water

MDPI

Article

Assessment of the Effect of Mulch Film on Crops in the Arid Agricultural Region of China under Future Climate Scenarios

Lu Deng [1,2,3], Xianyong Meng [4,5,*], Ruide Yu [1,*] and Qian Wang [1]

1 State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 The Institute of Economic Research, Xinjiang Uygur Autonomous Region Development and Reform Commission, Urumqi 830000, China
4 College of Resources and Environmental Science, China Agricultural University (CAU), Beijing 100094, China
5 Department of Civil Engineering, The University of Hong Kong (HKU), Pokfulam 999077, Hong Kong, China
* Correspondence: xymeng@cau.edu.cn (X.M.); ruideyu@ms.xjb.ac.cn (R.Y.)

Received: 29 July 2019; Accepted: 28 August 2019; Published: 31 August 2019

check for updates

Abstract: Plastic mulch film is widely used in agricultural production. However, there are very few studies on degradable mulch film. In order to investigate the effects of using degradable mulch film in arid regions on crop yield and water use efficiency, we used fully biodegradable mulch films on both maize and bare land cultivation experimental areas. The DeNitrification-DeComposition (DNDC) model was used to analyze changes in maize biomass in the future under different climate scenario models. We found that using fully biodegradable mulch film in an arid region had a positive effect on biomass yields. In 2015–2017, the annual maize biomass yield increased by 24.5%, 28.9%, and 32.9%, respectively. Hence, this method has expansion and promotion value. A comparison of the DNDC model simulated biomass yields and actual measured values found that the ranges of R2, root mean square error (*RMSE*), and model efficiency (*ME*) were 0.98–0.99, 0.38–0.86 mg C ha^{-1}, and 0.80–0.98. This result shows that the DNDC model can accurately simulate changes in maize biomass in this region. Under the premise of a good model fit, future climate scenario model data were used to drive the DNDC model. The results showed that the possible range of maize biomass yields in the future is −6.5% to 10.3%, with the most probable range being 0.2–1.5%. Using future climatic conditions, our work suggests that degradable mulch films can increase water use efficiency by an average of 9.5%. The results of this study can be used to promote the use of degradable mulch films in arid regions, significantly improving sustainable agricultural development.

Keywords: fully biodegradable mulch film; maize; biomass; water use efficiency; future climate scenario models

1. Introduction

Mulch film is widely used in agricultural production as it can increase soil temperature and plant productivity [1]. In particular, it is widely used in arid and semi-arid regions where water is limited to increase soil temperature, reduce evaporation, and increase crop yields [2–5]. Despite its positive effect on crop yields, plastic mulch film has poor degradability and, therefore, also causes problems like soil pollution, residual microplastics, and altered root development [6–8]. Using environmentally friendly and degradable mulch films to replace ordinary plastic mulch films is a potential technique to reduce the pollution from residual films. With the small scale of degradable mulch film application, there are few studies on it. Ren et al. [2] found that using degradable mulch films in the Loess Plateau can reduce the effects of drought on crop production. Subrahmaniyan and Zhou [9] studied the effects of different degradable mulch films on soil temperature, crop yield, and soil enzyme activities. Cirujeda et al. [10] and Weber [11] found that degradable mulch films can be used to effectively control weeds. Wang et al. [12] and Siwek et al. [13] found that degradable mulch films can be used to increase crop yields. These studies mainly employed field experiments and focused on the comparison of different types and compositions of degradable mulch films. However, it is extremely difficult to rely on short-term field experiments to systematically study the results of mulching for a long period of time.

To use the results of short-term field experimentation to determine the effect of extended use of mulch film on agricultural production. The use of the DeNitrification-DeComposition (DNDC) model can simplify the cycling processes of farmland ecosystems. The shortcomings of short durations and the difficulty in changing climate and management conditions in field experiments can be effectively overcome by inputting different meteorological data and setting management measures in the model.

Kroebel et al. [14] simulated wheat yield and soil nitrogen content in Canada by using the DNDC model. They found the model showed good simulation effects for spring wheat yield, but slightly overestimated the biomass and nitrogen absorbed by plants in the first half of the year. Borzecka-Walker et al. [15] employed the DNDC model to simulate Miscanthus yield and greenhouse gas emissions by Miscanthus plants, after calibration with onsite measurements, the model exhibits good simulation results. Gao et al. [16] employed the DNDC model to simulate the effects of using alfalfa green manure in Shanghai and found that the model can effectively simulate rice yield and methane emissions in rice cultivation. Xia et al. [17] employed the DNDC model to simulate the rice–wheat crop rotation system in the middle and lower reaches of the Yangtze River. They found that the model could effectively simulate ammonia volatilization and nitrous oxide emissions. Zhang et al. [18] employed the DNDC model to simulate a winter wheat–summer corn system in Hengshui and found that the model could very accurately simulate the changes in soil organic carbon. These studies show that the DNDC model returns good simulation results for a variety of crops. However, the measurement data from field experiments must be used to calibrate the model-related parameters before good simulation results can be obtained. In order to use this model to test the long-term effects of degradable mulch films in an arid agricultural systems, we conducted field experiments in arid regions and used the data obtained for calibration of the DNDC model-related parameters to improve the simulation accuracy. At the same time, the model output data was compared with actual measured data for validation of model simulation results.

Based on the study of Zhang et al. [19], the DNDC model can effectively simulate the effects of climate change and changes in management measures on soil carbon dynamics, emissions of small amounts of greenhouse gases, and crop biomass. Chen et al. [20] employed the DNDC model in the Loess Plateau and simulated the effects of climate change on crop yield and soil organic carbon under long-term fertilizer application conditions. Smith et al. [21] used the DNDC model in Canada to simulate the effects of future climate change on spring wheat yield and nitrous oxide emissions. He et al. [22] employed the DNDC model to predict the effects of climate change on crop yields and nitrous oxide emissions in Ontario, Canada under conventional and no-tillage conditions. Borzecka-Walker et al. [23] used the DNDC model to predict the potential productivity of Miscanthus and willow under future climate change conditions.

In order to test the fitness of the DNDC model for our system, field experiments were carried out in Changji city in the Xinjiang Uyghur Autonomous Region, China. This is an important maize cultivation region in China, and has a classic, continental arid climate with a water shortage, which is one of the important factors that limits agriculture development in this region. The use of degradable mulch film can effectively address water limitations to maize cultivation in an arid climate [2] and reduce agricultural plastic pollution. In this study, bare land cultivation was used as a control to compare the effects of using degradable mulch films that consists mainly of poly butyleneadipate-co-terephthalate

(PBAT) (>95%) on crop yields and water use efficiency. Even though the DNDC model has the capability to simulate the effects of climate change and changes in management measures on crop biomass and greenhouse gas emission, more work is needed to determine if this model is appropriate for mulch film-mediated maize cultivation in an arid environment.

On a global scale, there are many indications that climate change could result in major shifts in biomes by the turn of the century [24–26]. Therefore, climate change factors must be considered for the prediction of maize biomass. In order to assess the simulation results of the model for maize biomass in this region, measured soil and climate data were used to drive the DNDC model. The DNDC model requires temperature and precipitation parameters as input to drive it. As different climate models result in different future temperature and precipitation predictions, different climate models must be considered when driving the DNDC model. In this study, three different CMIP5 models were used to drive the DNDC model to simulate changes in maize biomass under different climate scenarios.

There are only a few studies on the effects of climate change on crop biomass under mulching conditions. In particular, there are no reports so far on the effects of climate change on crop biomass under degradable mulch film conditions. In order to investigate the simulation results of the DNDC model on maize biomass under degradable mulch film conditions, we used fully biodegradable mulch films in an important maize cultivation area of an arid region, using bare land cultivation as a control. We used the collected data to calibrate the DNDC model-related parameters and assessed the model simulation results. To make up for the deficiencies in field experiments alone, we used meteorological data under different climate scenarios to drive the DNDC model to study the effect of degradable mulch films on crop yields, as well as the interactive effect of using these films under predicted climate conditions. In summary, the main aims of this study were to: (1) conduct field experiments in this region to assess the results of using degradable mulch films on crop yields and water use efficiency, (2) collect relevant data to validate the simulation results of the DNDC model on maize biomass in this region, and (3) predict changes in maize biomass yield and water use efficiency in this region under different climate scenarios using the DNDC model system. The results of this study can be used to promote the use of degradable mulch films in arid regions, thereby bolstering the sustainable development of agriculture.

2. Materials and Methods

2.1. Field Site

The study site is located in Sanqi village, Erliugong town, Changji city, Xinjiang Uyghur Autonomous Region, China (87°13′E, 44°02′N), which has an altitude of 574 m. Figure 1 shows the specific location. The study site has a classic, continental arid climate, with cold winters and hot summers, and large diurnal temperature variation. The soil of the study site is grey desert soil. The degree of soil mellowing is poor and soil fertility is low. The experiment started in 2015 and ended in 2017. The mean annual rainfall was 174.5 mm, 187.6 mm, and 97.5 mm, and mean annual temperature was 7.8 °C, 7.1 °C, and 7.6 °C, for 2015, 2016, and 2017, respectively. Table 1 lists the basic physiochemical characteristics of the study site soils.

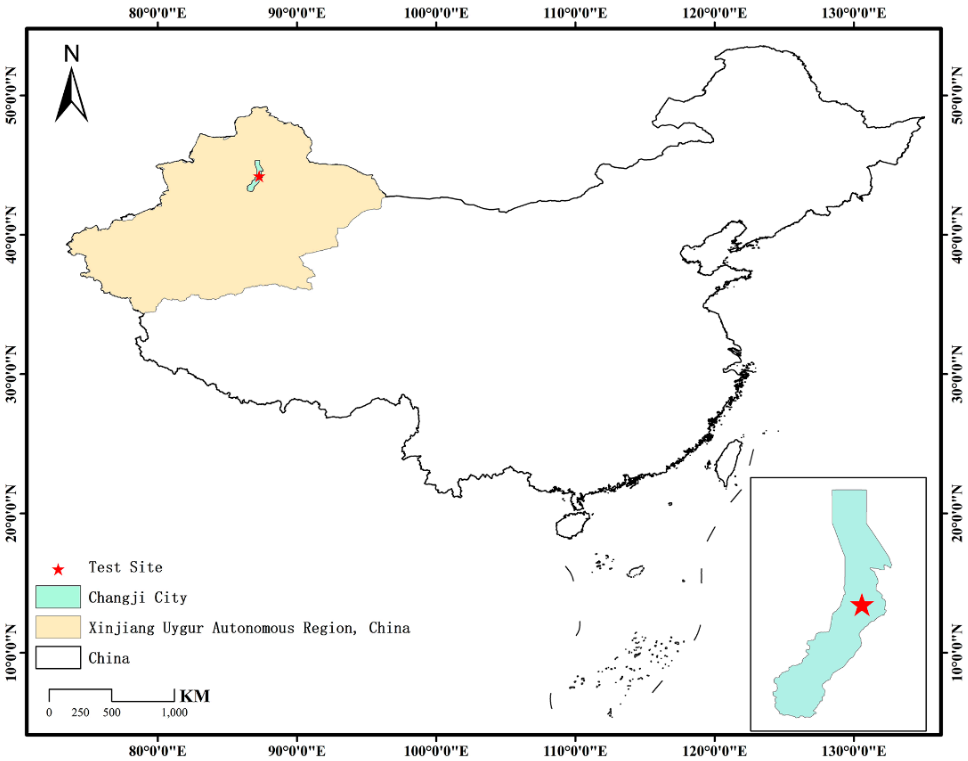

Figure 1. Map of the study site.

Table 1. Basic physiochemical characteristics of the study site soils by soil depth (mean ± standard deviation).

Soil Depth	0–20 cm	20–40 cm	40–60 cm
Organic matter (g·kg^{-1})	9.68 ± 0.37	6.00 ± 1.16	3.07 ± 0.14
Total nitrogen/(g·kg^{-1})	0.30 ± 0.02	0.21 ± 0.02	0.15 ± 0.00
Total phosphorous (g·kg^{-1})	1.07 ± 0.03	0.82 ± 0.05	0.72 ± 0.03
Total potassium (g·kg^{-1})	18.98 ± 0.44	17.54 ± 0.33	17.73 ± 0.52
Nitrate nitrogen (mg·kg^{-1})	16.41 ± 3.85	7.99 ± 2.54	4.00 ± 0.60
Ammoniacal nitrogen (mg·kg^{-1})	9.50 ± 0.66	10.57 ± 0.86	9.96 ± 0.67
Available phosphorous (mg·kg^{-1})	7.60 ± 0.51	4.46 ± 0.56	3.74 ± 0.33
Available potassium (mg·kg^{-1})	264.99 ± 27.46	234.87 ± 24.52	226.03 ± 13.71

2.2. Soil and Climate Conditions

The study site is located at a nationally important maize cultivation base in Xinjiang, accounting for 90% of the cultivation area in the Xinjiang region. Figure 2 shows the study field in test site. The cultivation status of maize in this region will directly affect maize cultivation in the entire country. From 2011 to 2017, the area of maize cultivation in Xinjiang increased from 728,000 hectares to 1,019,930 hectares and is steadily growing. In 2011–2015, the amount of plastic mulch film used in this region also increased from 18,300 tonnes to 26,900 tonnes (data from the National Bureau of Statistics of China, http://www.stats.gov.cn/). The large amounts of plastic mulch film used in this region also simultaneously result in severe residual film pollution.

Figure 2. Study site layout and sampling status.

Over the past 50 years, the annual mean air temperature and precipitation in the arid region of China (including Xinjiang, the northwestern section of Ningxia, the Hexi Corridor of Gansu Province, Qaidam Basin of Qinghai and the Alashan Plateau of Inner Mongolia) have increased by 1.5 °C and 37 mm, respectively, and this trend is predicted to continue in the future [27]. Figure 3 shows the temperature and precipitation status of the study site from 1988 to 2017.

The temperature and precipitation in this region showed a slight decreasing trend during our study period (Figure 3). Given the difficulty in accurately predicting local climatic conditions, it is necessary to examine potential changes to maize biomass yields under different climatic conditions in order to determine the effects of climate change.

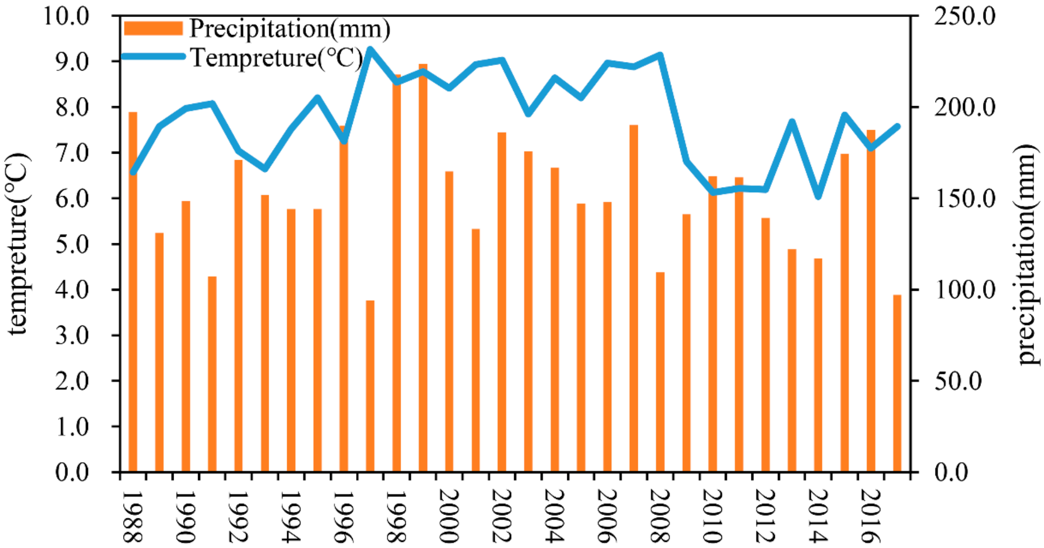

Figure 3. Annual temperature and precipitation data for the study site from 1988 to 2017.

2.3. Field Management and Experimental Design

The test crop was maize. The mulch film used was a transparent film that consisted mainly of PBAT (>95%), with a thickness of 0.010 mm. This product is completely degradable and will ultimately be converted to water and carbon dioxide. In addition, the material shows good degradability in soil [28].

We designed a randomized controlled experiment with an experimental treatment of the degradable mulch film that was applied to sample plot A, and a control treatment where no film was applied to sample plot B. Each plot was 30 m long and 20 m wide. Row spacing was 60 cm and the plant interval was 25 cm. Six replicates were used for each treatment. We applied 35 kg P ha^{-1} of diammonium phosphate as a base fertilizer to the entire study field, regardless of mulch film treatment. An all-in-one machine was used for mulching and sowing. After the seedlings emerged, any gaps were filled with seedlings to ensure a consistent rate of emergence. The test maize was sown on 27 April 2015, 25 April 2016, and 27 April 2017, and harvested on 15 September 2015, 16 September 2016, and 15 September 2017.

From after sowing until the end of August, drip irrigation was carried out at 10-day intervals. The amount of water used for irrigation was 45 mm. In the second to fifth irrigation, 50 kg N ha^{-1} of urea was applied to the soil along with the water. During the growth period, the field management measures remained identical for all treatment and control plots. At the key stages of maize growth (germination stage, seedling stage, jointing stage, heading stage, and maturation stage), a 5-point sampling method was used to collect all the maize plants in 1 m^2. Table 2 shows the specific time points.

Table 2. Maize biomass sampling time points.

Year	Germination Stage	Seedling Stage	Jointing Stage	Heading Stage	Maturation Stage
2015	27 April	29 May	21 June	25 July	4 September
2016	28 April	30 May	27 June	27 July	28 August
2017	29 April	27 May	29 June	18 July	28 August

After sampling the plant tissue, the soil, sand, and other impurities were removed. The plants were cut and dried in an oven before weighing to obtain their total biomass. The biomass per hectare was calculated.

2.4. The DeNitrification-DeComposition Model

The DNDC model (version 9.5) (Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, USA) contains six sub-models and was first used to predict greenhouse gas emissions from farmland soil [29–31]. The detailed model structure was described by Li et al. [32] and Han et al. [33]. In previous studies, this model could successfully predict changes in the yield of crops such as winter wheat, maize, and cotton, and the effect of different climate conditions on the yield [20,34]. Subsequently, this model was further improved to allow it to effectively simulate soil biochemical processes and crop yield changes under mulching conditions [33,35].

When using the model, primary parameters that need to be inputted include meteorological data (temperature and rainfall), soil parameters (soil organic carbon content, bulk density, pH, and texture), and field management measures (crop information, amount of fertilizer applied, irrigation amount, and mulch ratio). In this study, the meteorological data required for validation of the model simulation results originated from the meteorological station near the study site, while crop and farmland management data originated from measurements taken during the course of the field experiment. The 1988–2017 diurnal variation meteorological data (mean temperature and precipitation) was used to drive the model, with 1988–2017 being the model operation period. The 2015–2017 output biomass results were used to validate the simulation results of the model.

The coefficient of determination (R^2), root mean square error ($RMSE$), and model efficiency (ME) were used to validate the fit of the prediction results. The equations are shown as follows:

$$R^2 = \frac{\sum_{i=1}^{n}\left(Q_i - \overline{Q}\right)\left(P_i - \overline{P}\right)}{\sqrt{\sum_{i=1}^{n}\left(Q_i - \overline{Q}\right)^2 \sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2}}, \tag{1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - Q_i\right)^2}{n}}, \tag{2}$$

$$ME = 1 - \frac{\sum_{i=1}^{n}(P_i - Q_i)^2}{\sum_{i=1}^{n}\left(Q_i - \overline{Q}\right)^2}, \tag{3}$$

where Q is the observed value, P is the simulated value, $\overline{Q}$ is the mean of all observed values, $\overline{P}$ is the mean of all simulated values, and n is the number of observations or simulations. Under ideal circumstances, the model fit is the best when the root mean square error ($RMSE$) is equal to zero and when the coefficient of determination (R^2) and model efficiency (ME) are equal to 1.

2.5. Future Climate Scenarios

Based on the study results of He et al. [36], the Coupled Global Climate Model (CGCM3), Model for Interdisciplinary Research On Climate (MIROC5), and Norwegian Earth System Model (NorESM) can effectively simulate changes in temperature and precipitation in Xinjiang. We used three future climate scenarios (from 2018 to 2047) from the three climate models to evaluate the effect of mulching on plant biomass yields. The basic information of the study models are displayed in Table 3.

Table 3. Basic information on study models.

Climate Model	Center, Country of Model	Grid Points	Resolution
CGCM3	MRI, Japan	320 × 160	2.5 × 2.0
MIROC5	MIROC, Japan	256 × 128	2.8 × 2.8
NorESM	NCC, Norway	144 × 96	2.5 × 1.9

These study models contain three representative concentration pathway (RCP) scenarios (RCP2.6, RCP4.5, and RCP8.5). RCP2.6, RCP4.5, and RCP8.5 represent the radiative forcing of 2.6, 4.5, and 8.5 W m^{-2}, respectively, in the year 2100 (IPCC, 2013). The details of the climate models and scenarios can be obtained at http://cmip-pcmdi.llnl.gov/cmip5.

In this study, the 1988–2017 measurement data were used as the baseline meteorological data, and the 2018–2047 data under the CGCM3, MIROC5, and NorESM models were used as future climate scenario models to inform the DNDC model. Figure 4 shows the changes in temperature and precipitation (compared with the baseline) under the different climate models, highlighting The variation in temperature and precipitation predictions. Under the CGCM3 model, precipitation showed a slight decrease under the three emission concentrations, while temperature showed a slight decrease under RCP2.6 emission concentration and a slight increase under RCP4.5 and RCP8.5 emission concentrations. Under the MIROC5 model, temperature and precipitation were both increased. In particular, precipitation increases were more significant. Under the NORESM model, temperature and precipitation showed slight reductions.

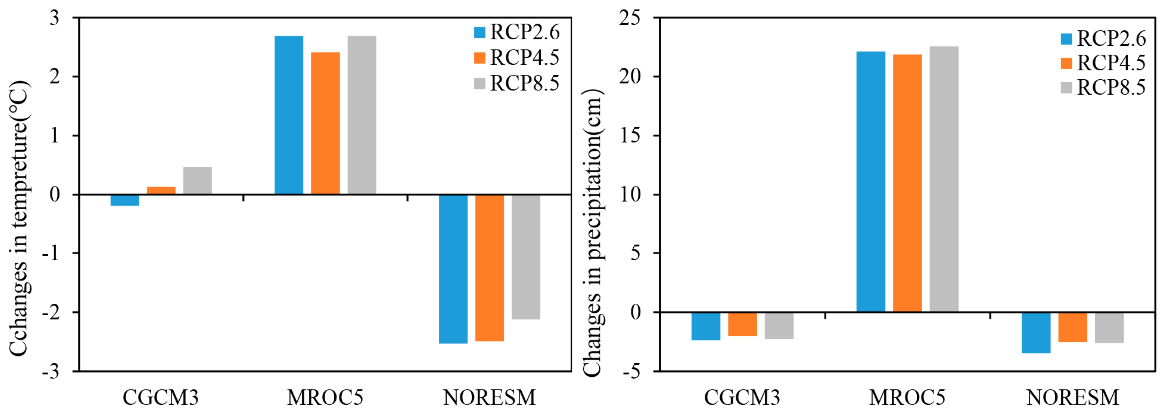

Figure 4. Changes in the temperature and precipitation predicted under different climate scenarios from 2018 to 2047 for the three climate models. RCP, representative concentration pathway.

2.6. Data and Graphics Processing

Statistical Product and Service Solutions Version13.0 (SPSS, Chicago, IL, USA) was used to process the data, while Excel (Version 2013) was used to process the graphs.

3. Results

3.1. Effect of Mulching on Maize Biomass

The results of the study showed that in 2015–2016, when degradable mulch film was used, maize biomass increases during the germination and seedling stages were not significant, but the biomass significantly increased during the jointing, heading, and maturation stages. In 2017, when degradable mulch films were used, the maize biomass increase at the germination stage was not significant, but the maize biomass increases in the seedling, jointing, heading, and maturation stages were significant ($p < 0.05$). Overall, the use of degradable mulch films can significantly increase maize biomass at later stages of plant development. Figure 5 shows specific details.

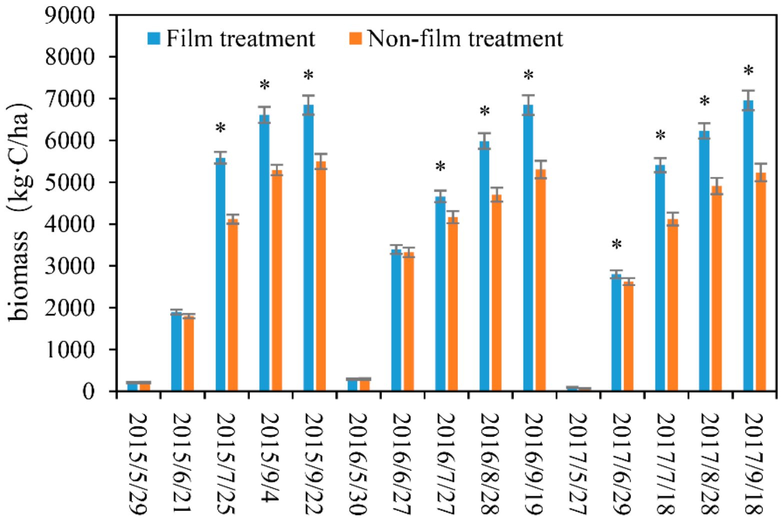

Figure 5. Biomass changes using degradable mulch film and non-filmed plots from 2015 to 2017 (* significant difference at the 5% level in plant biomass between the film treatment and non-film treatment).

The final biomass of the maize when no mulching was used was 5498.2 kg C ha^{-1}, 5304.5 kg C ha^{-1}, and 5235.5 kg C ha^{-1} for 2015, 2016, and 2017, respectively. When mulching was used, the final biomass of maize was 6845.3 kg C ha^{-1}, 6835.4 kg C ha^{-1}, and 6960.1 kg C ha^{-1} for 2015, 2016, and 2017, respectively. The relative increase in maize biomass yield when mulch film was used was 24.5%, 28.9%, and 32.9% for 2015, 2016, and 2017, respectively.

3.2. Validation of Model Simulation Results

The closer the root mean square error (*RMSE*) is to zero and the closer coefficient of determination (R^2) and model efficiency (*ME*) are to 1, the better the model simulation results. Figure 6 shows the simulation results of this experiment.

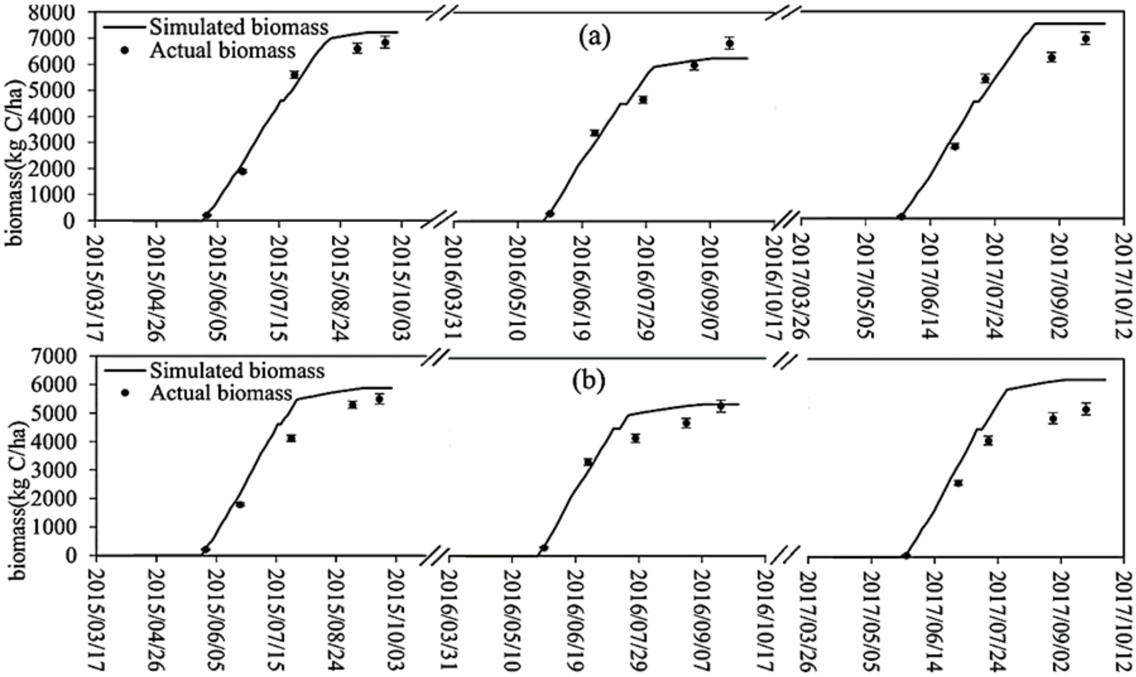

Figure 6. DeNitrification-DeComposition (DNDC) model simulation results for maize biomass under (**a**) degradable mulch film and (**b**) bare land cultivation techniques.

When mulching was used, the root mean square error (*RMSE),* the coefficient of determination*(*R^2*)* and model efficiency *(ME)* for the 2015–2017 data ranged from 0.38–0.71 mg C ha^{-1}, 0.98–0.99, and 0.92–0.98, respectively. When mulching was not used, the ranges of *RMSE*, R^2, and *ME* were 0.49–0.86 mg C ha^{-1}, 0.98–0.99, and 0.80–0.93, respectively. Overall, the model exhibits good simulation results for maize biomass yields. In fact, the simulation results were slightly better when mulch film was used than when mulching was not used. The model-simulated maize biomass relative to the measured maize biomass ranged from −17.6% to 26.40%. Under normal circumstances, the model overestimates the accumulation of maize biomass. The final biomass simulation range for maize was −8.63% to 19.67%.

3.3. Biomass Yields under Future Climate Scenario Models

Figure 7 shows that the changes in maize biomass estimated under different climate models in the DNDC model fit with our field experiment data.

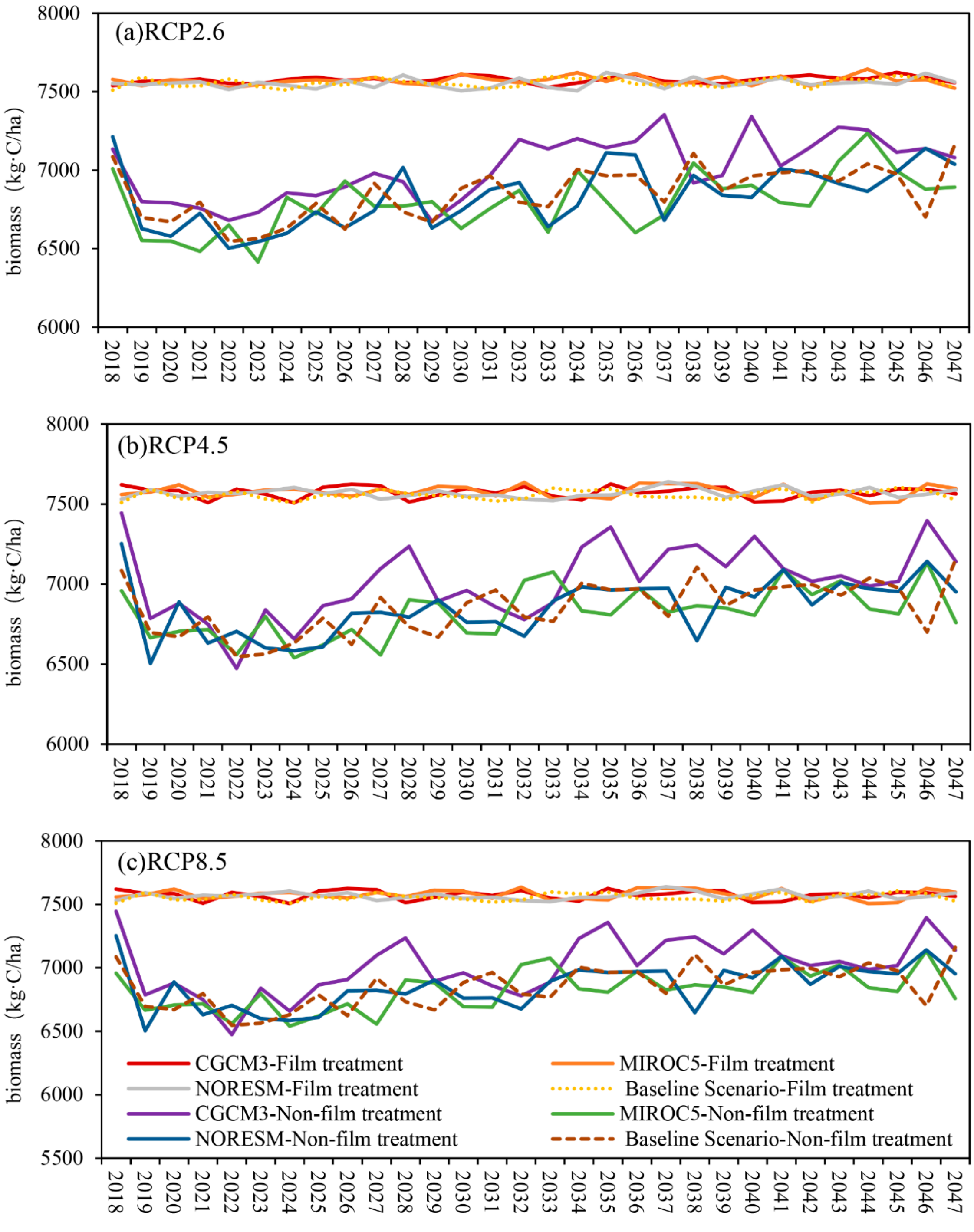

Figure 7. Maize biomass predictions for degradable mulch film and bare land treatment scenarios for 2018–2047 under three levels of emissions (**a**: RCP2.6, **b**: RCP4.5, **c**: RCP8.5).

Across the three global climate models, the DNDC model predicted that plant biomass yields would change by −1.2% to 1.7% in the mulched treatment and by −6.5% to 10.3% in the bare land cultivation, compared to the baseline scenario (Figure 7). Under the three different climate models, mulching (compared with bare land cultivation) effectively increased maize biomass yields by an average of 9.6%, with a range of increase from 2–18.18%. When mulching was used, the DNDC model predicted there would be no significant differences in biomass between the three climate models ($p < 0.05$). Under the RCP2.6 pathway when mulching was not used, there were no significant differences in predicted maize biomass between the CGCM3 and NORESM models, while maize biomass yield was increased by an average of 3.1% under the CGCM3 model compared with the MIROC5 model, and an average increase of 0.5% under the NORESM model compared with the MIROC5 model. Under the RCP4.5 pathway, maize biomass was increased by an average of 2.4% under the CGCM3 model compared with the NORESM model and decreased by an average of 0.5% under the MIROC5 model compared with the NORESM model. Under the RCP8.5 pathway, maize biomass was increased by an average of 2.5% under the CGCM3 model compared with the NORESM model and decreased by an average of 0.8% under the MIROC5 model compared with the NORESM model. Under the three different climate models, there was no significant difference in maize biomass between the different RCP pathways, regardless of whether mulching was carried out ($p < 0.05$). Based on DNDC predictions under the three climate models, when mulching was used, the standard deviation range for 30 year maize biomass was 21.9–38.8 kg C ha^{-1}. When mulching was not carried out, the standard deviation range for maize biomass was 156.9–223.3 kg C ha^{-1}. This shows that the effects of climate change on maize cultivation are lower when mulching is used. In summary, the use of degradable mulch films can increase maize biomass and simultaneously decrease the unfavorable effects caused by climate change.

4. Discussion

Mulch films have been shown to significantly increase crop yields in peanuts [27], potatoes [37], and maize [38]. In a meta-analysis of 266 papers, Gao [39] and colleagues found that mulching could significantly increase the yield of different crops, of which potatoes showed the best result, particularly in northwestern China. In summary, mulch film can be used in different regions and with different crops, but the results are different. This may be due to different climatic conditions and management measures. When there are changes in climatic conditions and management measures, the results of using mulch film may vary.

As degradable mulch films are less stable than ordinary mulch films, field experiments should be carried out at cultivation areas before mass production. These field experiments are necessary to prove the effectiveness of degradable mulch films. In this study, we conducted a 3 year field experiment in a maize cultivation and found that degradable mulch films can ultimately increase maize biomass during harvest by 1347.1 kg C ha^{-1}, 1530.9 kg C ha^{-1}, and 1724.6 kg C ha^{-1}, respectively, which was an increase of 24.5%, 28.9%, and 32.9%, respectively. Our results prove that degradable mulch films that mainly consist of PBAT have good, large scale suitability in arid regions.

The DNDC model can effectively simulate changes in biomass yield in rice [40] and spring wheat [41], maize, and other crops under different climatic conditions. The DNDC model can also effectively simulate the effects of using mulch film on biomass yield changes [33,35], but previous studies on mulch films have not considered the potential yield reduction effects of residual mulch film pollution. According to Gao et al. [39], who carried out a meta-analysis of 266 papers, crop yields will decrease when residual mulch film material reaches 240 kg ha^{-1}. Therefore, previous studies of plastic mulch films may have overestimated potential future crop yields. Previous studies linking crop yields via the DNDC model were also based on bare land cultivation or ordinary plastic mulch film. To our knowledge, there are no studies that validate the simulation results of the DNDC model using degradable mulch films. In this study, we conducted a 3 year field experiment using degradable mulch films to validate the simulation results of the model. We found that the model had good metrics of fit, including the coefficient of determination (R^2) (0.98–0.99), model efficiency *(ME)* (0.92–0.98), and a root mean square error (RMSE) within an acceptable range (0.38–0.71 mg C ha^{-1}). This shows that the model still exhibits good simulation results when degradable mulch films are used in this region.

As climate simulations remain uncertain, there is a need to examine the possible changes in maize biomass under different climate scenario models to obtain a reliable fluctuation range for future projections of maize biomass yields. Based on previous studies in the Xinjiang area, the CGCM3 and NORESM models can accurately simulate changes in temperature [36], while the MIROC5 model can predict changes in precipitation very well [42,43]. Based on the accuracy of these three climate models for our study area, we used the CGC3M, NORESM, and MIROC5 to drive the DNDC model and found that the maize biomass yield fluctuates between −6.5% and 10.3% compared to the baseline scenarios. Our simulations showed that the effects of climate change on crop yield are less severe than in the results of Smith et al. [21], which predicted climate changes to decrease crop yields. This discrepancy may be because our study site is more affected by anthropogenic effects, and maize biomass has already approached its potential production limit. Given the higher anthropogenic impacts and the highly productive crop yields already occurring in our field site, it is reasonable that the predicted effects of climate change on maize yield are relatively low.

As the simulation results of the single climate models contain uncertainty, a combination of multiple models can effectively decrease the effects of such uncertainty [44,45]. Figure 8 shows the changes in maize biomass after the three climate models were used for multi-model integration and averaging.

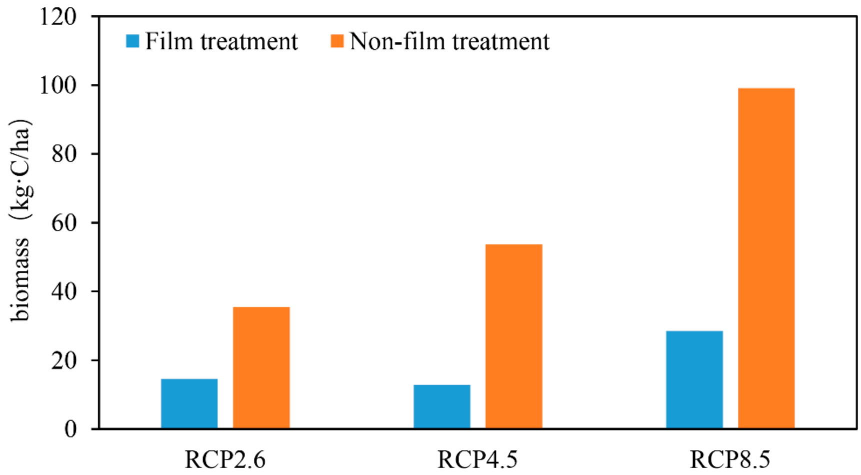

Figure 8. Changes in maize biomass under three emission pathways for average situations of the three climate scenarios.

We found that maize biomass was increased by 12.9–99.1 kg C ha^{-1} and the maize yield was increased by 5.16–39.64 kg C ha^{-1}, and the magnitude of increase was 0.2–1.5%. Therefore, future climate change in this region may cause maize biomass to increase, which is consistent with the findings of Wang et al. [46]. When mulch film was used under the three future climate models, the magnitude of increase in maize biomass is less than when no mulching was used. This may be because maize yield is already very high when mulching is used, and the potential yield increase is relatively low.

The study site is in an arid region, and the mean annual precipitation from 2015 to 2017 was 153.2 mm. Water shortage is the main factor limiting agricultural production in this region. Importantly, the use of degradable mulch films can significantly increase water use efficiency and does not cause pollution. The formula for calculating water use efficiency is: water use efficiency = grain yield (kg·ha^{-1})/total water consumed (mm). Total water consumed is the sum of the irrigation volume and rainfall, of which irrigation volume is around 550 mm per year, while rainfall in the precipitation data is the integration and averaging of multiple models. Figure 9 shows the water use efficiency of maize under future climate conditions. With mulching and bare land cultivation conditions, the water use efficiency of maize was 9.94–9.99 kg C ha^{-1}/mm and 9.07–9.12 kg C ha^{-1}, respectively. The use of mulching can increase water use efficiency by an average of 9.5% while simultaneously increasing yield. Agricultural water usage accounted for more than 90% of water use in this region. Hence, the use of mulch films to increase water use efficiency has significance for the sustainable development of local agriculture.

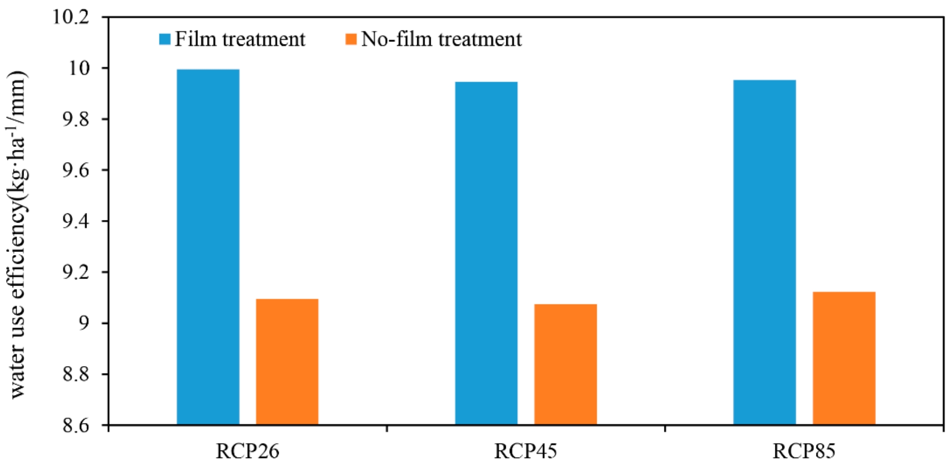

Figure 9. Water use efficiency under three emission pathways for average situations of the three climate scenarios.

In this study, we measured the effect of using degradable mulch films on maize production in the Xinjiang region. We then used our experimental data to validate the simulation results of the DNDC model. On the basis of model validation, we predicted changes in maize biomass under future climate scenario models. However, we did not examine the effects of fertilizer application volume and irrigation volume on maize biomass, which will be examined in future studies in order to identify the most rational cultivation method.

5. Conclusions

After using fully biodegradable mulch films in a 3 year field experiment and employing the DNDC model to predict changes in maize biomass under future climate scenarios, we came to the following conclusions:

(1) When compared to bare land cultivation, the use of degradable mulch films can effectively increase maize biomass, supporting the adoption of this technique over a larger area.

(2) A comparison of simulation data and measurement data showed that the DNDC model can effectively simulate changes in maize biomass for bare land cultivation and mulch film practices were used. This validates the effectiveness of the DNDC model for this region, and proves that this model can be used for prediction of maize biomass.

(3) We predicted changes in maize biomass under different climate models and obtained a range of possible variation for maize biomass. In addition, we found that future climatic conditions may cause a slight increase in maize yield, regardless of the mulch films being used.

(4) Under future climatic conditions, using degradable mulch films can effectively increase water use efficiency. Through field experiments and model predictions, we found that degradable mulch films show good application effects in this region. However, we did not examine the effects of different nutrient management measures on maize biomass, which will be the logical direction for further studies.

Author Contributions: L.D. wrote the manuscript and analyzed the data. X.M., R.Y., and Q.W. contributed to discussing the results. All authors reviewed the manuscript.

Funding: This work was financially joint supported by the Impact Assessment of Biodegradable Plastic Film on Soil Environment funded by Science and Technology Department of Xinjiang Uygur Autonomous Region under Grant number 2016B02017-4 and West Light Foundation of The Chinese Academy of Sciences under Grant number 2017-XBQNXZ-B-014.

Acknowledgments: Special thanks to the anonymous reviewers for their invaluable comments and the work of editor, which have led to a significant improvement of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kasirajan, S.; Ngouajio, M. Polyethylene and biodegradable mulches for agricultural applications: A review. *Agron. Sustain. Dev.* **2012**, *32*, 501–529. [CrossRef]
2. Ren, X.L.; Zhang, P.; Chen, X.L.; Jia, Z.K. Impacts of ridge-furrow rainfall concentration systems and mulches on corn growth and yield in the semiarid region of China. *J. Sci. Food Agric.* **2016**, *96*, 3882–3889. [CrossRef] [PubMed]
3. Lu, X.; Li, Z.; Bu, Q.; Cheng, D.; Duan, W.; Sun, Z. Effects of Rainfall Harvesting and Mulching on Corn Yield and Water Use in the Corn Belt of Northeast China. *Agron. J.* **2014**, *106*, 2175–2184. [CrossRef]
4. Bu, L.D.; Liu, J.L.; Zhu, L.; Luo, S.S.; Chen, X.P.; Li, S.Q.; Hill, R.L.; Zhao, Y. The effects of mulching on maize growth, yield and water use in a semi-arid region. *Agric. Water Manag.* **2013**, *123*, 71–78. [CrossRef]
5. Liu, C.A.; Zhou, L.M.; Jia, J.J.; Wang, L.J.; Si, J.T.; Li, X.; Pan, C.C.; Siddique, K.H.M.; Li, F.M. Maize yield and water balance is affected by nitrogen application in a film-mulching ridge–furrow system in a semiarid region of China. *Eur. J. Agron.* **2014**, *52*, 103–111. [CrossRef]
6. Qian, H.; Meng, Z.; Liu, G.; Lu, T.; Qu, Q.; Du, B.; Pan, X. Effects of Soil Residual Plastic Film on Soil Microbial Community Structure and Fertility. *Water Air Soil Pollut.* **2018**, *229*, 261. [CrossRef]
7. Yang, N.; Sun, Z.X.; Feng, L.S.; Zheng, M.Z.; Chi, D.C.; Meng, W.Z.; Hou, Z.Y.; Bai, W.; Li, K.Y. Plastic Film Mulching for Water-Efficient Agricultural Applications and Degradable Films Materials Development Research. *Adv. Manuf. Processes* **2015**, *30*, 143–154. [CrossRef]
8. Kyrikou, I.; Briassoulis, D. Biodegradation of Agricultural Plastic Films: A Critical Review. *J. Polym. Environ.* **2007**, *15*, 125–150. [CrossRef]
9. Zhou, K.S.W. Soil Temperature Associated with Degradable, Non-Degradable Plastic and Organic Mulches and Their Effect on Biomass Production, Enzyme Activities and Seed Yield of Winter Rapeseed. *J. Sustain. Agric.* **2008**, *32*, 611–627.
10. Cirujeda, A.; Aibar, J.; Anzalone, Á.; Martín-Closas, L.; Meco, R.; Moreno, M.M.; Pardo, A.; Pelacho, A.M.; Rojo, F.; Royo-Esnal, A.; et al. Biodegradable mulch instead of polyethylene for weed control of processing tomato production. *Agron. Sustain. Dev.* **2012**, *32*, 889–897. [CrossRef]
11. Weber, C.A. Biodegradable mulch films for weed suppression in the establishment year of matted-row strawberries. *Horttechnology* **2003**, *13*, 665–668. [CrossRef]
12. Qi, W.; Song, X.; Li, F.; Hu, G.; Liu, Q.; Zhang, E.; Wang, H.; Davies, R. Optimum ridge–furrow ratio and suitable ridge-mulching material for Alfalfa production in rainwater harvesting in semi-arid regions of China. *Field Crop. Res.* **2015**, *180*, 186–196.
13. Siwek, P.; Domagala-Swiatkiewicz, I.; Kalisz, A. The influence of degradable polymer mulches on soil properties and cucumber yield. *Agrochimica* **2015**, *59*, 108–123.
14. Kröbel, R.; Smith, W.N.; Grant, B.B.; Desjardins, R.; Campbell, C.; Tremblay, N.; Li, C.; Zentner, R.; McConkey, B. Development and evaluation of a new Canadian spring wheat sub-model for DNDC. *Can. J. Soil Sci.* **2017**, *4*, 503–520. [CrossRef]
15. Borzecka-Walker, M.; Faber, A.; Syp, A.; Pudelko, R.; Mizak, K. Simulation of greenhouse gases from miscanthus cultivation in Poland using the DNDC model. *J. Food Agric. Environ.* **2012**, *10*, 1187–1190.
16. Gao, X.Y.; Yuan, S.L.; Ai-Min, L.V.; Zhou, P.; Yuan, A.N. Effects of alfalfa green manure on rice production and greenhouse gas emissions based on a DNDC model simulation. *Acta Prataculturae Sin.* **2016**, *12*, 14–26.
17. Xia, W.; Zhou, W.; Liang, G.; Wang, X.; Sun, J.; Liu, D.; Li, S. Evaluating the validity and sensitivity of the DNDC model to estimate nitrogen cycling in rice-wheat rotation system. *Plant Nutr. Fertil. Sci.* **2012**, *18*, 77–88.
18. Zhang, J.; Hu, K.; Li, K.; Zheng, C.; Li, B. Simulating the effects of long-term discontinuous and continuous fertilization with straw return on crop yields and soil organic carbon dynamics using the DNDC model. *Soil Till Res.* **2017**, *165*, 302–314. [CrossRef]
19. Yu, Z.; Li, C.; Zhou, X.; Iii, B.M. A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture. *Ecol. Model.* **2002**, *151*, 75–108.
20. Chen, H.; Ying, Z.; Hao, F.; Li, H.; Sun, B. Assessment of climate change impacts on soil organic carbon and crop yield based on long-term fertilization applications in Loess Plateau, China. *Plant Soil* **2015**, *390*, 401–417. [CrossRef]

21. Smith, W.N.; Grant, B.B.; Desjardins, R.L.; Kroebel, R.; Li, C.; Qian, B.; Worth, D.E.; McConkey, B.G.; Drury, C.F. Assessing the effects of climate change on crop production and GHG emissions in Canada. *Agric. Ecosyst. Environ.* **2013**, *179*, 139–150. [CrossRef]
22. He, W.; Yang, J.Y.; Drury, C.F.; Smith, W.N.; Grant, B.B.; He, P.; Qian, B.; Zhou, W.; Hoogenboom, G. Estimating the impacts of climate change on crop yields and N_2O emissions for conventional and no-tillage in Southwestern Ontario, Canada. *Agric. Syst.* **2017**, *159*, 187–198. [CrossRef]
23. Borzęcka-Walker, M.B.; Faber, A.; Kozyra, J.; Pudełko, R.; Mizak, K.; Syp, A. Modelling the impact of climate change on miscanthus and willow for their potential productivity in Poland. *J. Food Agric. Environ.* **2012**, *10*, 1437–1440.
24. Tebaldi, C.; Hayhoe, K.; Arblaster, J.M.; Meehl, G.A. Going to the Extremes: An Intercomparison of Model-Simulated Historical and Future Changes in Extreme Events. *Clim. Chang.* **2006**, *79*, 233–234. [CrossRef]
25. Oreskes, N. The scientific consensus on climate change. *Science* **2005**, *306*, 1686. [CrossRef] [PubMed]
26. Bergengren, J.C.; Waliser, D.E.; Yung, Y.L. Ecological sensitivity: A biospheric view of climate change. *Clim. Chang.* **2011**, *107*, 433. [CrossRef]
27. Liu, J.; Du, H.; Wu, Z.; He, H.S.; Wang, L.; Zong, S. Recent and future changes in the combination of annual temperature and precipitation throughout China: Changes in the Combination of Temperature and Precipitation over China. *Int. J. Climatol.* **2017**, *37*, 821–833. [CrossRef]
28. Weng, Y.X.; Jin, Y.J.; Meng, Q.Y.; Wang, L.; Zhang, M.; Wang, Y.Z. Biodegradation behavior of poly (butylene adipate-co-terephthalate) (PBAT), poly (lactic acid) (PLA), and their blend under soil conditions. *Polym. Test.* **2013**, *32*, 918–926. [CrossRef]
29. Changsheng, L.I.; Frolking, S.; Frolking, T.A. A model of nitrous oxide evolution from soil driven by rainfall events. I—Model structure and sensitivity. II—Model applications. *J. Geophys. Res. Atmos.* **1992**, *97*, 9777–9783.
30. Li, H.; Wang, L.; Li, J.; Gao, M.; Zhang, J.; Zhang, J.; Qiu, J.; Deng, J.; Li, C.; Frolking, S. The development of China-DNDC and review of its applications for sustaining Chinese agriculture. *Ecol. Model.* **2017**, *348*, 1–13. [CrossRef]
31. Zhang, Y.; Niu, H. The development of the DNDC plant growth sub-model and the application of DNDC in agriculture: A review. *Agric. Ecosyst. Environ.* **2016**, *230*, 271–282. [CrossRef]
32. Li, C.; Frolking, S.; Harriss, R. Modeling carbon biochemistry in agricultural soils. *Glob. Biogeochem. Cy.* **1994**, *8*, 237–254. [CrossRef]
33. Han, J.; Jia, Z.; Wu, W.; Li, C.; Han, Q.; Zhang, J. Modeling impacts of film mulching on rainfed crop yield in Northern China with DNDC. *Field Crop. Res.* **2014**, *155*, 202–212. [CrossRef]
34. Yu, Y.; Hui, T.; Yao, H.; Zhao, C. Assessment of the effect of plastic mulching on soil respiration in the arid agricultural region of China under future climate scenarios. *Agric. For. Meteorol.* **2018**, *256*, 1–9. [CrossRef]
35. Zhang, F.; Zhang, W.; Li, M.; Zhang, Y.; Li, F.; Li, C. Is crop biomass and soil carbon storage sustainable with long-term application of full plastic film mulching under future climate change? *Agric. Syst.* **2017**, *150*, 67–77. [CrossRef]
36. He, Q.; Yuan, Y.J.; Zhao, Y.; Yang, L.M. *Investigation on Climate Change in Central Asia*; Meteorological Press: Beijing, China, 2015.
37. Qiang, L.; Li, H.; Zhang, S. Yield and water use efficiency of dryland potato in response to plastic film mulching on the Loess Plateau. *Acta Agric. Scand. Sect. B Soil Plant Sci.* **2018**, *68*, 175–188.
38. Wang, Y.P.; Li, X.G.; Zhu, J.; Fan, C.Y.; Kong, X.J.; Turner, N.C.; Siddique, K.H.M.; Li, F.M. Multi-site assessment of the effects of plastic-film mulch on dryland maize productivity in semiarid areas in China. *Agric. For. Meteorol.* **2016**, *220*, 160. [CrossRef]
39. Gao, H.; Yan, C.; Liu, Q.; Ding, W.; Chen, B.; Li, Z. Effects of plasticmulching and plastic residue on agricultural production: A meta-analysis. *Sci Total Environ.* **2019**, *651*, 484–492. [CrossRef]
40. Fumoto, T.; Hasegawa, T.; Cheng, W.; Hoque, M.M.; Yamakawa, Y.; Shimono, H.; Kobayashi, K.; Okada, M.; Li, Z.; Yagi, K. Application of a process-based biogeochemistry model, DNDC-Rice, to a rice field under free-air CO2 enrichment (FACE). *J. Agric. Meteorol.* **2013**, *69*, 173–190. [CrossRef]

41. Sansoulet, J.; Pattey, E.; Kröbel, R.; Grant, B.; Smith, W.; Jégo, G.; Desjardins, R.L.; Tremblay, N.; Tremblay, G. Comparing the performance of the STICS, DNDC, and DayCent models for predicting N uptake and biomass of spring wheat in Eastern Canada. *Field Crop. Res.* **2014**, *156*, 135–150. [CrossRef]
42. Ta, Z.; Yu, Y.; Sun, L.; Chen, X.; Mu, G.; Yu, R. Assessment of Precipitation Simulations in Central Asia by CMIP5 Climate Models. *Water* **2018**, *10*, 1516. [CrossRef]
43. Yu, X.J.; Zhao, Y.; Ma, X.J.; Yao, J.Q.; Li, H.J. Projected changes in the annual cycle of precipitation over central Asia by CMIP5 models. *Int. J. Climatol.* **2018**, *38*, 5589–5604. [CrossRef]
44. Jeong, H.I.; Lee, D.Y.; Ashok, K.; Ahn, J.B.; Lee, J.Y.; Luo, J.J.; Schemm, J.K.; Hendon, H.H.; Braganza, K.; Ham, Y.G. Assessment of the APCC coupled MME suite in predicting the distinctive climate impacts of two flavors of ENSO during boreal winter. *Clim. Dyn.* **2012**, *39*, 475–493. [CrossRef]
45. Kripalani, R.H.; Oh, J.H.; Chaudhari, H.S. Response of the East Asian summer monsoon to doubled atmospheric CO2: Coupled climate model simulations and projections under IPCC AR4. *Theor. Appl. Climatol.* **2007**, *87*, 1–28. [CrossRef]
46. Wang, J.; Mendelsohn, R.; Dinar, A.; Huang, J.; Rozelle, S.; Zhang, L. The impact of climate change on China's agriculture. *Agric. Econ.* **2010**, *40*, 323–337. [CrossRef]