agronomy

MDPI

Article

Is Cattle Manure Application with Plastic-Film Mulch a Good Choice for Potato Production?

Chaobiao Meng [1], Fengxin Wang [1,*], Bernard A. Engel [2], Kaijing Yang [1] and Youliang Zhang [3]

1 Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China; cau-mcb@cau.edu.cn (C.M.); 18810552168@163.com (K.Y.)
2 Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907, USA; engelb@purdue.edu
3 College of Hydraulic Energy and Power Engineering, Yangzhou University, Yangzhou 225009, China; youliangzhang@yzu.edu.cn
* Correspondence: fxinwang@cau.edu.cn; Tel.: +86-1364-123-2337

Received: 18 July 2019; Accepted: 9 September 2019; Published: 11 September 2019

Abstract: Using manure in potato production has been considered for its potential environmentally friendly effects. Two years of field experiments were conducted to evaluate the effects of different kinds of fertilizer and soil surface treatments on potato growth. Experimental treatments consisted of three soil surface treatments, including black plastic-film mulch (BM), transparent film-plastic mulch (TM), and non-mulched (NM) treatment, and two fertilizer treatments, including inorganic fertilizer (IF), and cattle manure (CM). The results showed that low environmental temperatures at early growth stages harmed potato growth. The more suitable hydrothermal environment under BM treatment induced 9–67%, 1–223%, 15–30%, −1–11% and 18–34% greater plant height, leaf area index (LAI), tuber yield, crop evapotranspiration (ETc) and water use efficiency (WUE), respectively, than NM and TM treatments. Plastic-film mulch increased soil carbon dioxide concentration, especially for the TM treatment. With low soil nitrogen content during the whole growth stage, and high soil carbon dioxide concentration during sprout and seedling stages, the CM treatment reduced plant height, LAI, tuber yields, ETc and WUE by 27–155%, 2–96%, 6–23%, 2–6% and 8–25%, respectively. These results suggest that inorganic fertilizer with black plastic-film mulch is still the best choice for potato production, and further studies are needed to identify the best level of cattle manure used under black plastic-film mulch.

Keywords: cattle manure; inorganic fertilizer; plastic-film mulch; potato

1. Introduction

Potato has been identified as the fourth staple food following rice, wheat, and maize in China, and more than 50 percent of the tuber production is expected to be consumed as a staple food by 2020 [1]. Annual tuber production increased from 81.5 million tons to 99.1 million tons from 2010 to 2016, making China the world's largest producer. Nonetheless, increasing potato production through modern agronomic measures is necessary to meet the growing demand by a growing population.

To increase production, more and more inorganic N fertilizer has been applied in the last 30 years in China. The amount of inorganic N fertilizer applied in 2016 was 30.5 million tons and was 2.5 times the amount used in the USA [2]. Excessive inorganic N inputs have induced a series of environmental problems, such as increasing greenhouse gas emissions [3], aggravating nitrate pollution in agricultural watersheds [4], decreasing biodiversity, and changing the bacterial composition in soil [5]. According to the "Zero Increase Action Plan" announced by the Chinese Ministry of Agriculture and Rural Affairs in 2015, reducing N fertilizer input is one of the most important requisites for Chinese agricultural production. Applying manure to soil as an organic fertilizer has been a common practice in many countries, although the management has changed since the 1980s due to the increasing affordability of inorganic fertilizers in China [6]. Manure provides nutrients for crops, contains organic matter that increases soil organic C [7], and has the advantages of increasing soil pH and increasing the size of microbial communities [8]. However, manure is normally only partially mineralized or composted before being applied to soil [9]. Hence, nutrients released from manure depend on the mineralization in soil, which is dependent on the soil hydrothermal environment [10].

Plastic-film mulching has been widely used worldwide for agronomic water-saving, soil temperature retention, and increasing soil surface measures [11–13] and has been frequently reported to strongly affect the soil hydrothermal environment [14,15]. Moreover, it is still controversial how different colors of plastic-film mulch affect potato production. Zhang et al. [16] found that both black and transparent plastic-film mulch increased potato yields, and transparent plastic-film mulch had numerically higher WUE, while Li et al. [17] indicated that black plastic-film mulch had higher WUE. When plastic-film is combined with manure application, soil carbon dioxide concentration should increase due to the mineralization of the applied manure and a greater amount of microbial respiration under the high soil temperature and humidity from the plastic-film mulching effect [18,19]. Hence, in this study, it is hypothesized that manure application with plastic-film mulch might induce a relative anaerobic environment, which would not be conductive to further manure mineralization and potato growth [20,21]. To our knowledge, there have been few studies focused on evaluating the effect of manure application with plastic-film mulch on potato growth.

The objectives of this study were to investigate the effect of different soil surface and fertilizer treatments on potato growth, evapotranspiration, water use efficiency, and tuber yield, and to determine whether manure application could give satisfactory potato production in semiarid regions as an alternative to inorganic fertilizer under plastic-film mulch.

2. Materials and Methods

2.1. Experimental Site and Soil Properties

Field experiments were conducted over two growing seasons (2017 and 2018) at the Shiyanghe Experimental Station (N 37°52′, E 102°50′, altitude 1581 m) of China Agricultural University. The research station is located at Wuwei, Gansu province. This region has a mean annual temperature of 8.8 °C and a mean annual precipitation of 164 mm. The groundwater depth is around 25 m. Soil texture is sandy loam with a field capacity of 0.26 cm^3 cm^{-3} and a bulk density of 1.56 g cm^{-3} at 0–60 cm soil depth. Prior to the experiments, soil chemical compositions (0–40 cm) were performed and showed the following concentrations: NO_3^-–N 4.2 ± 2.2 mg kg^{-1}, NH_4^+–N 0.6 ± 0.4 mg kg^{-1}, organic carbon 4.4 ± 1.7g kg^{-1} in 2017; and NO_3^-–N 4.5 ± 0.2 mg kg^{-1}, NH^{4+}–N 2.2 ± 0.8 mg kg^{-1}, and organic carbon 5.6 ± 1.3 g kg^{-1} in 2018. Air temperature and precipitation measurements were obtained from a weather station located within 50 m of the experimental fields.

2.2. Experimental Treatments and Agronomic Practices

Experimental treatments consisted of a factorial combination of three soil surface treatments, including black plastic-film mulch (BM), transparent film-plastic mulch (TM) and no mulch (NM) treatment, and two fertilizer treatments, including inorganic fertilizer (IF), and cattle manure (CM), applied to attain the same amount of total nitrogen. Treatments were inorganic or organic fertilizer under three soil surface treatments: inorganic fertilizer under black plastic-film mulch (BM-IF), cattle manure under black plastic-film mulch (BM-CM), inorganic fertilizer under transparent plastic-film mulch (TM-IF), cattle manure under transparent plastic-film mulch (TM-CM), inorganic fertilizer without mulch (NM-IF), and cattle manure without mulch (NM-CM). Soil surface treatment TM was not tested in 2018. Each treatment had three replicates.

Fresh cattle manure was composted with a leavening agent (Shandong Junde Bio-tech Co., Ltd., Shandong, China) near the experimental fields for 10 to 15 days. The cattle manure compost had a total nitrogen concentration of 1.3 ± 0.1%, total potassium of 1.8 ± 0.1%, total phosphorus of 0.5 ± 0.0%, and organic carbon of 38.0 ± 2.7 g kg^{-1} in 2017; total nitrogen of 1.0 ± 0.1%, total potassium of 1.3 ± 0.2%, total phosphorus of 0.5 ± 0.2% and organic carbon of 22.0 ± 1.4 g kg^{-1} in 2018. All cattle manure compost was scattered on the soil manually to supply 200 kg N ha^{-1} on April 16 in 2017 and 220 kg N ha^{-1} on April 3 in 2018, and then incorporated into the soil with a rotary cultivator before bedding. The total amount of inorganic nitrogen fertilizer was 200 (2017) or 220 (2018) kg N ha^{-1} (urea), 180 kg K ha^{-1} (K_2SO_4) and 150 kg P ha^{-1} (P_2O_5), the amounts of inorganic fertilizer were within the recommended value by the previous experiments in this area [22,23]. Total phosphorus and 40% of total nitrogen and potassium were broadcast when manure was applied, and the remaining 60% of nitrogen and potassium were fertigated through a drip irrigation system on 11 June and 15 July in 2017, and 6 June and 5 July in 2018.

Each plot was 5.6 m wide and 5 m long. Each potato bed was 0.8 m apart and 0.3 m tall. The black and transparent plastic-film mulch was 1.2 m wide and 0.008 mm thick and was laid tightly on the soil surface after bedding and installation of the drip irrigation system. The drip irrigation system consisted of a valve, a pressure gauge, and a water meter. Drip tapes (Beijing lvyuan Plastic Co., Ltd., Beijing, China) were placed on the center of potato beds. The emitter spacing was 0.2 m and the emitter flow rate was 1.38 L h^{-1} at an operating pressure of 0.1 MPa.

Potato seeds (cv. Kexin NO.1) were planted by hand in holes every 0.2 m in the center of the beds at a depth of 0.15 m on 26 April in 2017 and 17 April in 2018. The holes with a diameter of 8 cm were punched through plastic film by a soil auger. Potatoes were harvested on 29 August in 2017 and on 28 August in 2018.

Approximately 25 mm irrigation water was applied to all plots in order to assure uniform potato germination after the seeds were planted. Irrigation events for the same soil surface treatment was launched at the time when the average soil matric potential reached −25 kPa [24]. Each treatment had two tensiometers installed in two different plots in order to measure soil matric potential. The tensiometer (Model WST-2B, Beijing Waterstar Technology Co., Ltd., Beijing, China) was installed at 0.2 m soil depth between two potato plants. The amount of water I (mm) for each irrigation was determined by the equation:

$$\mathrm{I} = \mathrm{hP}(\theta_a - \theta_b)/\eta \tag{1}$$

where h is the planned wetted depth (mm), 40 mm; θ_a is the volumetric soil moisture content of the planned wetted layer after irrigation (cm^3 cm^{-3}); θ_b is the volumetric soil moisture content of the planned layer before irrigation (cm^3 cm^{-3}); P is the soil wetted proportion, 55%; and η is the utilization coefficient of irrigation water, 0.95.

2.3. Plant and Tuber Sampling and Analysis

Ten plants in the second row of each plot were tagged to measure their plant heights with a steel ruler.

Leaf area index (LAI) was measured by a weighing method at the end of three growth stages: seedling, tuber initiation, and tuber bulking. LAI was calculated by the equation:

$$LAI = \frac{M_t/M_p \times S_p}{n \times a \times b} \tag{2}$$

where n is the number of plant samples, M_t is the weight of total leaves of all plant samples (g), M_p is the weight of 20 to 30 pieces of leaves randomly selected from all leaves (g), S_p is the area of the selected leaves (cm^2), measured by a leaf area scanner (AM300, ADC BioScientific Ltd., Herts, England), a is the spacing of plants (cm), and b is the width of each bed (cm). The middle three beds of all plots were harvested for yield measurement.

2.4. Soil Sampling and Analysis

Soil samples at 0–20 cm soil depth under the drip line between two plants in two replicates were collected to test the concentrations of soil NH^{4+}-N and NO_3^--N with a flow autoanalyzer (AutoAnalyzer3, Bran + Luebbe, SEAL Analytical GmbH, Germany) during the growing seasons.

Soil water content at 0 and 40 cm from the drip line and at increments down to 20, 40, 60, 80, and 100 cm soil depths in each plot were determined by gravimetric measurements before seed planting and at harvest.

2.5. Soil Carbon Dioxide Gas Sampling and Analysis

Soil carbon dioxide gas samples at 10 and 20 cm soil depth under drip tape lines between two plants in one plot of each treatment were extracted through a gas collector during the growing seasons. The gas collector was made from PVC-U (Unplasticized polyvinyl chloride. Beijing lvyuan Plastic Co., Ltd., Beijing, China) tube with a length of 5 cm and a diameter of 2 cm. Eight holes with a diameter of 2 mm were set at 1 cm from the tube bottom. The bottom of the tube and all holes were wrapped by nylon gauze preventing soil from clogging the holes. A PVC plug with a diameter of 20 mm blocked the top of the tube, providing an airtight seal. A silicone tube with a diameter of 6 mm was inserted to the collector through the PVC plug. A tee valve was mounted on the silicone tube for collecting gas with a 50 mL plastic syringe and a 50 mL gas sampling bag (Dalian Pulaite Gas packing Co., LTD., Dalian, Shenyang, China).

Carbon dioxide concentrations were determined by gas chromatography (GC-2014 series, Shimadzu (China) Co., Ltd., Shanghai, China) with a flame ionization detector (FID) within 48 h after the gas sampling.

2.6. Calculation and Statistical Analysis

Potato evapotranspiration (ET_c, mm) was calculated using the soil water balance:

$$\mathrm{ET_c} = \mathrm{I} + \mathrm{R} - \Delta\mathrm{S} - \mathrm{RO} - \mathrm{D} \tag{3}$$

where I is the irrigation amount, R is the precipitation, ΔS is the change of soil water storage, RO is the surface runoff, and D is the drainage below the crop root zone, and the units of all terms are mm. Precipitation was assumed to be consistently effective for both mulched treatments and non-mulched treatments. The water content of different soil layers was determined by the method discussed in Section 2.4. We considered RO negligible because of the small precipitation, small irrigation amount and barriers blocking runoff along the furrows. In addition, D is negligible because the experimental site was in an arid area and each individual irrigation was small [25].

Water use efficiency (WUE, kg m^{-3}) was calculated by the equation:

$$\mathrm{WUE} = \mathrm{Y}/\mathrm{ET_c} \times 10^{-1} \tag{4}$$

where Y is the tuber yield (kg ha^{-1}), and ET_c is the potato evapotranspiration (mm).

The data of plant height, leaf area index, tuber yield, potato evapotranspiration, water use efficiency, tuber starch content, and soil inorganic nitrogen content in each year were analyzed statistically by analysis of variance to evaluate the effect of different soil surface treatments, different fertilizer treatments and their interactions at the 0.05 probability level. Significant differences were tested by the least significant difference test (LSD) at 0.05 probability level. The Statistical Product and Service Solutions software (SPSS version 24.0 for windows, SPSS Inc., Chicago, Illinois USA) was used for the statistical analysis.

Origin (Origin version 2017, OriginLab Crop., Massachusetts, USA) was used to create graphs.

3. Results

3.1. Air Temperature and Precipitation during Two Growing Seasons

Air temperature during the two growing seasons was normal for this region (Figure 1). Daily average temperatures ranged from 14–22.6 °C and 13.8–22.5 °C over the five growth stages with a total average temperature of 20.2 and 20.4 °C in the 2017 and 2018 growing seasons, respectively (Table 1). Daily minimum temperatures were 1.5–11.9 °C and −1.5–13.0 °C over the five growth stages in 2017 and 2018, respectively. Daily maximum temperatures were 26.5–37.8 °C and 26.2–38.4 °C over the five growth stages in 2017 and 2018, respectively. Days of minimum air temperature below 10 °C, defined as biological zero point, were 27 in 2017 and 36 in 2018. Days of maximum air temperature above 30 °C, detrimental to optimal tuber growth, were 48 in 2017 and 43 in 2018. Days of rain were 34 and 25, with total precipitation of 124.8 and 143 mm, in 2017 and 2018, respectively.

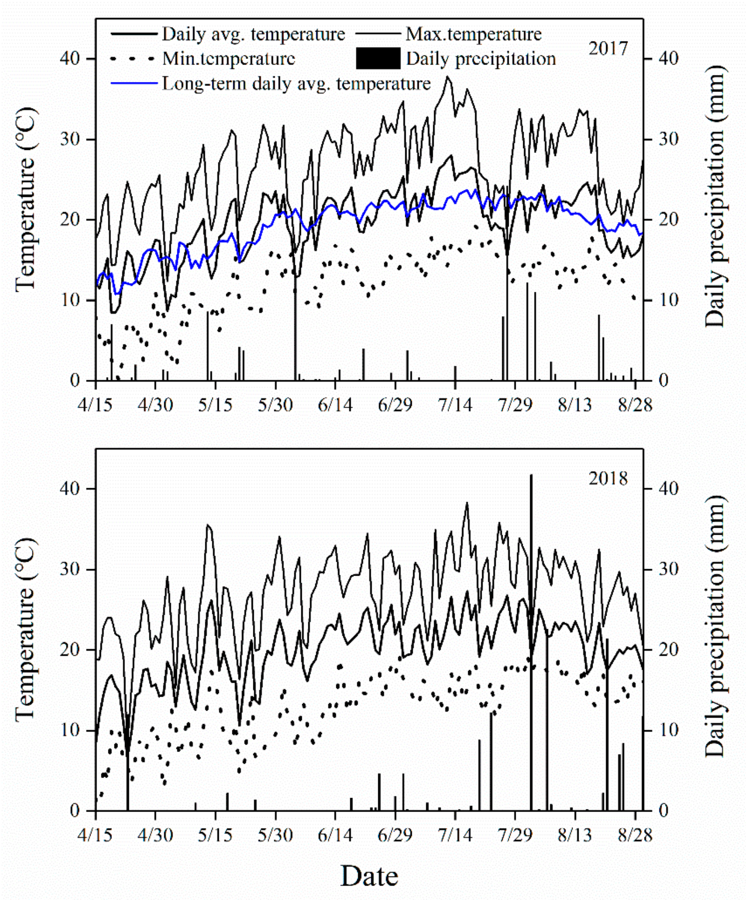

Figure 1. Long-term daily average air temperature from 2008 to 2018, daily average air temperature, daily maximum air temperature, daily minimum air temperature and daily precipitation in 2017 and 2018 at Wuwei, China.

Table 1. Daily average air temperature (T_a), minimum air temperature (T_{min}), maximum air temperature (T_{max}), days of minimum temperature below 10 °C, days of maximum temperature above 30 °C, precipitation days and precipitation amount during each potato growth stage in 2017 and 2018 at Wuwei, China.

Season		Growth Stage				
		Sprout	Seedling	Tuber Initiation	Tuber Bulking	Tuber Maturity
2017	Date	4/26–5/11	5/12–6/10	6/11–7/13	7/14–8/5	8/6–8/23
	T_a (°C)	14.6	18.5	22.6	22	21.2
	T_{min} (°C)	1.5	6.3	10.2	11.9	11.4
	T_{max} (°C)	26.5	31.9	37.8	36.3	33.8
	Days $T_{min} \leq 10$ °C	13	14	0	0	0
	Days $T_{max} \geq 30$ °C	0	5	21	12	10
	Precipitation days	2	10	8	7	7
	Precipitation (mm)	2.6	33.6	12.4	57.6	18.6
2018	Date	4/17–5/1	5/2–6/5	6/6–7/4	7/5–7/25	7/26–8/22
	T_a (°C)	13.8	18.1	21.5	22.5	22.4
	T_{min} (°C)	−1.8	2.8	7.9	11.4	13.0
	T_{max} (°C)	26.2	35.6	34.5	38.4	34.8
	Days $T_{min} \leq 10$ °C	14	19	3	0	0
	Days $T_{max} \geq 30$ °C	0	6	10	12	13
	Precipitation days	1	3	7	6	8
	Precipitation (mm)	12	4.6	13.6	23.2	89.6

3.2. Soil Inorganic Nitrogen Concentration

Fertilizer treatments significantly ($p < 0.05$) influenced soil nitrate nitrogen in both growing seasons, but neither soil surface treatments nor the fertilizer x soil surface treatment interaction had any effect (Table 2). No significant effect by any treatment or the interaction was found for soil ammonium nitrate, but all effects were significant for plant height, except for the interaction in 2017. Under inorganic fertilizer, soil nitrate nitrogen showed a two-peak pattern and soil ammonium nitrogen showed a slightly decreasing pattern during both growing seasons (Figure 2). Under cattle manure, soil nitrate nitrogen and ammonium nitrogen slightly decreased during both growing seasons. Soil nitrate nitrogen concentrations for the IF treatment were generally higher than those for the CM treatment. Plastic-film mulch had numerically higher soil nitrate nitrogen than no mulch. Similar soil nitrate concentrations were measured for BM and TM treatments. Concentrations of soil ammonium nitrogen stayed low and were numerically similar for all treatments.

Table 2. Effect of different treatments on soil nitrate nitrogen, soil ammonium nitrogen and plant height were analyzed by analysis of variance in 2017 and 2018 using SPSS.

Season	Treatment	Soil Nitrate Nitrogen	Soil Ammonium Nitrogen	Plant Height
2017	Soil surface treatment	NS [1]	NS	*
	Fertilizer	*	NS	*
	Soil surface treatment × fertilizer	NS	NS	NS
2018	Soil surface treatment	NS	NS	*
	Fertilizer	*	NS	*
	Soil surface treatment × fertilizer	NS	NS	*

[1] NS: difference among different treatments was not significant for F-test at $p < 0.05$ level. *: difference among different treatments was significant for F-test at $p < 0.05$ level.

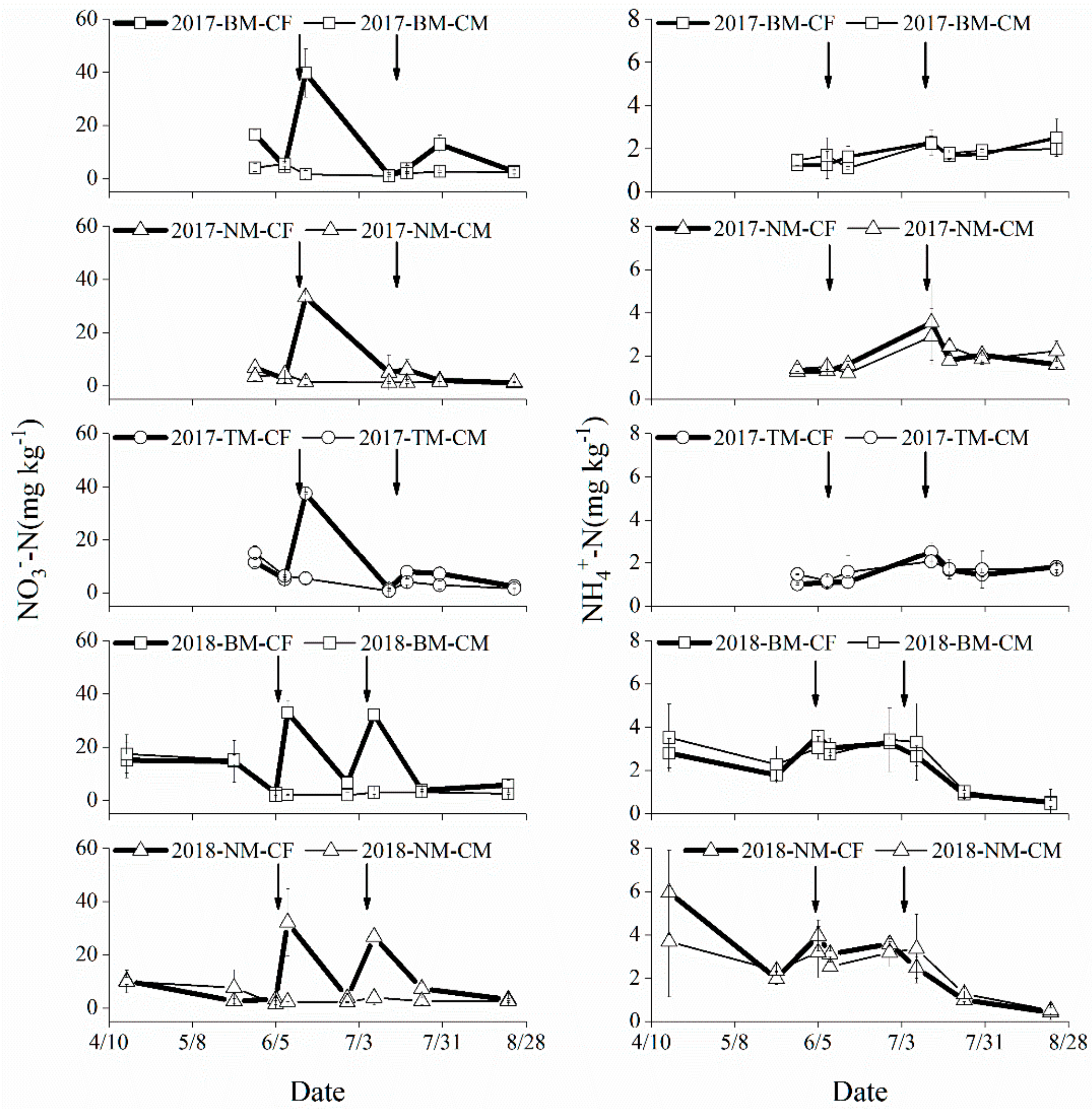

Figure 2. Soil nitrate nitrogen and ammonium nitrogen at 20 cm soil depth for the different kinds of fertilizer and different soil surface treatments for potato production at Wuwei, China: inorganic fertilizer (IF) and cattle manure (CM); black plastic-film mulch (BM), transparent plastic-film mulch (TM) and no mulch (NM) during 2017 and 2018. Arrows indicate dates of inorganic fertilizer topdressing: 11 June and 15 July in 2017 and 6 June and 5 July in 2018. Bars represent standard deviations ($n = 2$). Values are means of two replicates.

3.3. Soil Carbon Dioxide Concentration

Soil carbon dioxide concentrations during 2017 were higher than those during 2018 (Figure 3). Soil carbon dioxide concentrations for the BM treatment were higher than those for the NM treatment but lower than those for the TM treatment.

For soil covered with plastic-film mulch, soil carbon dioxide concentrations were higher for CM treatment than IF treatment until the date of top dressing of the IF treatment. Soil carbon dioxide concentrations with mulch rose immediately after the fertigation in the IF treatment, exceeding those using manure. Without mulch, soil carbon dioxide concentrations for the CM treatment were generally higher than those for the IF treatment during the whole growth stage, although the fertigation promoted the concentrations to some extent.

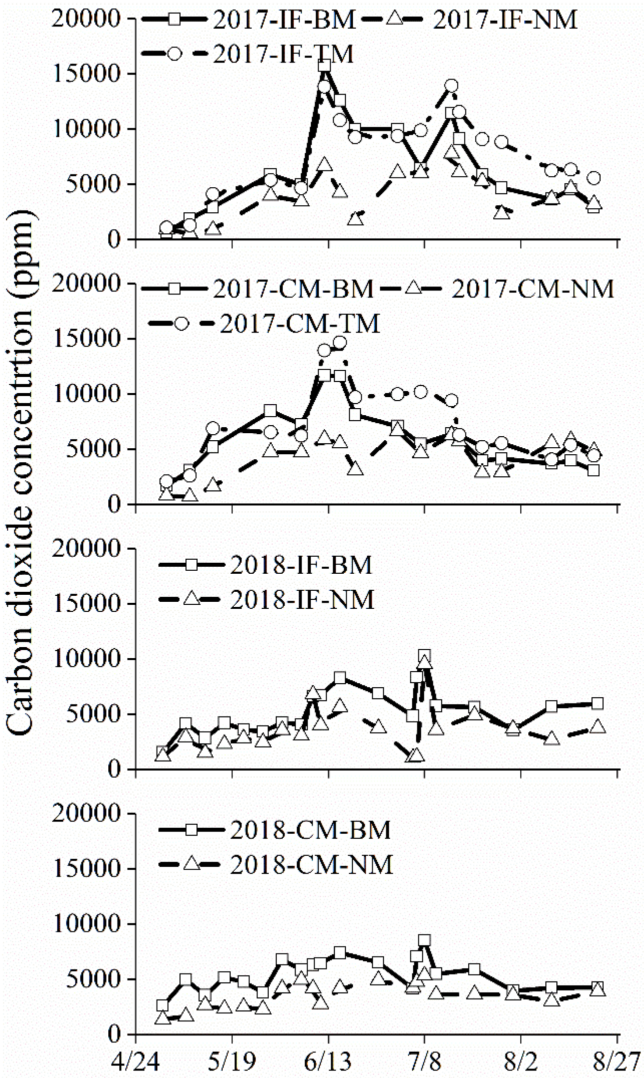

Figure 3. Carbon dioxide concentration at 20 cm soil depth for the different kinds of fertilizer and different soil surface treatments for potato production at Wuwei, China: inorganic fertilizer (IF) and cattle manure (CM); black plastic-film mulch (BM), transparent plastic-film mulch (TM) and no mulch (NM) during 2017 and 2018. No statistical analyses could be applied to these data because each value represents a single plot of each treatment.

3.4. Plant Height

The effect of soil surface treatment and fertilizer treatment on plant height was significant ($p < 0.05$) for both growing seasons (Table 2). The synergistic effect of soil surface and fertilizer treatments was significant ($p < 0.05$) in 2018.

Plant heights for the different treatments changed with a similar pattern over both growing seasons (Figure 4). They increased rapidly during seedling and tuber initiation stages, then the growth rate slowed down or even decreased for some treatments. Plant heights were greater in 2017 than those in 2018. Plant heights with IF treatment were greater than those with CM treatment. The difference between the two fertilizer treatments became significant ($p < 0.05$) after the tuber initiation stage. Plant heights with the BM treatment were significantly higher ($p < 0.05$) than those of NM and TM treatments during the seedling stage in 2017 and the whole growing season in 2018. After the seedling stage on 10 June in 2017, plant heights with BM treatment were numerically higher than those of NM and TM treatments. The lowest plant heights among the three soil surface treatments were measured for TM. With the inorganic fertilizer treatment, the BM treatment had the highest plant height (102 cm in 2017 and 97 cm in 2018), followed by the NM treatment (96 cm in 2017 and 58 cm in 2018), and the TM treatment (94 cm in 2017). Under the cattle manure treatment, the BM treatment had the highest plant height (85 cm in 2017 and 71 cm in 2018), followed by the NM treatment (82 cm in 2017 and 53 cm in 2018) and the TM treatment (77 cm in 2017).

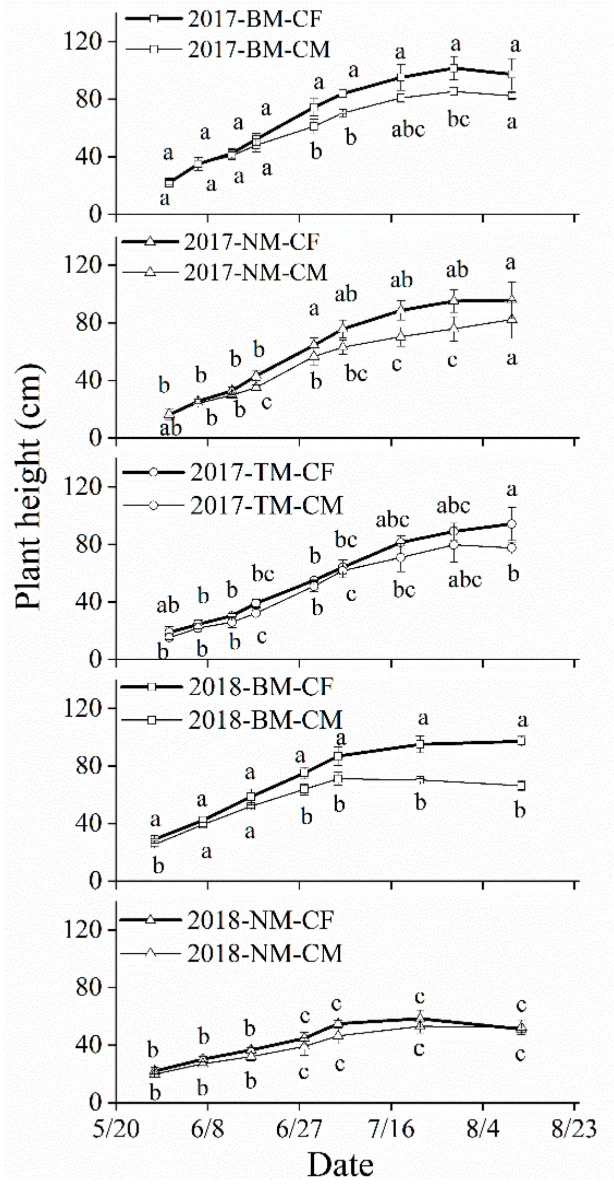

Figure 4. Plant heights for the different kinds of fertilizer and soil surface treatments: inorganic fertilizer (IF) and cattle manure (CM); black plastic-film mulch (BM), transparent plastic-film mulch (TM) and no mulch (NM) for potato production during 2017 and 2018 at Wuwei, China. Note: different letters (a, b, c and d) on points means that the differences among values with different treatments for the same date were significant at the $p < 0.05$ level according to the LSD test. Bars represent standard deviations ($n = 3$). Values are the means of three replicates.

3.5. Leaf Area Index

The effect of soil surface treatment on LAI was significant ($p < 0.05$) at the seedling stage in 2017 and all three growth stages in 2018 (Table 3). The effect of fertilizer on LAI was significant ($p < 0.05$) at the tuber initiation and bulking stages. The synergistic effect of soil surface and fertilizer treatments was significant ($p < 0.05$) at the tuber bulking stage in 2018.

Table 3. The effect of different treatments on potato leaf area index was analyzed by analysis of variance in 2017 and 2018 using SPSS.

Season	Treatment	Growth Stage		
		Seedling	Tuber Initiation	Tuber Bulking
2017	Soil surface treatment	* [1]	NS	NS
	Fertilizer	NS	NS	NS
	Soil surface treatment × fertilizer	NS	NS	NS
2018	Soil surface treatment	*	*	*
	Fertilizer	NS	*	*
	Soil surface treatment × fertilizer	NS	NS	*

[1] NS: difference among different treatments was not significant for F-test at $p < 0.05$ level. *: difference among different treatments was significant for F-test at $p < 0.05$ level.

The greatest LAI occurred at the tuber initiation stage for both growing seasons, being 5.1–6.3 in 2017 and 1.5–5.8 in 2018, respectively (Figure 5). The leaf area index under the IF treatment was 18–61%, 15–96% and 13–18% greater than that under the CM treatment for BM, TM and NM treatments in 2017 and was 11–204% and 2–65% greater than that under the CM treatment for BM and NM treatments in 2018, respectively. Black plastic-film mulch had the greatest LAI at all growth stages. Under inorganic fertilizer treatment, the LAI for the BM treatment was 5–9% and 6–40% greater than that for the NM and TM treatments in 2017 and was 121–223% greater than that for the NM treatment in 2018. Under CM treatment, LAI for the BM treatment was 1–136% and 1–64% greater than that for the NM and TM treatments in 2017 and was 22–205% bigger than that for the NM treatment in 2018.

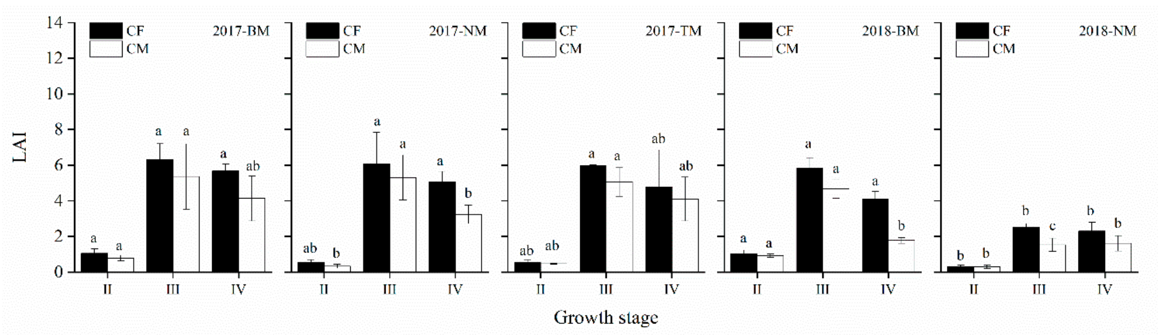

Figure 5. Leaf area index at the end of three growth stages at Wuwei, China: II seedling stage on June 10, III tuber initiation stage on July 13 and IV tuber bulking stage on August 5 for the different kinds of fertilizer and different soil surface treatments: inorganic fertilizer (IF) and cattle manure (CM); black plastic-film mulch (BM), transparent film-plastic mulch (TM) and no mulch (NM) during 2017 and 2018. Note: different letters (a, b, c and d) on points indicates that the differences among values with different treatments at the

3.6. Irrigation, Tuber Yields, Potato Evapotranspiration and Water Use Efficiency (WUE)

More irrigation was applied in 2017 than in 2018 (Table 4). In 2017, the NM treatment received the greatest amount of irrigation water, being 1.1 and 1.2 times that for the TM treatment and BM treatment, respectively. All treatments had the same irrigation water in 2018.

Fertilizer and soil surface treatment each significantly ($p < 0.05$) affected tuber yield in 2017. Soil surface treatment alone significantly ($p < 0.05$) affected tuber yield in 2018 (Table 4). Tuber yields were higher in 2017 than in 2018. Across two growing seasons, tuber yields under the IF treatment were 6–23% higher than those under the CM treatment. Tuber yields under the BM treatment were 6–15% and 12–22% higher than those of the NM and TM treatments in 2017 and were 29–30% higher than those of the NM treatment in 2018.

Table 4. Irrigation, tuber yields, evapotranspiration and water use efficiency for potatoes grown with different mulch treatments and different fertilizer treatments in 2017 and 2018 at Wuwei, China.

Season	Treatment	Soil Surface Treatment	Fertilizer	Irrigation (mm)	Yields (t ha^{-1})	ETc (mm)	WUE (kg m^{-3})
2017	BM-IF	Black	Inorganic fertilizer	397	100.0 ± 6.6a	500 ± 11d	20.0 ± 1.4a
	BM-CM		Cattle manure	397	87.6 ± 7.2ab	534 ± 5c	16.4 ± 1.4bc
	TM-IF	Transparent	Inorganic fertilizer	417	82.3 ± 1.9b	548 ±2 b	15.0 ± 0.4c
	TM-CM		Cattle manure	417	77.9 ± 0.4c	562 ± 7a	13.9 ± 0.2d
	NM-IF	Non-mulch	Inorganic fertilizer	459	94.0 ± 3.5a	560 ± 7ab	16.8 ± 0.4b
	NM-CM		Cattle manure	459	76.3 ± 5.7c	572 ± 5a	13.4 ± 0.9d
ANOVA							
Soil surface treatment					[1]*	*	*
Fertilizer					*	*	*
Soil surface treatment × fertilizer					NS	*	NS
2018	BM-IF	Black	Inorganic fertilizer	396	82.7 ± 3.6a	559 ± 11b	15.4 ± 1.4a
	BM-CM		Cattle manure	396	76.9 ± 1.3a	590 ± 10a	13.0 ± 0.1b
	NM-IF	Non-mulch	Inorganic fertilizer	396	63.6 ± 1.0b	555 ± 9.6b	11.5 ± 2.0b
	NM-CM		Cattle manure	396	59.7 ± 3.4b	577 ± 10ab	10.5 ± 0.9b
ANOVA							
Soil surface treatment					*	NS	*
Fertilizer					NS	*	NS
Soil surface treatment × fertilizer					NS	NS	NS

[1] NS: difference among treatments was not significant for the F-test at $p < 0.05$ level. *: difference among treatments was significant for the F-test at the $p < 0.05$ level. Different letters (a, b, c and d) on points indicates that the differences among values with different treatments at the same growth stage were significant at the $p < 0.05$ level according to the LSD test. Values with the same letter were statistically similar at the $p < 0.05$ level by the F-test.

Fertilizer treatments, soil surface treatments, and their interaction effects made significant differences ($p < 0.05$) on ETc for all treatments in 2017 (Table 4). Fertilizer treatments had a significant effect ($p < 0.05$) on ETc in 2018. Across two growing seasons, ETc for IF treatment was 2–6% lower than that for the CM treatment. ETc for the BM treatment was 7–11% and 5–9% lower than that of the NM and TM treatments in 2017, and was 1–2% higher than that of the NM treatment in 2018.

Fertilizer and soil surface treatment individually and significantly ($p < 0.05$) affected WUE in 2017. In contrast, soil surface treatment alone affected ($p < 0.05$) WUE in 2018 (Table 4). Manure application decreased WUE by 8–25% compared to inorganic fertilizer across two growing seasons. Water use efficiency with BM treatment increased by 18–34% and 19–22% compared to the NM and TM treatments in 2017, and by 24–34% compared to the NM treatment in 2018.

4. Discussion

Air temperature is one of the most important factors affecting soil temperature, which in turn affects potato crop growth. Lower average air temperature and more extreme low air temperatures in the early growth stage in 2018 inhibited sprouting of potato seeds and decreased plant height and leaf area index, reducing potato yields as a result of reduction of uptake of nutrients and water [13,26].

Plastic-film mulch had a warmer and more stable soil thermal environment for the emergence and growth of sprouts and seedlings. Early emergence could promote the growth of biomass above ground [27,28], resulting in the greatest plant height, LAI, and tuber yield seen under black plastic-film mulch in this study. On the other hand, plastic-film mulch was found to have negative effects on potato growth. Extremely high soil temperature occurred under transparent plastic-film mulch as reported by Zhang et al. [29], restraining potato above-ground growth at the seedling stage and tuber initiation and bulking [28]. High temperatures interfered with the onset of micro tuber dormancy and promoted growth of tuber apical buds during the tuber bulking stage [30,31]. Mulching for the whole period of a crop can considerably lower the yield because of consistently higher soil carbon dioxide concentration in the microclimate [32]. In this study, transparent plastic-film mulch had no advantage on plant height and LAI over no mulch treatment and it decreased tuber yield, although the weakening effect was not significant, generally because of extremely and consistently higher soil temperatures and carbon dioxide concentrations. Meanwhile black plastic-film mulch created suitable thermal conditions and a relatively good aeration environment for potato growth in this study. Black plastic-film mulch also increased soil mineral N concentration, reduced evaporation from the soil surface in addition to modifying soil temperature, reduced irrigation water input, and improved water use efficiency as reported by Ma et al. [33].

Different results for plant height, leaf area index, and tuber yields between inorganic fertilizer and manure treatments were mainly constrained by nitrogen released into the soil from different kinds of fertilizer [34]. Soil nitrogen levels in this study were generally lower for manure treatment during the whole growth stage, although they were similar to those of the inorganic fertilizer treatment during the first month. Similar results where nitrogen released from manure was slow have been reported [35]. The mineralization rate of manure was high within the first 30–40 days and then decreased [9,36]. Only a small proportion of organic N was mineralized from manure over time [36]. Applying manure as an alternative to or partial substitute for inorganic fertilizer rather than as a supplement restrains plant growth, leaf area index and tuber production [7,37–39]. Results also showed that carbon dioxide concentrations for manure treatment were higher than those using inorganic fertilizer before the first inorganic fertilizer topdressing. That is to say, the mineralization of manure contributed to the high carbon dioxide concentration and negatively affected the plant growth, considering that the soil nitrogen content was similar for inorganic fertilizer and manure treatment during the early growth stage. Carbon dioxide concentrations were higher with inorganic fertilizer after topdressing due to the strong growth of the plants and roots. The results indicated that the positive effect of topdressing of inorganic fertilizer on potato growth due to the increase in nutrients outweighed the negative effects caused by the increase in soil carbon dioxide. On the other hand, manure treatment decreased water use efficiency due to high evapotranspiration and low tuber yield. High evapotranspiration occurred under manure treatment because more water was consumed by manure mineralization and soil microbes that were enriched by the manure addition [5,40].

In this study, low amounts of total phosphorus in cattle manure could be another factor resulting in low plant height, low LAI, and low tuber yields for cattle manure treatment. Phosphorus is an important nutrient for promoting plant growth, increased leaf size, plant dry matter and tuber production [41,42]. Further research needs to be done on the change of phosphorus content in soil with different kinds of fertilizer application.

5. Conclusions

In the current study, the different results of plant height, LAI and tuber yield for NM treatment during two growing seasons suggested that environmental temperature plays an important role in potato growth. Low average environmental temperature and more extreme low air temperatures during the seedling stage did harm to the plant growth.

Black plastic-film mulch provided a more suitable soil environment for potato growth, providing the greatest potato yields. It provided a good warming and warm maintenance capacity, high soil mineral N concentration and moderate soil carbon dioxide concentrations. Black plastic-film mulch significantly ($p < 0.05$) reduced evapotranspiration in 2017 but numerically increased it in 2018, while black plastic-film mulch improved water use efficiency. Transparent plastic-film mulch did not show any advantage for plant height, LAI and tuber yield due to its excessive warming effect and extremely high soil carbon dioxide concentration.

Manure applied as an alternative to inorganic fertilizer reduced plant height, LAI, tuber yields and WUE due to the low soil nitrogen released from the manure applied in the soil. On the other hand, high soil carbon dioxide during the seedling stage for manure treatment harmed plant growth.

In conclusion, inorganic fertilizer with black plastic-film mulch was still the best production system for potatoes among those tested in this research. The low nitrogen released from manure should be considered and further studies should be conducted for investigating the quantity of manure that should be applied if manure were to be used in future potato production.

Author Contributions: Conceptualization, C.B.M. and F.X.W.; methodology, C.B.M., F.X.W., Y.L.Z. and K.J.Y.; investigation, C.B.M.; resources, F.X.W.; writing—original draft preparation, C.B.M.; writing—review and editing, F.X.W. and B.A.E.; supervision, F.X.W.; project administration, F.X.W.; funding acquisition, F.X.W.

Funding: This research was funded by Ministry of Water Resources of China, grant number 201501017 and National Natural Science Foundation of China, grant number 51579240.

Acknowledgments: Thanks to Shaozhong Kang and Taisheng Du et al. for providing help for our research. We also thank the fruitful comments by the editors and anonymous reviewers.

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

References

1. Ministry of Agriculture and Rural Affairs of the People's Republic of China. Potato will Become the Fourth Staple Food in China, and How to Make Potato as Staple Food in China. Available online: http://www.moa.gov.cn/ztzl/mls/mlszxxx/201507/t20150702_4728612.htm (accessed on 12 April 2019).
2. FAO (Food and Agriculture Organization of the United Nations). FAOSTAT Online Database. 2018. Available online: http://www.fao.org/faostat/en/#data/RA (accessed on 11 April 2019).
3. Liu, X.; Zhang, F. Nitrogen fertilizer induced greenhouse gas emissions in China. *Curr. Opin. Environ. Sust.* **2011**, 407–413. [CrossRef]
4. Ji, X.; Xie, R.; Hao, Y.; Lu, J. Quantitative identification of nitrate pollution sources and uncertainty analysis based on dual isotope approach in an agricultural watershed. *Environ. Pollut.* **2017**, *229*, 586–594. [CrossRef] [PubMed]
5. Wang, Q.; Jiang, X.; Guan, D.; Wei, D.; Zhao, B.; Ma, M.; Chen, S.; Li, L.; Cao, F.; Li, J. Long-term fertilization changes bacterial diversity and bacterial communities in the maize rhizosphere of Chinese Mollisols. *Appl. Soil Ecol.* **2018**, *125*, 88–96. [CrossRef]

6. Ishii, S.; Ikeda, S.; Minamisawa, K.; Senoo, K. Nitrogen cycling in rice paddy environments: Past achievements and future challenges. *Microbes Environ.* **2011**, *26*, 282–292. [CrossRef] [PubMed]
7. Yan, X.; Gong, W. The role of chemical and organic fertilizers on yield, yield variability and carbon sequestration—Results of a 19-year experiment. *Plant Soil* **2010**, *331*, 471–480. [CrossRef]
8. Ding, J.; Jiang, X.; Ma, M.; Zhou, B.; Guan, D.; Zhao, B.; Zhou, J.; Cao, F.; Li, L.; Li, J. Effect of 35 years inorganic fertilizer and manure amendment on structure of bacterial and archaeal communities in black soil of northeast China. *Appl. Soil Ecol.* **2016**, *105*, 187–195. [CrossRef]
9. Gale, E.S.; Sullivan, D.M.; Cogger, C.G.; Bary, A.I.; Hemphill, D.D.; Myhre, E.A. Estimating Plant-Available Nitrogen Release from Manures, Composts, and Specialty Products. *J. Environ. Qual.* **2006**, *35*, 2321. [CrossRef] [PubMed]
10. Eckhardt, D.P.; Redin, M.; Jacques, R.J.S.; Lorensini, F.; Santos, M.L.D.; Weiler, D.A.; Antoniolli, Z.I. Mineralization and efficiency index of nitrogen in cattle manure fertilizers on the soil. *Ciência Rural* **2016**, *46*, 472–477. [CrossRef]
11. Ghosh, P.K.; Dayal, D.; Bandyopadhyay, K.K.; Mohanty, M. Evaluation of straw and polythene mulch for enhancing productivity of irrigated summer groundnut. *Field Crops Res.* **2006**, *99*, 76–86. [CrossRef]
12. Ramakrishna, A.; Tam, H.M.; Wani, S.P.; Long, T.D. Effect of mulch on soil temperature, moisture, weed infestation and yield of groundnut in northern Vietnam. *Field Crops Res.* **2006**, *95*, 115–125. [CrossRef]
13. Li, Q.; Li, H.; Zhang, L.; Zhang, S.; Chen, Y. Mulching improves yield and water-use efficiency of potato cropping in China: A meta-analysis. *Field Crops Res.* **2018**, *221*, 50–60. [CrossRef]
14. Li, S.; Li, Y.; Lin, H.; Feng, H.; Dyck, M. Effects of different mulching technologies on evapotranspiration and summer maize growth. *Agric. Water Manag.* **2018**, *201*, 309–318. [CrossRef]
15. Zhao, Y.; Zhai, X.; Wang, Z.; Li, H.; Jiang, R.; Lee Hill, R.; Si, B.; Hao, F. Simulation of soil water and heat flow in ridge cultivation with plastic film mulching system on the Chinese Loess Plateau. *Agric. Water Manag.* **2018**, *202*, 99–112. [CrossRef]
16. Zhang, Y.; Wang, F.; Shock, C.C.; Yang, K.; Kang, S.; Qin, J.; Li, S. Influence of different plastic film mulches and wetted soil percentages on potato grown under drip irrigation. *Agric. Water Manag.* **2017**, *180*, 160–171. [CrossRef]
17. Li, Q.; 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. B Soil Plant Sci.* **2018**, *68*, 175–188. [CrossRef]
18. Zhang, F.; Li, M.; Zhang, W.; Li, F.; Qi, J. Ridge–furrow mulched with plastic film increases little in carbon dioxide efflux but much significant in biomass in a semiarid rainfed farming system. *Agric. For. Meteorol.* **2017**, *244*, 33–41. [CrossRef]
19. Yu, Y.; Tao, H.; 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]
20. Tiquia, S.M.; Lloyd, J.; Herms, D.A.; Hoitink, H.A.J.; Michel, F.C. Effects of mulching and fertilization on soil nutrients, microbial activity and rhizosphere bacterial community structure determined by analysis of TRFLPs of PCR-amplified 16S rRNA genes. *Appl. Soil Ecol.* **2002**, *21*, 31–48. [CrossRef]
21. Li, Z.; Zhang, C.; Zhang, R.; Wang, X.; Wang, J.; Tian, C. Carbon Dioxide Fluxes and Concentrations in a Cotton Field in Northwestern China: Effects of Plastic Mulching and Drip Irrigation. *Pedosphere* **2011**, *21*, 178–185. [CrossRef]
22. Yang, K.; Wang, F.; Shock, C.C.; Kang, S.; Huo, Z.; Song, N.; Ma, D. Potato performance as influenced by the proportion of wetted soil volume and nitrogen under drip irrigation with plastic mulch. *Agric. Water Manag.* **2017**, *179*, 260–270. [CrossRef]
23. Wang, F.; Feng, S.; Hou, X.; Kang, S.; Han, J. Potato growth with and without plastic mulch in two typical regions of Northern China. *Field Crops Res.* **2009**, *110*, 123–129. [CrossRef]
24. Wang, F.; Kang, Y.; Liu, S.; Hou, X. Effects of soil matric potential on potato growth under drip irrigation in the North China Plain. *Agric. Water Manag.* **2007**, *88*, 34–42. [CrossRef]
25. Wang, F.; Wu, X.; Shock, C.C.; Chu, L.; Gu, X.; Xue, X. Effects of drip irrigation regimes on potato tuber yield and quality under plastic mulch in arid Northwestern China. *Field Crops Res.* **2011**, *122*, 78–84. [CrossRef]
26. Wang, X.; Xing, Y. Effects of Mulching and Nitrogen on Soil Nitrate-N Distribution, Leaching and Nitrogen Use Efficiency of Maize (*Zea mays* L.). *PLoS ONE* **2016**, *11*, e161612. [CrossRef] [PubMed]
27. Ren, X.; Cai, T.; Chen, X.; Zhang, P.; Jia, Z. Effect of rainfall concentration with different ridge widths on winter wheat production under semiarid climate. *Eur. J. Agron.* **2016**, *77*, 20–27. [CrossRef]

28. Liang, S.M.; Ren, C.; Wang, P.J.; Wang, X.T.; Li, Y.S.; Xu, F.H.; Wang, Y.; Dai, Y.Q.; Zhang, L.; Li, X.P.; et al. Improvements of emergence and tuber yield of potato in a seasonal spring arid region using plastic film mulching only on the ridge. *Field Crops Res.* **2018**, *223*, 57–65. [CrossRef]
29. Zhang, Y.; Wang, F.; Shock, C.C.; Yang, K.; Kang, S.; Qin, J.; Li, S. Effects of plastic mulch on the radiative and thermal conditions and potato growth under drip irrigation in arid Northwest China. *Soil Tillage Res.* **2017**, *172*, 1–11. [CrossRef]
30. Pantelić, D.; Dragićević, I.Č.; Rudić, J.; Fu, J.; Momčilović, I. Effects of high temperature on in vitro tuberization and accumulation of stress-responsive proteins in potato. *Hortic. Environ. Biotechnol.* **2018**, *59*, 315–324. [CrossRef]
31. Hou, X.; Wang, F.; Han, J.; Kang, S.; Feng, S. Duration of plastic mulch for potato growth under drip irrigation in an arid region of Northwest China. *Agric. For. Meteorol.* **2010**, *150*, 115–121. [CrossRef]
32. Liu, Y.; Li, S.Q.; Yang, S.J.; Hu, W.; Chen, X.P. Diurnal and seasonal soil CO_2 flux patterns in spring maize fields on the Loess Plateau, China. *Acta Agric. Scand. B Soil Plant Sci.* **2010**, *3*, 245–255. [CrossRef]
33. Ma, D.; Chen, L.; Qu, H.; Wang, Y.; Misselbrook, T.; Jiang, R. Impacts of plastic film mulching on crop yields, soil water, nitrate, and organic carbon in Northwestern China: A meta-analysis. *Agric. Water Manag.* **2018**, *202*, 166–173. [CrossRef] [PubMed]
34. Roinila, P.; Väisänen, J.; Granstedt, A.; Kunttu, S. Effects of Different Organic Fertilization Practices and Mineral Fertilization on Potato Quality. *Biol. Agric. Hortic.* **2003**, *21*, 165–194. [CrossRef]
35. Liu, C.; Li, F.; Zhou, L.; Zhang, R.; Yu-Jia Lin, S.; Wang, L.; Siddique, K.H.M.; Li, F. Effect of organic manure and fertilizer on water and crop yields in newly-built terraces with loess soils in a semi-arid environment. *Agric. Water Manag.* **2013**, 123–132. [CrossRef]
36. Masunga, R.H.; Uzokwe, V.N.; Mlay, P.D.; Odeh, I.; Singh, A.; Buchan, D.; De Neve, S. Nitrogen mineralization dynamics of different valuable organic amendments commonly used in agriculture. *Appl. Soil Ecol.* **2016**, *101*, 185–193. [CrossRef]
37. Edmeades, D.C. The long-term effects of manures and fertilisers on soil productivity and quality: A review. *Nutr. Cycl. Agroecosyst.* **2003**, *66*, 165–180. [CrossRef]
38. Ding, X.; Han, X.; Liang, Y.; Qiao, Y.; Li, L.; Li, N. Changes in soil organic carbon pools after 10 years of continuous manuring combined with chemical fertilizer in a Mollisol in China. *Soil Tillage Res.* **2012**, *122*, 36–41. [CrossRef]
39. Martínez, E.; Domingo, F.; Roselló, A.; Serra, J.; Boixadera, J.; Lloveras, J. The effects of dairy cattle manure and mineral N fertilizer on irrigated maize and soil N and organic C. *Eur. J. Agron.* **2017**, *83*, 78–85. [CrossRef]
40. Curtin, D.; Beare, M.H.; Hernandez-Ramirez, G. Temperature and Moisture Effects on Microbial Biomass and Soil Organic Matter Mineralization. *Soil Sci. Soc. Am. J.* **2012**, *76*, 2055. [CrossRef]
41. Bechmann, M. The effect of phosphorus application and balance on concentrations in streams from agricultural dominated catchments in Norway. *Acta Agric. Scand. B Soil Plant Sci.* **2014**, *63*, 162–171. [CrossRef]
42. Sun, Y.; Cui, X.; Liu, F. Effect of irrigation regimes and phosphorus rates on water and phosphorus use efficiencies in potato. *Sci. Hortic. Amst.* **2015**, *190*, 64–69. [CrossRef]