2009 and 2010, respectively. The planting density remained at 48,600 plants ha^{-1} across the years. Fertilizers were applied at rates of 230 urea-N kg ha^{-1} and 150 P_2O_5-P kg ha^{-1} at planting. The fields were totally rainfed with no irrigation. The soil was tilled to make the row ridges and furrows ten days prior to planting. The corn seeds were planted at the bottom of the furrows. Each of the fields was divided into two plots for film mulching (FM) treatment and control (Control, i.e., without film cover), respectively. Each plot (4.7 m × 4.2 m) contained four ridges and three furrows with a row spacing of 60 cm. The plastic film utilized in the experiments was transparent. As only a half of the surface of the FM plot was covered with the film, all the water from the rainfalls was able to totally enter the very plot. During the experimental periods, the temperature of the topsoil (5 cm) was measured at monthly time intervals. Soil cores (0–20 cm) were collected monthly from the plots for soil moisture measurement using the oven method. The corn yield was determined based on the grain dry matter for each plot at harvest.

Daily weather data (maximum and minimum air temperature and precipitation) were collected from a local climate station at the experimental site in 2008–2010. Based on the weather data, the annual precipitation was 451, 500 and 524 mm for 2008, 2009 and 2010, respectively. The majority of the precipitation occurred from June to September (Fig. 1). As the air temperature, precipitation, soil moisture and temperature were measured in synchronism, the experiments provided a unique dataset for model tests in the study.

2.2. DNDC modification

The DNDC model was originally developed for predicting carbon (C) sequestration in and greenhouse gas emissions from the U.S. agroecosystems (Li et al., 1992, 1994, 1996). However, during the past two decades, as more international and domestic researchers were involved in the modeling effort, DNDC has been substantially enhanced and become a generic agroecosystem model capable of simulating not only soil C and N biogeochemistry but also crop growth and soil climate for both upland and wetland ecosystems (Giltrap et al., 2010; Fumoto et al., 2008; Deng et al., 2011). DNDC consists of six sub-models for simulating soil climate, crop growth, decomposition, nitrification, denitrification and fermentation, respectively (Li, 2000a; Zhang et al., 2002b). The soil climate sub-model simulates soil temperature, moisture and redox potential profiles driven by daily weather data in conjunction with soil texture and plant demand for water. The plant growth sub-model calculates crop growth and development driven by air temperature, soil water and nitrogen availability at a daily time step. The decomposition sub-model tracks the turnover of soil organic matter that produces carbon dioxide emitted from the soil as well as inorganic nitrogen released from mineralization. The remaining three sub-models calculate trace gas emissions from nitrification, denitrification and fermentation by simulating microbial activities (Fig. 2). The six sub-models interact with each other to describe the cycles of water, carbon and nitrogen for the target ecosystem. If any change in climate, soil or management occurs, the change will simultaneously affect a series of soil environmental factors, such as temperature, moisture, redox potential, pH and substrate

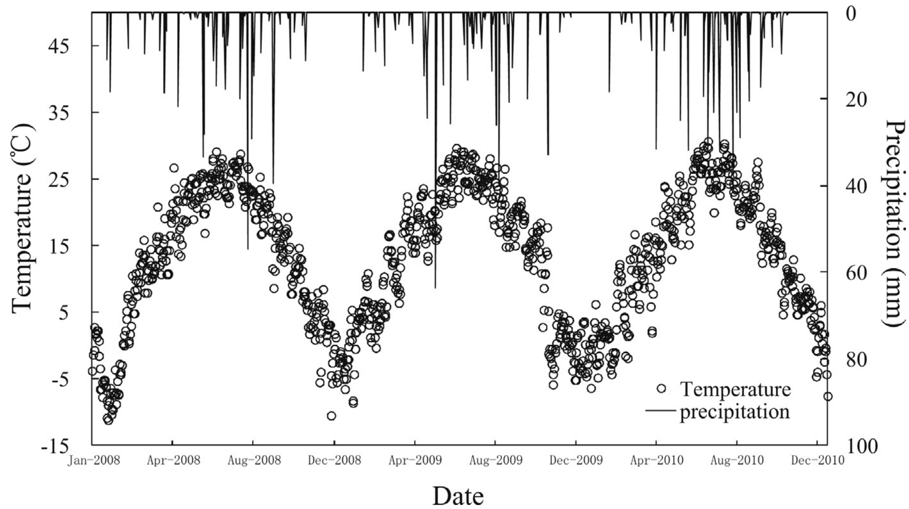

Fig. 1. Daily average air temperature and precipitation during 2008–2010 at the experiment site in Heyang Upland Experimental Station, Shaanxi, China.

concentration, and the changes in the soil environmental factors will collectively affect a group of biogeochemical reactions, such as plant growth, decomposition, nitrification, and denitrification. By integrating the interactions among the primary drivers, the soil environmental factors and the soil biogeochemical reactions, DNDC is capable of predicting impacts of climate change or management alternatives on crop yield and soil biogeochemistry.

As shown in Fig. 3, DNDC simulates interactions between crop growth and soil climate at daily time step. Driven by daily weather data (i.e., air temperature, precipitation, wind speed, etc.), DNDC first calculates daily potential evapotranspiration rate (PET) based on the Penman-Monteith Equation. Then, DNDC calculates crop demand for water (i.e., potential transpiration or PT) based on the daily crop growth rate which is quantified based on the crop physiological parameters (e.g., maximum production, biomass partitioning, water requirement index, growing stage, etc. See details in Li, 2007). If there is enough water in the soil profile, the PT will be met; otherwise, water stress will occur to reduce the daily crop production. The calculation results in actual daily transpiration (AT) based on the actual daily crop growth. DNDC then calculates potential evaporation (PE) as the difference between PET and AT. The water left in the soil will be further reduced to meet PE. Through this day-by-day calculation, DNDC precisely tracks the soil water content as well as the crop growth subject to water stress at daily time step. Equipped with the above listed functions, DNDC has been tested against a number of observations of soil water dynamics

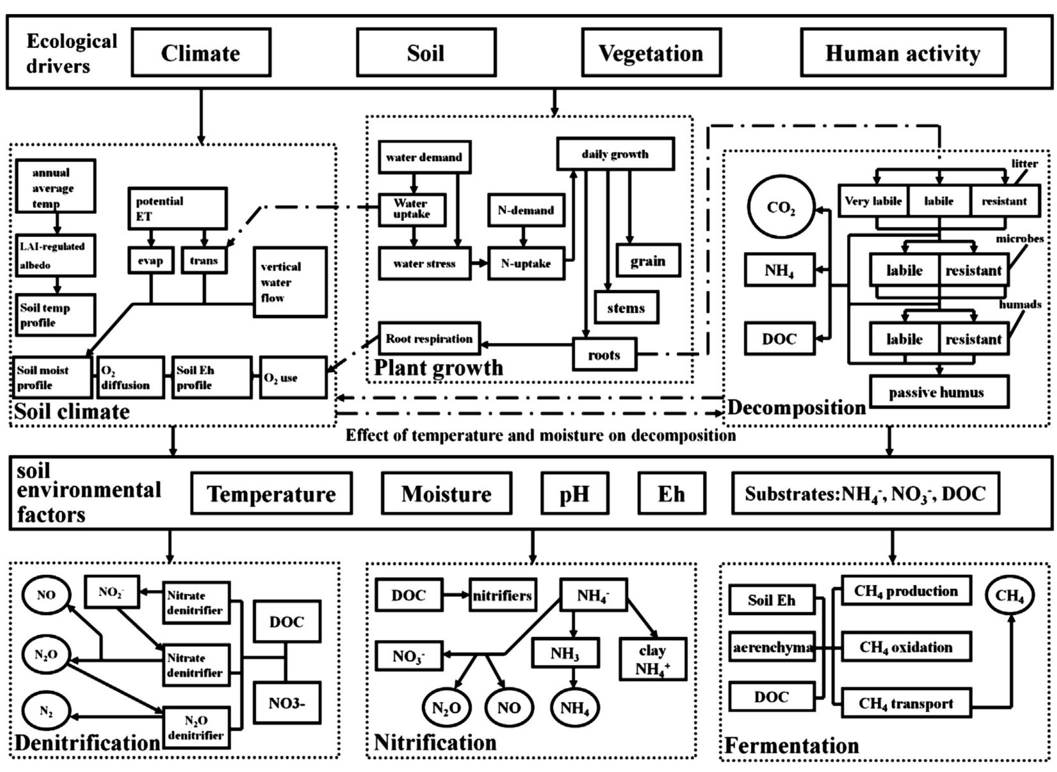

Fig. 2. Structure of the DNDC model. In DNDC, plant growth is controlled by climate, soil moisture and soil nutrient status. Soil moisture is a function of the soil water input from precipitation or irrigation and the soil water output by transpiration, evaporation and leaching. Application of film mulching will reduce soil evaporation and hence alter the soil water balance to leave more water for transpiration.

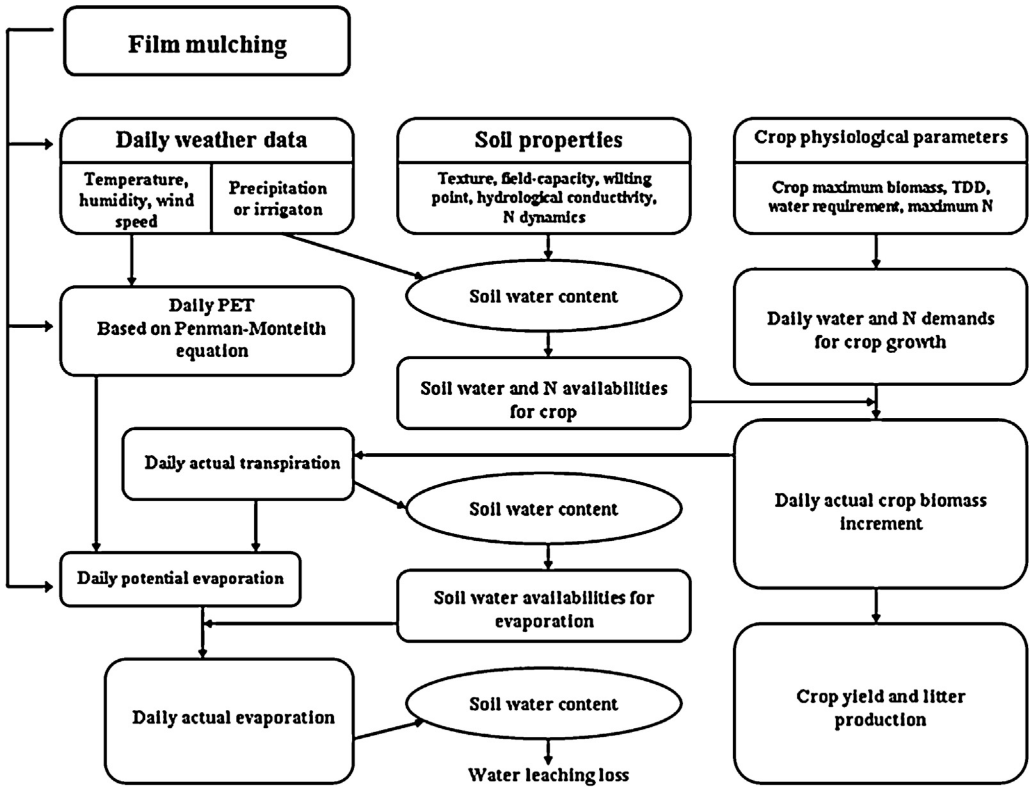

Fig. 3. DNDC-modeled interactions between soil water and crop growth. DNDC simulates interactions between soil moisture and crop growth at daily time step. Driven by the user-defined coverage and duration of film mulch, DNDC simulates impacts of the film mulching on soil temperature, wind speed, humidity and evaporation rate. Film mulching keeps more water in the soil profile, which can be used by the crop to better meet its water demand.

in U.S. cropland with encouraging results (Zhang et al., 2002a; Li et al., 2006; Tonitto et al., 2007, 2010). However, the original DNDC was lack of functions to simulate impacts of plastic film mulching practices.

To make DNDC suitable for the study focusing on film mulching (FM), we developed a new module in the DNDC framework. The new module allows the users to install film mulch (FM) in field by defining the FM coverage and duration. The revised DNDC calculates reduction of the soil evaporation as well as increase in soil temperature under the FM conditions. The effects of FM on the soil climate can be adjusted by varying the covered percent of the soil surface and/or covered time period, two input parameters defined by the users.

Given the FM coverage and duration, the module first calculates soil surface temperature under the FM conditions. In the original version of DNDC, the soil surface temperature was set equal to the air temperature because the heat exchange between the air and soil surface can quickly reach equilibrium. In the new module, when the plastic film is applied, the heat transfer between the soil surface and the air will be hindered. The new soil surface temperature will be determined by the difference between the air and soil temperatures as well as by the film thickness and thermal conductivity:

$$dH = (T_{soil} - T_{air}) * D_{film} * TC_{film} * dt \quad (1)$$

$$T_{soil} = T_{soil} + \frac{dH}{SH_{soil}}$$

where dH is heat flux (J s^{-1}) from the soil to the air through the film, T_{soil} is the soil temperature (°C), T_{air} is the air temperature (°C), D_{film} is the film thickness (m), TC_{film} is the film thermal conductivity (0.25 J s^{-1} m^{-1} °K^{-1}), dt is the unit of time (s), SH_{soil} is the soil specific heat capacity (J kg^{-1} °K^{-1}).

As soon as the soil surface temperature is determined with the new module, DNDC will continue calculating the temperatures at different depths in the soil profile (0–50 cm) based on the soil heat transfer and the soil heat conductivity (see details in Li et al., 1992).

The new module simulates impacts of FM on soil moisture by reducing soil evaporation. As the film coverage is always defined to be less than 100% that allows all the rainfall water to enter the soil. This configuration is to mimic the farmers' actual practices that collect all the water falling on the film and transfer the water to the soil through the holes or slots on the film. The framers usually realized the water saving practice by carefully bedding the field to create furrows for water collection.

Under the FM conditions, the wind speed for the soil is reduced to zero due to the film coverage. All the effects of soil temperature, water input and wind speed count in the PET calculation with the Penman-Monteith Equation and other relevant functions. In the revised DNDC, the FM coverage percent linearly affects PET. As we assume that the FM application doesn't affect transpiration (AT), soil potential evaporation (PE) is the difference between PET and AT. Actual evaporation (AE) rate is the minor between PE and soil water availability for evaporation at daily time step. Thus, counting the precipitation water conservation meanwhile the reduction of soil evaporation under the FM conditions, the revised DNDC is capable of quantifying the soil water savings to support the crop growth at daily time step (Fig. 3).

DNDC simulates crop growth based on a group of physiological parameters that define the plant growth curve affected by weather, soil and farming management conditions. These parameters include maximum crop yield, accumulative thermal degree days (TDDs), biomass partitions to grain, leaves, stems and roots, C/N ratios of grain, leaves, stems and roots, water requirement, and N fixation. DNDC provides default values of the parameters mostly based on the observations reported in North America. To make

Table 1
Crop parameters determined for the simulated corn based on calibration.

Crop parameter	Value	Note
Maximum yield	5600	kg C ha^{-1}
Biomass partitions	0.5/0.4/0.1	Grain/(leaf + stem)/root
C/N ratio	60/100/100	Grain/(leaf + stem)/root
Total N demand	149.4	kg N ha^{-1}
Thermal degree days (TDD)	3400	°C
Water requirement	100	kg water/kg dry matter
N fixation	1	
Optimum temperature	35	°C

DNDC suitable to simulate the corn planted in Northern China, we calibrated the corn parameters against measured data. The yield data measured in 2008 were utilized for the calibration, and the data of 2009 and 2010 were used for model validations. During the 2008 simulations, several of the crop parameters listed above were adjusted until the modeled crop yield and phenology were in agreement with observations. The fixed crop parameters are shown in Table 1.

2.3. DNDC validation test

Driven by daily weather data, soil properties, crop parameters and farming management practices (e.g., tillage, fertilization etc.), DNDC was run for 2009 and 2010 for all of the experimental plots with or without FM application in Heyang, Shaanxi. The modeled daily results of soil temperature and moisture as well as the crop yields were recorded for comparison with observations.

Two statistical indexes, the Nash-Sutcliffe index of model efficiency (ME) and the coefficient of determination (R^2), were employed for quantitative comparisons. ME is a measure of improvement in prediction compared with the mean of observations (Eq. (2)). A positive ME value indicates that the model prediction is better than the mean of the field, and the best model performance has a ME value equal to 1 (Nash and Sutcliffe, 1970; Miehle et al., 2006). The coefficient of determination (R^2) examines the correlation between the model predictions and field observations (Eq. (3)).

$$ME = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (2)$$

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(P_i - \bar{P})^2}} \right)^2 \quad (3)$$

where O_i and P_i are the field and modeled values, O and P are their respective averages and n is the number of values.

The field measurement data showed that, in comparison with the Control plots without FM application, the FM treatment averagely increased soil moisture by 10%, soil temperature by 1.8–1.9 °C and corn yield by 20.4% for the period of 2009–2010. The modeled results were in agreement with the measured data. The details of the comparison are summarized as follows.

During the growing seasons (late April–early September) of 2008, 2009 and 2010, the measured soil temperatures varied between 18.7 and 28.7 °C with a daily mean of 24.3 °C at the Control plots. In contrast, at the FM plots, the measured soil temperatures varied between 20.1 and 33.7 °C with a daily mean of 27.1 °C, which was 2.8 °C higher than that of the Control plots. The results from DNDC simulations for the same plots during the same time periods showed that the top soil temperatures varied between 14.5 and 31.8 °C with a mean value of 24.7 °C for the Control plots, and between 17.4 and 34.7 °C with a mean of 27.6 °C for the FM plots. The modeled soil temperatures are very close to observations regarding the seasonal patterns and magnitudes (Fig. 4). The calculated statistical indices indicate that the modeled soil temperatures are significantly correlated with observations (R^2 = 0.80, p < 0.01; ME = 0.63 for Control; and R^2 = 0.86, p < 0.01; ME = 0.75 for FM) (Fig. 5a and b).

The soil moisture data measured during the growing seasons (April–September) showed a strong correlation with the rainfall events. The measured soil moisture values in water-filled porosity (wfps) ranged from 0.23 to 0.61 with a mean of 0.42 at the Control

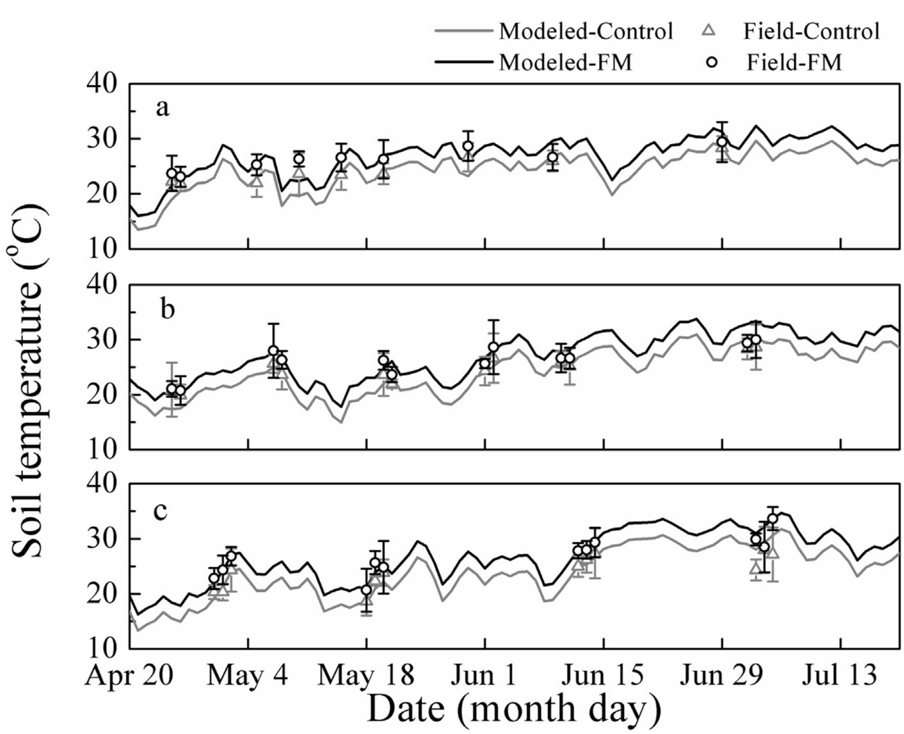

Fig. 4. Modeled and measured soil temperature at 5 cm deep in Control and FM treatments for 2008 (a), 2009 (b) and 2010 (c) (2008 data were used for model calibration).

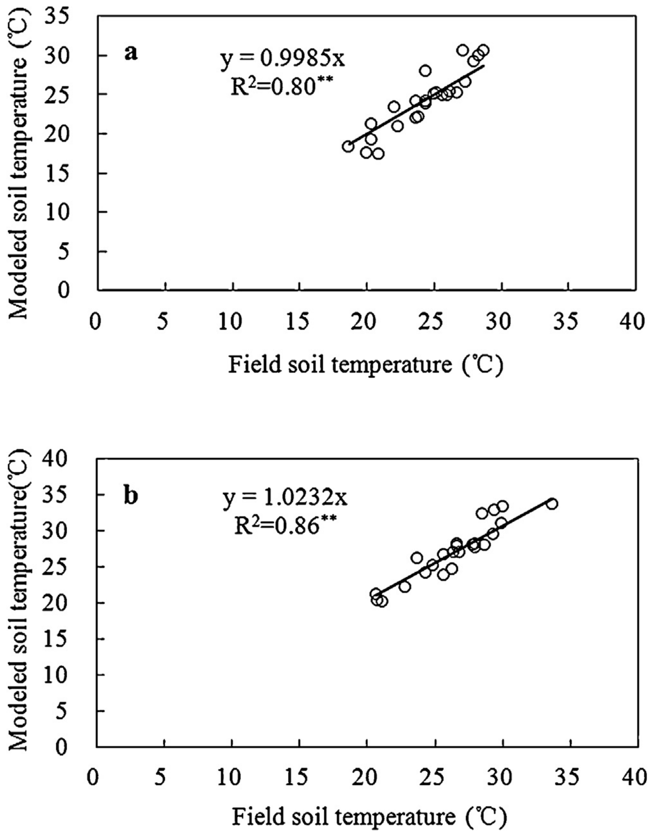

Fig. 5. Comparisons between modeled and field soil temperature at 5 cm deep in Control (a) and FM treatments (b) from 2009 to 2010. The solid lines represent the zero-intercept linear regression. Fields are the mean values of three duplicates.

plots and from 0.31 to 0.64 with a mean of 0.48 at the FM plots. The soil moisture in the FM plots was higher than that in the Control plots on average. The DNDC-simulated soil moisture ranged from 0.24 to 0.63 with a mean of 0.44 for Control, and from 0.27

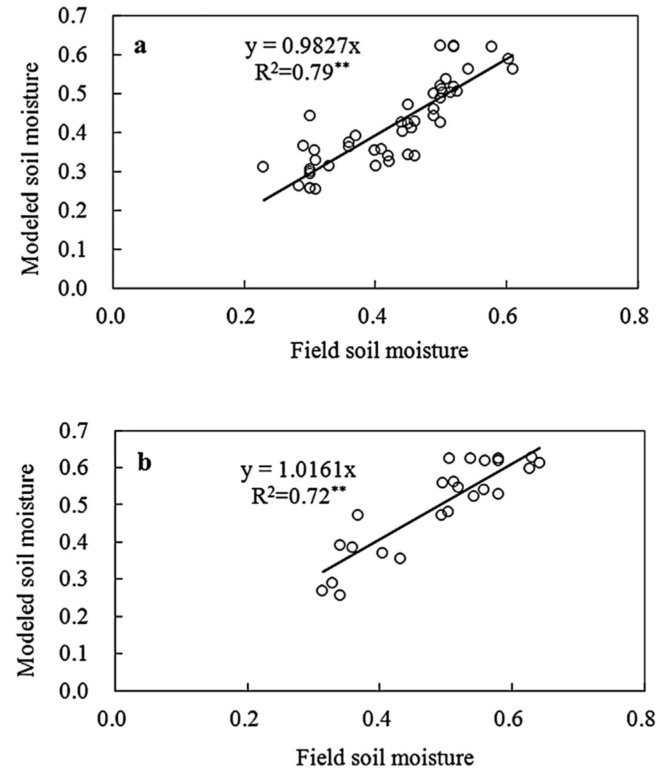

Fig. 7. Comparisons between modeled and field soil moisture at 20 cm deep in Control (a) and FM treatments (b) from 2009 to 2010. The solid lines represent the zero-intercept linear regression. Field data are the mean values of three duplicates.

to 0.64 with a mean of 0.49 for FM for 2009 or 2010 (Fig. 6). The correlation between the modeled and measured soil moisture values was statistically significant for the FM plots ($R^2 = 0.72$, $p < 0.01$; $ME = 0.65$, Fig. 7a) as well as the Control plots ($R^2 = 0.79$, $p < 0.01$; $ME = 0.70$, Fig. 7b). The modeled data showed that the decrease in soil moisture following rainfall events at the FM plots was slower

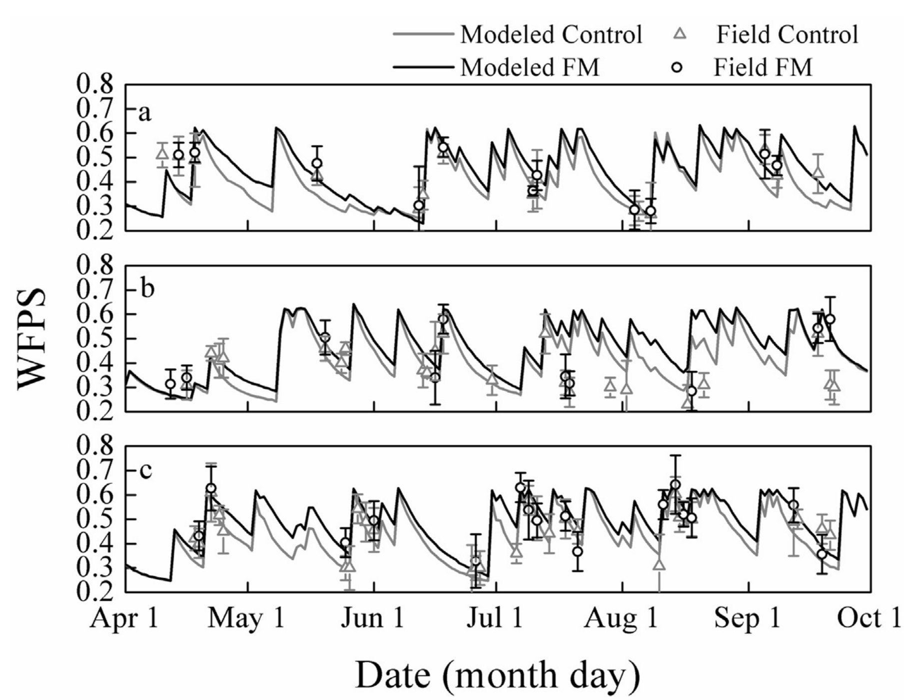

Fig. 6. Modeled and field soil moisture at 20 cm deep in Control (a) and FM treatments for 2008 (a), 2009 (b) and 2010 (c) (2008 data were used for model calibration).

Table 2
Comparisons between modeled and field yields of corn in the experimental field (Field yields are the mean values of three replicates).

Year	Field-control (kg ha^{-1})	Modeled-control (kg ha^{-1})	Field-FM (kg ha^{-1})	Modeled-FM (kg ha^{-1})
2008	10,025	10,400	12,308	13,473
2009	9785	12,955	11,463	13,580
2010	11,455	11,763	13,863	13,313
Average	10,422	11,706	12,544	13,455

than that at the Control plots that demonstrated the model capacity for capturing the effect of the plastic film on soil evaporation.

The crop yields were measured by the end of each growing season. The measured data showed that the crop yields of the FM plots were consistently higher than that of the Control plots. The increase in yield due to the FM practice was approximately 2000 kg ha^{-1} across the three experimental years (Table 2). The DNDC simulated corn yields with FM application were 3073, 625 and 1550 kg ha^{-1} higher than that without FM for 2008, 2009 and 2010, respectively. However, the modeled yields were higher than the measured yields for both the FM and Control plots. The discrepancy could be related to the insufficient processes of crop phenology embedded in the model. For example, based on field observation, a drought occurring in the spring of 2009 impeded the germination of the corn seeds while DNDC underestimated the impact of water stress on germination in the early stage of the crop development.

In summary, the revised DNDC well simulated both the soil climate and crop yield under the conditions with and without the FM practice that should have provided a decent basis for the model to apply for film mulching studies.

2.4. Sensitivity tests

DNDC simulates crop yield in a comprehensive context that include collective effects of weather, soil and farm management conditions. The modeled impacts of FM on yield will vary when any of the driving factors changes. It is crucial for applying DNDC at regional scale to understand its behaviors under varied climate, soil or management conditions. In this study, a series of sensitivity tests were conducted to investigate the general behaviors of the revised DNDC.

The experimental field in Shaanxi was selected as a target site to serve the sensitivity tests. In the tests, the baseline was set based on the actual climate, soil and management conditions at the site, and the alternative scenarios were created by varying one of four major factors potentially affecting the effectiveness of FM. The tested factors were precipitation, temperature, soil texture and fertilizer application rate. The details of the baseline and alternative scenarios are summarized in Table 3. All the baseline and alternative scenarios were simulated with and without FM for one year. Results from the sensitivity tests showed that the crop yields with and without FM had different responses to climate change. Under the baseline conditions, the crop yields with and without FM were 13,468 and 11,378 kg ha^{-1}, respectively. When precipitation was decreased by 10%, the yield with FM remained unchanged while the yield without FM decreased to 10,433 kg ha^{-1}. If the precipitation was further decreased by 20%, the yields of the FM and control were decreased by 6% (to 12,705 kg ha^{-1}) and by 17% (to 9,468 kg ha^{-1}), respectively (Table 4). Varying temperature affected the yields for both the FM and Control treatments with same trends. Like temperature, changes in soil texture or fertilizer application rate had impacts on the yields with and without FM in parallel, although the yields with FM were systematically higher than that without FM. The results implied that the modeled effectiveness of FM for the rainfed field was mainly related to precipitation across the temperature, soil texture and fertilization conditions (Table 4).

Table 3
Baseline and alternative climate, soil and management conditions for the sensitivity test for the corn field in Heyang County, Shaanxi.

Scenario	Descriptions
Control (baseline)	Climate: 2010 daily temperature and precipitation with mean annual temperature 13.6 °C and precipitation 524.3 mm Soil: loam; soil pH 8.2; bulk density 1.37 g cm^{-3}; initial SOC content 0.007 kg C kg^{-1} Crop: spring corn, planted on April 22 and harvest on September 17 Tillage: ploughing with moldboard to 20 cm depth on April 12 Fertilization: 230 kg urea-N ha^{-1} per year, no manure applied Plastic film mulch: no
FM (baseline)	Climate, soil, tillage and fertilization are same as Control Plastic film mulch: covered fraction 0.5
Change in precipitation	Decrease (PD) by 10% and 20% and increase (PI) by 10% and 20%
Change in temperature	Decrease (TD) by 1 °C and 2 °C and increase (TI) by 1 °C and 2 °C
Change in soil texture	Sandy loam (SL), silty clay loam (SCL), clay loam (CL), clay (C)
Change in fertilizer application rate	Decrease (FD) by 50, 100 and 150 kg N ha^{-1} and increase (FI) by 50, 100 and 150 kg N ha^{-1}

Based on the results of the sensitivity tests, we concluded that the FM practice could play an effective role in maintaining optimum yields against droughts across a wide range of temperature variations, soil textures or other farming management practices, such as fertilizer application. The FM-induced benefit is inherently higher for the areas with low precipitation than that with high precipitation. The modeled results are in agreement with the observations reported from other sites where film mulching was applied in China (Ren et al., 2008).

Table 4
Sensitivity test of corn yield to management alternatives for the Control and FM treatments.

Alternative management	Control yield (kg ha^{-1})	FM yield (kg ha^{-1})
Baseline	11,378	13,468
PI0.1	12,013	13,463
PI0.2	12,478	13,468
PD0.1	10,433	13,398
PD0.2	9468	12,705
TI1	10,988	13,078
TI2	11,028	12,578
TD1	11,718	13,703
TD2	11,723	13,548
SL	9893	12,618
SCL	10,308	12,338
CL	10,318	12,303
C	11,305	12,888
FI50	11,378	13,460
FI100	11,378	13,458
FI150	11,378	13,455
FD50	10,918	13,308
FD100	8948	12,525
FD150	6163	8363

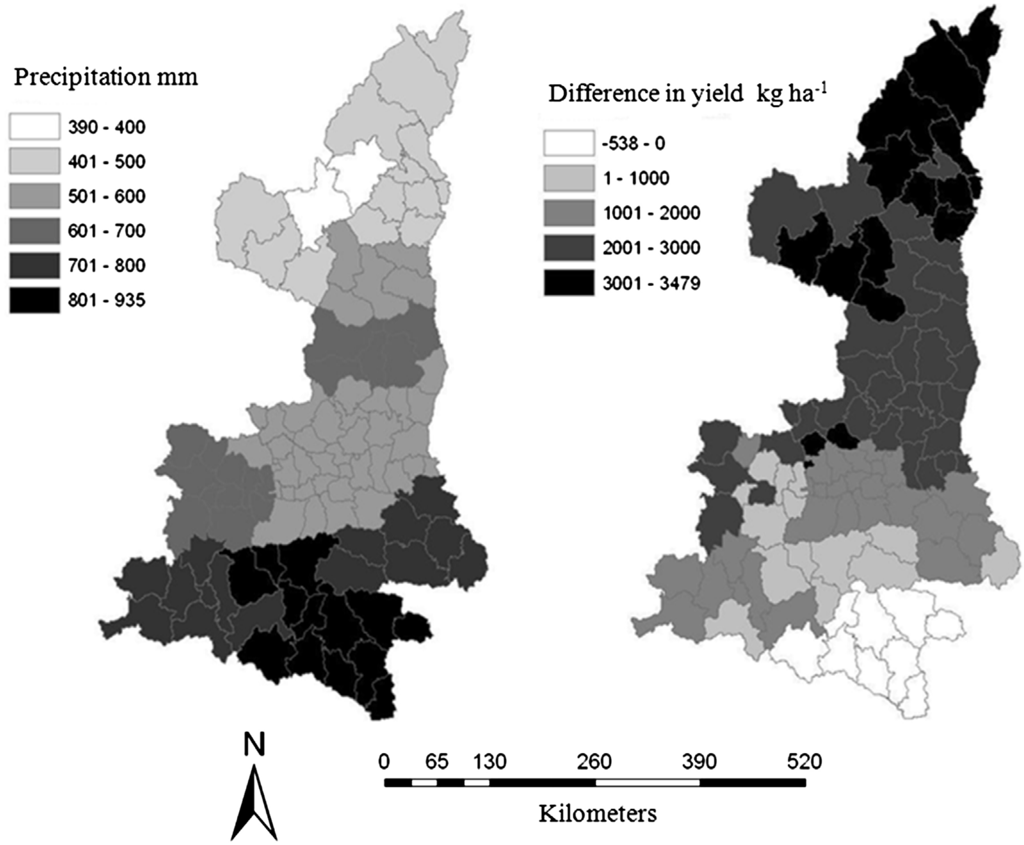

Fig. 8. Geographic distribution of average annual precipitation and difference in average annual corn yield between Control and FM treatments across Shaanxi from 2001 to 2010.

3. Upscaling with DNDC

DNDC is one of a few existing models that include both site and regional modes sharing the same suite of biogeochemical processes. This character enables us to calibrate the model at site scale and then apply it to regions. In this study, Shaanxi Province was selected as a geographic domain to estimate the impact of FM on crop yield at regional scale.

Shaanxi Province consisting of 99 counties is located in the eastern edge of Northwest China, which has been a major food producing region since the Tang Dynasty (618–907 A.D.). The province possesses three climatic zones with an obvious precipitation increasing gradient from north to south. The northern zone is located on the Loess Plateau with a typical semi-arid climate (annual precipitation 400–600 mm); the middle zone is located on the alluvial plain along the Wei River with precipitation of 500–700 mm; and the southern zone is on the southern slope of the Qin-Ling Mountains with the typical monsoonal climate (precipitation 700–900 mm). Upland cultivation is prevalent across the three climatic zones, and corn is one of the dominant crops. In the regional simulations, all the 1.2 million ha of rainfed corn fields in Shaanxi were chosen as the modeled domain. A geographic information system (GIS) database was constructed to hold the spatially differentiated data of climate, soil properties and farming management practices for the 99 counties. The climate data included daily air temperature and precipitation; the soil data contained bulk density, texture, pH and soil organic carbon (SOC) content; and the management data consisted of corn field area, tillage, fertilization and manure amendment. County was selected as the basic unit of the database. The acreage of rainfed corn fields for each county was collected from the local agricultural census. The weather data (daily maximum and minimum temperature and daily precipitation) for 2001–2010 were obtained from the Shaanxi Meteorological Administration. The soil data were extracted from the National Soil Atlas of China (1: 14,000,000, Institute of Soil Science, 1986). All of the input data required for the regional simulations are summarized in Table 5.

Linked to the database, DNDC was run for all of the rainfed corn fields in each county in Shaanxi with two alternative management scenarios, i.e., with and without film mulching (FM) practice, for 10 years (2001–2010). The average annual corn production for each county was calculated based on the modeled yields and the harvested area of the rainfed corn fields in the county. The county-level corn production data produced with and without the FM practice were utilized to assess effectiveness of FM across the entire domain.

3.1. Impacts of film mulching on regional corn production

The total corn production at the regional scale for Shaanxi was obtained by summing the county-level productions under the

Table 5
Input parameters required for regional simulation with DNDC.

Items	Input parameters
Location and climate	Longitude, latitude, rainfall N concentration
Soil properties	Maximum and minimum SOC, maximum and minimum soil texture, maximum and minimum pH, maximum and minimum bulk density
Crop parameters	Acreage, maximum yield, thermal degree days, water demand
Management practices	Planting date, harvest date, fertilizer application rate, film mulch, manure amendment, tillage, residue incorporation

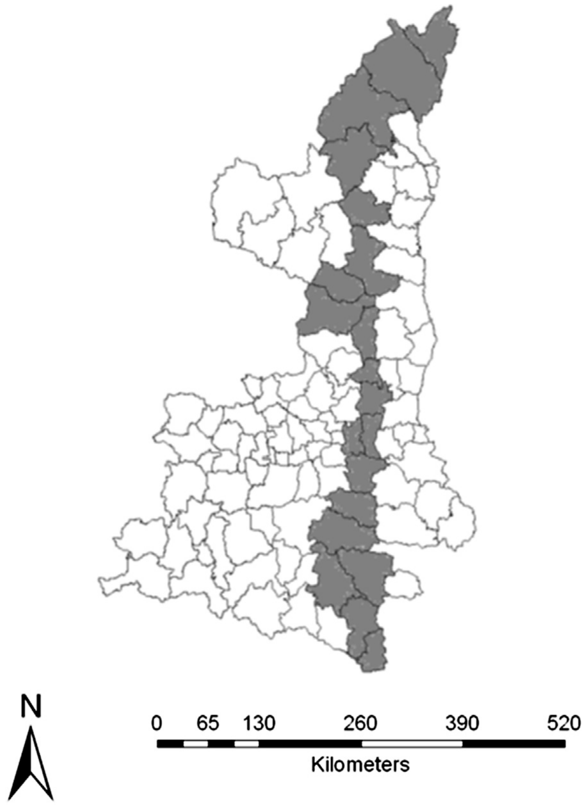

Fig. 9. Geographic distribution of 20 counties selected for analyzing temporal variations in the corn yields with and without film mulching practice in Shaanxi in 2001–2010.

management conditions with and without FM. The results indicated that the regional corn productions were 13.2 and 11.4 million tons yr^{-1} for the FM and Control scenarios, respectively. It means that the provincial corn production increased by 1.8 million tons yr^{-1} or 16% due to the application of FM for all of the rainfed corn fields within the domain. By converting the production to yield, we obtained the regional average yields as 11,671 and 9,932 kg ha^{-1} yr^{-1} for the FM and Control scenarios, respectively. The results indicate that the benefit gained with the FM application is significant.

3.2. *Spatially differentiated impacts of film mulching*

Comparing the county-level corn yields between the FM and Control, we noticed that the FM-induced benefits are highly uneven in space (Fig. 8). The mapping of the FM-induced increases in yield showed that (1) the highest benefits (yield increased by 2000–3500 kg ha^{-1}) were gained in the northern counties, where the precipitation was lower than 500 mm; (2) the benefits gradually decreased from north to south; and (3) almost no benefit was gained in the very southern counties in Shaanxi where precipitation is higher than 700 mm. The spatial pattern of the FM-induced benefits was apparently related to precipitation (Fig. 8).

3.3. *Inter-annual variation in impacts of film mulching*

Further analysis was conducted to explore the inter-annual variations of the impacts of FM on crop yield across the domain. To conduct the analysis, we set a geographic transect by selecting 20 countries located along a line from the northern border to the southern border of Shaanxi (Fig. 9). These selected counties are Fugu, Shenmu, Yulin, Hengshan, Zichang, Yanan, Ganquan, Fuxian, Luochuan, Baishui, Pucheng, Weinan, Lintong, Lantian, Zhashui, Zhenan, Xunyang, Ankang, Pingli and Zhenping from north to south (Fig. 9). The annual crop yields simulated with and without FM were compared across the counties for each year. Fig. 9 shows that all of the yields with FM were higher than that without FM for all the counties but four in the very southern part of the domain. The four counties were Xunyang, Ankang, Pingli and Zheping where the precipitation was high and the modeled yields with and without FM were almost equal. For most of the counties located in the northern and middle zones of Shaanxi, the differences in the annual yields between FM and Control gradually increased along with decrease in precipitation from south to north. The inter-annual variations in yield were higher for the northern counties, where the inter-annual variations in precipitation were also greater (Fig. 10). In the northern counties (e.g., Yulin), where average precipitation was lower than 500 mm, the droughts almost diminished the yield without the FM application in the dry years such as 2005 or 2006. The application of FM rescued the counties from the fatal hazard in the dry years. In contrast, the inter-annual variations in yield were much smaller in the southern counties, where the annual precipitation was typically higher than 700 mm, and the FM practice had less effect on the crop yield. In fact, the modeled results showed that the yields with FM were even slightly lower than that without FM. By carefully studying on the modeled data, we found that the high precipitation caused nitrogen leaching losses and hence decreased the yield in the southernmost counties. In summary, the results from the regional simulations indicated that the application of film mulching practice for the rainfed corn fields in Shaanxi increased its corn production by 16%; however, the benefits were mainly gained in the northern or middle counties with annual precipitation less than 700 mm.

4. Discussions

Modeling agricultural production is becoming an important issue in agro-ecosystem studies given the uncertainty generated by the global climate change (RÖtter et al., 2011). Predicting impacts of alternative management practices on crop yield is a challenge due to the complex interactions among climate, soil, plant and management factors. During the past decade a number of agro-ecosystem models have been developed to cope with the complex interactions. This kind of models has been utilized to assess the best management practice strategies in a range of scales from individual farms to region (Ahuja et al., 2000; Zhang et al., 2002b; Donner and Kucharik, 2003). In this study, we adopted a well documented and widely applied biogeochemical model, DNDC, to assist our evaluation on the film mulching (FM) application, one of the widely tested alternative farming management practices in China, We first modified the model by adding the FM-related algorithms and validated it against our observations. Further sensitivity tests were conducted to verify general behaviors of the revised model under varied climate, soil or management conditions. The sensitivity tests indicated that precipitation was the most sensitive factor determining the effectiveness of FM. Results from the tests indicate that the model is capable of simulating impacts of FM on rainfed crop yield in China. The goal of the validation and sensitivity tests were to assist applications of the revised DNDC at regional scale to prove or disprove the effectiveness of FM across climatic zones, soil types and management regimes. The regional results provided clear information for how to maximize the FM-induced benefit and minimize the cost by applying FM in the right areas where precipitation is marginal for agricultural production. In our case, the highest benefits of FM were gained in the northern counties, where the precipitation was lower than 500 mm. The FM method

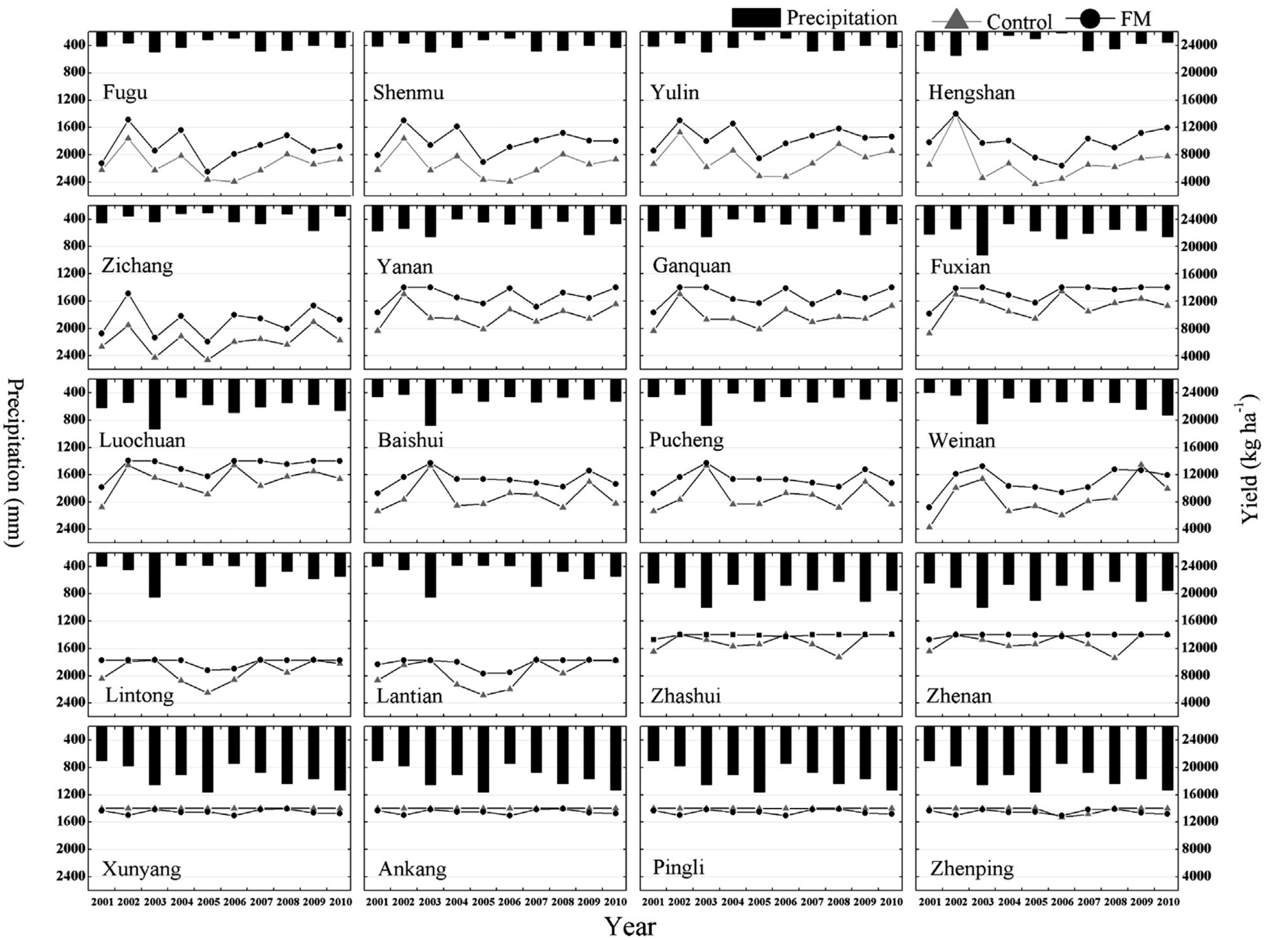

Fig. 10. Precipitation and modeled 10-years corn yields of Control and FM treatments for 20 counties in Shaanxi Province in 2001–2010.

has little effect on rainfed crop yields in the areas with abundant precipitation. The conclusion is in line with studies reported by other researchers (e.g., Araya and Stroosnijder, 2010; Wiyo et al., 2000; Jensen et al., 2003). The study reported in the paper is the first attempt to apply advanced, process-oriented models such as DNDC to predict impacts of film mulching on crop yield in China. The study has demonstrated the strength as well as weakness of the model. For example, the model appeared unsophisticated in capturing the detailed phenology, especially for the early stage of the crop growth. Further improvements are apparently required in future studies. China is faced by the challenge of feeding more than 1.4 billion people with less arable lands in comparison with the world average. A large portion of Chinese agriculture directly or indirectly relies on precipitation. Moreover, droughts have been recognized as a major hazard that damages agricultural productions almost every year in China. The significant role of water-saving system with film mulching in improving water and crop productivity in arid and semi-arid regions has been reported (Li and Gong, 2002; Wang et al., 2011; Zhou et al., 2012). However, the field experiments conducted in Northwest China indicated that in comparison with the controls, the corn yield with the film mulching practice increased by 68–71% at the site in Ningxia Province but only increased by 21–93% in Gansu Province (Wang et al., 1999; Li et al., 2001). Simulations can be a substitute for expensive and long-term field studies to evaluate effects of water-saving system in response to different seasonal rainfall patterns, soil texture and fertility levels. Faced by the ever increasing demand for sophistical tools for quantifying impacts of alternative management practices on agricultural production in China, we expect the modeling tool improved through this study will find a way to help with the sustainability of the Chinese agriculture.

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