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Optimizing Sowing Patterns and Nitrogen Management Strategies Used to Balance Maize Crop Productivity, N₂O Emissions, and Economic Benefits in the Loess Plateau Region of China

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Abstract: Understanding the combined effects of sowing patterns and nitrogen (N) management strategies on crop productivity, environmental costs, and economic benefits is important to ensuring the sustainable development of dryland agriculture. Thus, we conducted a three-year field experiment to explore two spring maize sowing patterns (FS, flat sowing; RFPM, ridge and furrow plastic film mulching) and four N management strategies (N0, no N fertilizer; N1, normal urea as base fertilizer; N2, split application of normal urea at sowing and a large flare period at a ratio of 3:2; N3, all controlled-release urea as base fertilizer) on growth, the grain yield, the N uptake and utilization efficiency, N₂O emissions, and economic benefits in the Loess Plateau region of China. Our results showed that compared to FS, RFPM promoted growth of the spring maize canopy and increased the grain yield, cumulative N uptake, and N use efficiency. RFPM promoted N_2O emissions by improving the soil's hydrothermal environment, but it reduced the environmental cost (yield-scaled N₂O emission). RFPM increased the production cost, but it increased the net income by improving the total output. Compared to traditional N management strategies (N1), N2 and N3 treatments improved the spring maize productivity and net income, and they reduced the environmental costs by improving the synchronization of the nitrogen supply. However, due to the decreasing rural labor force available in China, N3 is more beneficial in terms of reducing labor inputs. Therefore, we suggest that RFPM and N3 can be combined to form an efficient management strategy for spring maize production in the Loess Plateau that balances crop productivity, N₂O emissions, and economic benefits.

Keywords: economic benefit; N fertilizer management; N₂O emission; productivity; ridge and furrow plastic film mulching; spring maize

1. Introduction

Improving crop productivity plays an important role in maintaining food supplies needed to enable sustainable population growth, but it can also lead to environmental problems that must be addressed, especially increased greenhouse gas emissions. Thus, coordinating improvements in crop productivity and environmental sustainability is now a major focus in agricultural production [1]. Optimizing field management measures is considered to be an important method in terms of balancing this relationship to achieve efficient and clean agricultural production [2].

Nitrous oxide (N_2O) is considered to be one of the most important greenhouse gases [3] because although its concentration is relatively low, its warming potential is 298 and



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). 12 times that of carbon dioxide (CO₂) and methane (CH₄), respectively [4]. Studies have shown that the N₂O produced by agricultural activities accounts for 70% of total soil production [5] and more than 13% of global anthropogenic emissions [4]. In agricultural production, N₂O emissions are often affected by changes in the soil environment caused by field management measures, especially changes in the soil moisture, heat, and NO₃⁻-N and NH₄⁺-N contents. Parton et al. (2001) [6] found that N₂O emissions increased as the soil temperature increased and reached a peak at 20–35 °C, with Koponen et al. (2006) [7] and Castaldi (2000) [8] achieving comparable results. Studies have also shown that N₂O emissions have a significant positive correlation with the soil water content within a certain range [9]. NO₃⁻-N and NH₄⁺-N are used as the substrates for N₂O production [10,11], and their higher levels in soil tend to promote N₂O emissions [12].

The Loess Plateau is the largest dryland farming area in China, and it plays an important role in maintaining food security [13]. Spring maize (*Zea mays* L.) is an important food crop in this area, and its production accounts for 27.3% of the agricultural land used in China. Due to the lack of suitable irrigation conditions in the region (lack of rivers and insufficient groundwater sources), scarce and uneven precipitation has become the only water source available for use in agricultural production; thus, spring maize productivity in this region is far lower than the China-wide average [14,15]. Therefore, improving crop productivity in this area also greatly depends on the efficient collection and utilization of precipitation [16,17]. After years of research, ridge and furrow plastic film mulching (RFPM) is now considered to be one of the most effective in situ water harvesting techniques [18]. This technique combines micro-topography modification and plastic film coverage to allow efficient water harvesting and suppress evaporation [19–21], thereby improving the micro-environment in the crop root zone and significantly increasing the crop's productivity compared to traditional bare-land flat sowing (FS) [22–24].

RFPM has many advantages in terms of improving crop productivity, but its impacts on N₂O emissions have always been controversial. Some studies have shown that RFPM increases the soil temperature because the film cover may increase the rate of soil nitrogen mineralization [25], thereby increasing soil N₂O spillover [26,27]. However, other studies have concluded that RFPM reduces N₂O emissions compared to FS for the following two reasons: (1) the plastic film acts as a physical barrier to limit N₂O emission, i.e., the area available for N₂O emissions is reduced [9,28,29]; (2) the improved crop productivity under RFPM increases the absorption and utilization of N in the soil, thereby reducing soil N availability and N₂O emissions [30,31]. Due to the complexity of changes in the soil microenvironment, the effects of RFPM on N₂O emissions and the mechanism involved remain unclear.

N fertilizer is an important factor to consider when trying to balance the relationship between crop productivity and environmental risk [9,32]. The application of N fertilizer has an essential role in improving crop productivity, but in most cases, its application does not comply with the "4R" nutrient strategy of fertilizer application "at the right time, with the right source, in the right place, and at the right rate," which leads to the loss of large amounts of N, causing environmental pollution [33,34], including increased N₂O emissions. In the Loess Plateau region, using urea alone as a base fertilizer is a common N fertilizer management method [35]. This fertilization method usually leads to an excessive soil N supply in the early stage of crop growth and large losses; thus, the N supply in the middle and late stages is insufficient to meet the crop demand [36]. Therefore, improving the synchronization between the soil N supply and crop N demand is a key strategy in terms of increasing crop productivity and reducing N₂O emissions [36,37].

Split urea application is a "4R" nutrient management practice that ensures that an adequate N supply is available when the crops need it most [37]. A recent meta-analysis showed that compared to a single application of urea, the split application of urea significantly increased the grain yield and protein content in wheat, especially when the application of urea was split 3–4 times, with recorded increases in the wheat grain yield and protein content of 7.0% and 5.2%, respectively [38]. Wang et al. (2016) [39] found that

compared to a single application of urea in the Loess Plateau region, the split application of urea significantly increased the spring maize grain yield. They also found that splitting the application of urea two times (before sowing and in the jointing period) could significantly reduce N₂O emissions, but this effect occurred due to the influence of rainfall. Controlled-release urea (CRU) is another highly effective N fertilizer management strategy due to its surface being covered with a protective (non-water-soluble) substance to control water infiltration and achieve the goal of controlling nutrients' dissolution and release rates [40]. Studies have shown that the S-type N release pattern of controlled release urea is synchronized with the absorption pattern of most crops to improve the relationship between the soil N supply and crop N demand, thus increasing crop productivity [41,42]. A meta-analysis showed that compared to a single application of urea, CRU could increase the corn yield and nitrogen fertilizer use efficiency by 5.3% and 24.1%, respectively, as well as significantly reduce N_2O emissions by 23.8% [43]. The split application of urea and CRU are efficient N fertilizer management strategies, but both strategies increase the labor or production costs compared to a single application of urea; thus, the final net benefit and the most effective choice of N fertilizer management strategy are not clear.

Evidently, balancing the crop productivity and N_2O emissions by optimizing field management strategies is not a simple process. Few previous studies have investigated the effects of RFPM combined with different N fertilizer management strategies on crop productivity and N_2O emissions. We hypothesized that RFPM combined with a reasonable N fertilizer management strategy can help to balance the spring maize productivity and N_2O emissions. Thus, we conducted a three-year field experiment, and the aims of this study were as follows: (1) to clarify the effects of RFPM combined with different N fertilizer management strategies on spring maize productivity, including growth, the grain yield, and N use efficiency; (2) to determine the effects of RFPM combined with N fertilizer management strategies on N_2O emissions and the mechanism involved; (3) to analyze the effects of RFPM combined with different N fertilizer management strategies on the economic benefits. The results obtained in this study provide valuable information regarding the formulation of effective field management practices used in spring maize production in the Loess Plateau region, as well as a scientific basis for efficient and sustainable agricultural production in this region.

2. Materials and Methods

2.1. Experimental Site Description

The field experiment was conducted in 2015, 2016, and 2017 at Doukou Experimental Station ($34^{\circ}36'$ N, $108^{\circ}52'$ E), which is operated by Northwest Agriculture and Forestry University in Shaanxi Province, China. The study site is located in the southern part of the Loess Plateau in a typical dry semi-humid area with an annual mean temperature of 12.9 °C and annual mean precipitation of 527 mm over the past 30 years. Approximately 60% of annual precipitation occurs between July and September. Air temperature and precipitation data during the experimental period were recorded via an automatic weather station, type Vantage Pro2 (Davis Instruments Corporation, Hayward, CA, USA), which is located near the experimental site, and the detailed data are shown in Figure 1. The soil properties in the top 20 cm soil layer were as follows: the pH was 8.0, the organic carbon was 8.43 g kg⁻¹, the total N was 0.85 g kg⁻¹, the NO₃⁻-N was 16.54 mg kg⁻¹, the NH₄⁺-N was 4.79 mg kg⁻¹.



Figure 1. The rainfall and temperature during the spring maize growth period in 2015 (**a**), 2016 (**b**), and 2017 (**c**).

2.2. Experimental Design and Management Practices

The experiment was conducted using a two-factor randomized block design. The two factors were the sowing pattern and N management method. The sowing patterns comprised FS and RFPM. The N management methods comprised no N fertilizer (N0), normal urea only as base fertilizer (N1, i.e., the traditional N fertilizer management measure), split application of normal urea at sowing and in the large flare period at a ratio of 3:2 (N2), and CRU alone as base fertilizer (N3), in which the N application rate was 225 kg ha^{-1} under N1, N2, and N3 treatments. The six treatments tested comprised FS-N0, FS-N1, FS-N2, FS-N3, RFPM-N0, RFPM-N1, RFPM-N2, and RFPM-N3. Each treatment was repeated three times with a total of 18 plots, and each plot had an area of 30 m² (5 m \times 6 m). The N contents of the normal urea and CRU (Shaanxi Jinzheng Da Agricultural Science and Technology Co. Ltd., Weinan, China) were more than 46% and 28%, respectively, and the two N fertilizers contained no phosphorus or potassium. The application rates of superphosphate (12% P₂O₅) (Yunnan Anning Xingya Phosphorous Chemical Co., Ltd., Anning, China) and potassium sulfate (52% K2O) (Sdic Xinjiang Lop Nur Potash Salt Co., Ltd., Kuerle, China) were 150 kg P_2O_5 ha⁻¹ and 150 kg K_2O ha⁻¹, respectively, and they were both applied to the soil in the form of a base fertilizer. After spreading all of the base fertilizers evenly on the surface of the soil, a rotary tiller was used to combine them with the topsoil (0–10 cm). Artificial ridges and furrows were the created on the surface, with each ridge or furrow having a width of 60 cm, and plastic film (Wanfeng Plastic Industry Co., Ltd., Xianyang, China) with a thickness of 0.015 mm was applied to cover the ridges. For the N3 treatment, artificial ditching was used to carry out topdressing (fertilization

depth of 5 cm), and topdressing was applied on 2 June, 7 June, and 4 June in the growing seasons in 2015, 2016, and 2017, respectively.

The maize variety used in the experiment was "Zhengdan 958" (Henan Qiu Le Seed Industry Technology Co., Ltd., Zhengzhou, China). The sowing density was 65,000 plant ha⁻¹ with plant spacing of 25 cm, and artificial sowing was performed at the boundaries of the ridges and furrows. The sowing dates were 21 April, 22 April, and 24 April in the growing seasons in 2015, 2016, and 2017, respectively, and the harvest dates were 6 September, 4 September, and 9 September. Irrigation was not conducted during the spring maize growth period. Weeds, diseases, and insect pests were treated via artificial chemical control.

2.3. Measurements and Calculations

2.3.1. Spring Maize Growth

The plant height and leaf area index (LAI) of spring maize crops were measured in the silking stage during the 2015, 2016, and 2017 growing seasons. LAI was determined using a SunScan canopy analyzer (Delta-T, London, UK).

2.3.2. N₂O Flux

 N_2O gas samples were collected using the closed static chamber method [44]. Each chamber comprised a top chamber (50 × 50 × 50 cm) and a stainless steel base frame (50 × 50 × 10 cm) with a groove, which was filled with water to seal the top chamber in an airtight manner during the sampling period. The base frame covered half of the rows and open spaces between rows in FS, as well as half of the plastic mulched ridges and unmulched furrows in RFPM. In the growing seasons of 2015 and 2016, the sampling intervals were 10 and 7 days, respectively. The sampling frequency increased after fertilization and precipitation. The sampling frequency was restored to once per week when the gas flux decreased to the same level as that recorded prior to strong emissions. The usual sampling time was between 09:00 and 11:00 on a sunny day. Four gas samples were collected and stored using 50-milliliter medical plastic syringes with triple valves at 10-min intervals after the chamber was sealed (i.e., at 0, 10, 20, and 30 min). Gas samples were analyzed within 72 h using a gas chromatograph (GC, Agilent 7890 B, Agilent Technologies, Santa Clara, CA, USA) and an electron capture detector. The temperatures used in the oven and electron capture detector were 55 °C and 350 °C, respectively.

The N₂O emission rate (F, μ g N₂O-N m⁻² h⁻¹) was calculated as follows:

$$F = \rho \times h \times \frac{dc}{dt} \times \frac{273}{273 + T}$$
(1)

where ρ is the standardized state gas density of N₂O (mg cm⁻³), *h* is the height of the chamber (m), $\frac{dc}{dt}$ is the ratio of N₂O accumulation in the chamber (the linear regression varied based on the N₂O concentration, and the R² value was used to determine the degree of fit), and *T* is the temperature in the box (absolute temperature in °C).

The cumulative N₂O emissions were calculated as follows:

$$\sum N_2 O = \sum_i^n (R_i \times D_i)$$
⁽²⁾

where R_i is the mean N₂O emission in the sampling interval, D_i is the sampling interval, and n is the number of sampling intervals.

The loss of N fertilizer as N_2O was noted the difference between the cumulative N_2O emissions under fertilization and no fertilization treatments. The N_2O emission factor was calculated as the ratio (%) of the loss of nitrogen fertilizer as N_2O to the N application rate. The yield-scaled N_2O emissions were determined as the ratio of cumulative N_2O emissions relative to the spring maize grain yield.

2.3.3. Soil Properties

Before maize sowing was performed in 2015, a five-point sampling method was used to collect 0–20-cm soil layer soil samples. pH was determined via the potentiometric method in a KCl solution at a concentration of 1 mol L^{-1} , using a pH 538 laboratory pH meter and a WTW electrode (WTW, Berlin, Germany). The content of organic carbon (OC) was determined using a TOC Analyzer (Shimadzu Corporation, Kyoto, Japan) and an SSM-5000A (Solid Sample Module) adapter. Total N was assayed via the Kjeldahl distillation method after the mineralization of ash and soil in concentrated sulfuric acid (VI) through the addition of hydrogen peroxide as a catalyst. Wet digestion of samples was performed using a speed digester K-439 digestion furnace (BUCHI Labortechnik AG, Flawil, Switzerland) equipped with a scrubber K-415 vapor absorber (BÜCHI Labortechnik AG, Flawil, Switzerland). Nitrogen distillation was performed using a K-355 steam still (BUCHI Labortechnik AG, Flawil, Switzerland). The content of available phosphorus was determined via molybdenum-antimony resistance colorimetry (Ultraviolet and visible spectrophotometer, Uniko (Shanghai) Instrument Co., Ltd., Shanghai, China). The available potassium was determined via flame spectrophotometry (Flame photometer, Sherwood Scientific Ltd., London, UK).

During the gas sampling process, an electronic thermometer was used to measure the soil temperature at a depth of 10 cm for each gas chamber, and a soil drill was used to collect the soil (0–20 cm) to determine the soil water and mineral N (NO_3^- -N and NH_4^+ -N) contents used by the AA3 continuous flow analyzer (Seal Analytical, Ltd., Mequon, WI, USA). The soil moisture content was determined using the drying method. The water-filled pore space (WFPS, %) was calculated based on soil bulk density [45].

2.3.4. Grain Yield, Accumulated Nitrogen Uptake, Nitrogen Partial Factor Productivity (NPFP), and Nitrogen Apparent Use Efficiency (NAUE)

At physiological maturity, two rows of plants were selected to be harvested in each plot (not including the side rows) to determine the yield. Fifteen ears were randomly selected in each plot to determine the ear characteristics, number of grains per ear, and 100-kernel weight.

At the maturity stage, three spring corn plants with uniform growth were selected in each plot. The grain and straw sub-samples were dried and weighed to assess the plant biomass, and they were then ground to pass through a 0.25-mm mesh screen to determine the N concentration. The samples of different plant parts were ground and passed through a 2-mm sieve to analyze the N concentration in different parts using the Kjeldahl method [46]. NPFP and NAUE were calculated as follows:

$$NPFP = \frac{\text{Grain yield by N treatment}}{\text{N application rate}}$$
(3)

$$NAUE = \frac{N \text{ accumulation by N treatment} - N \text{ accumulation without N treatment}}{N \text{ application rate}}$$
(4)

2.3.5. Economic Benefits

The net income was calculated as the difference between the total output and total input. The total input comprised the labor and material inputs. The labor inputs mainly comprised the labor required to transform the farmland topography, film mulching, sowing, weeding during the growth period, and harvesting, and the material inputs mainly comprised the plastic film, seeds, and chemical fertilizers. The total output only comprised the grain and straw revenues.

2.3.6. Statistical Analysis

SPSS v. 20.0 (IBM, New York, NY, USA) and GraphPad Prism 8.0 (GraphPad Software, Boston, MA, USA) were used to perform data analysis and create mapping plots, respec-

tively. The least significant difference test was used to detect differences between means when a significant treatment effect was indicated at p < 0.05.

3. Results

3.1. Spring Maize Growth

Compared to FS, RFPM significantly increased the plant height, LAI, and biomass during the three growing seasons (Figure 2). Under the same sowing pattern, the N management method had no significant effect on plant height (Figure 2a–c). In most cases, the LAI and biomass followed a consistent trend among the different N management methods, i.e., N3 > N2 > N1 > N0 (Figure 2a–f).



Figure 2. The effects of the sowing pattern and N management method on the LAI and biomass of spring maize in 2015 (**a**,**d**), 2016 (**b**,**e**), and 2017 (**c**,**f**), respectively. The vertical bars indicate standard errors of the mean. The lowercase letters indicate significant differences between treatments, and the capital letters indicate differences between sowing patterns. SP and NM refer to sowing pattern and N management method, respectively. ** indicates significant differences at p < 0.01; * indicates significant differences.

3.2. Spring Maize Productivity

3.2.1. Grain Yield and Yield Components

Due to the effects of inter-annual climate factors, the spring maize grain yields were 9.91–12.2 t ha⁻¹, 4.20–7.21 t ha⁻¹, and 5.63–7.99 t ha⁻¹ in 2015, 2016, and 2017, respectively (Tables 1 and S1). Compared to FS, RFPM significantly increased the grain yields by 6.9%, 46.6%, and 23.3% in 2015, 2016, and 2017, respectively. Under the two sowing patterns, the grain yields were consistent with different N management strategies, i.e., N3 (8.31 t ha⁻¹) > N2 (8.23 t ha⁻¹) > N1 (7.69 t ha⁻¹) > N0 (7.18 t ha⁻¹), but there was no significant difference between the N2 and N3 treatments. The changes in the grain number per spike and the 100-grain weight were consistent with those identified in the grain yield, but the spike number per hectare did not significantly differ between treatments.

Factor		GY (t ha ⁻¹)	Spike Number per Hectare	Grain Number per Spike	100-Grain Weight (g)	Accumulation of N Uptake (kg ha ⁻¹)	NPFP (kg kg ⁻¹)	NAUE (%)
Growing season	2015	11.20 a	65,414.13 a	557.13 a	26.46 a	209.51 a	51.46 a	26.90 a 14.91 b
	2016	5.69 c	62,248.13 c	407.29 c	26.54 a	140.02 c	25.92 c	
	2017	6.69 b	64,822.50 b	434.50 b	26.54 a	183.69 b	30.87 b	14.50 b
SP	FS	7.15 b	63,145.75 b	435.53 b	25.79 b	159.58 b	32.53 b	15.20 b
	RFPM	8.57 a	65,177.42 a	497.08 a	27.23 a	195.90 a	39.64 a	22.34 a
NM	N0	7.18 c	64,215.83 ab	443.67 c	25.70 с	146.08 c	/	/
	N1	7.70 b	63,861.33 b	460.56 b	26.23 bc	173.53 b	34.16 b	12.21 c
	N2	8.24 a	64,191.33 ab	479.33 a	26.78 ab	193.69 a	36.88 a	21.17 b
	N3	8.32 a	64,377.83 a	481.67 a	27.33 a	197.66 a	37.22 a	22.92 a
F test (Y)		**	**	**	**	**	**	**
F test (SP)		**	**	**	**	**	**	**
F test (NM)		**	**	**	**	**	**	**
F test (Y*SP)		**	**	** NS **		**	*	**
F test (Y*NM)		NS	NS	**	** NS NS		NS	NS
F test (SP*NM)		NS	NS	NS	NS NS NS		NS	NS
F test (Y*SP*NM)		NS	NS	NS	NS	NS	NS	NS

Table 1. The effect of the sowing pattern (SP) and N management method (NM) on the grain yield (GY), yield components, accumulation of N uptake (ANU), NPFP, and NAUE of spring maize in 2015, 2016, and 2017.

Notes: The different small letters indicate significant differences between various treatments at the p = 0.05 level. *, and **, denote significant differences at p = 0.05, and p = 0.01 probability levels, respectively. NS represents non-significant differences at the p = 0.05 level.

3.2.2. The Accumulation of N Uptake, NRFP, and NAFP

The year, sowing pattern, and N management strategy in question all had significant main effects on N uptake, NPFP, and NAUE (Tables 1 and S1). The differences between the accumulated N uptake, NPFP, and NAUE values were consistent among the three years, i.e., 2015 > 2017 > 2016. Compared to FS, RFPM increased the accumulated N uptake, NPFP, and NAUE by 22.74%, 21.76%, and 47.11% (three-year averages), respectively. Under the two sowing patterns, the accumulated N uptake followed a consistent trend under the following different N management strategies: N3 (197.67 kg ha⁻¹) > N2 (193.70 kg ha⁻¹) > N1 (173.55 kg ha⁻¹) > N0 (146.07 kg ha⁻¹). Under the same sowing pattern, NPFP and NAUE were significantly higher under the N2 and N3 treatments than N1 treatment in most cases, but there were no significant differences between N2 and N3 treatments (p > 0.05).

3.3. N_2O Emissions

3.3.1. N₂O Emission Flux

Compared to FS, RFPM increased the N₂O emission flux in the early stage of spring maize growth, especially the emission peak, but there were no significant differences in the later stage (Figure 3). Under the two sowing patterns, the N₂O emission flux did not noticeably fluctuate under N0 treatment, and it was always lower than those under the other N management strategies. In regard to the other N management strategies, the N₂O emission flux tended to initially increase and then decrease, at which point a second emission peak occurred under N2 treatment after topdressing (Figure 3). Clearly, in the early stage of spring maize growth, the N₂O flux and emission peak were higher under N1 treatment than the N2 and N3 treatments. In particular, under FS, the N₂O emission peaks under N1, N2, and N3 treatments were 239.85 µg m⁻² h⁻¹, 146.70 µg m⁻² h⁻¹, and 164.15 µg m⁻² h⁻¹, respectively; under RFPM, the emission peaks under N1, N2, and N3 treatment were 264.90 µg m⁻² h⁻¹, 159.45 µg m⁻² h⁻¹, and 179.60 µg m⁻² h⁻¹, respectively.



Figure 3. The effects of the sowing pattern and N management method on N₂O fluxes in 2015 (**a**,**b**) and 2016 (**c**,**d**). Data points represent mean value (n = 3) and the bar indicates one standard error to the mean.

3.3.2. Cumulative N_2O Emission and Yield-Scaled N_2O Emission

Compared to 2016, the cumulative N_2O emissions, loss of N fertilizer as N_2O , and emission factor were higher in 2015, but the yield-scaled N_2O emissions were lower (Figure 4). Compared to FS, RFPM increased the average cumulative N_2O emissions, loss of N fertilizer as N_2O , and emission factor over two years by 7.89%, 14.29%, and 14.05, respectively, but the yield-scaled N_2O emissions decreased by 14.51%.



Figure 4. The effects of the sowing pattern and N management method on seasonal cumulative N₂O emissions (**a**,**b**), yield-scaled N₂O emissions (**c**,**d**), loss of nitrogen fertilizer as N₂O (**e**,**f**) and emission factor (**g**,**h**) in 2015 and 2016. The vertical bars indicate the standard errors of the mean. The lowercase letters indicate significant differences between treatments. SP and NM refer to sowing pattern and N management method, respectively. ** indicates significant differences at *p* < 0.01; * significant indicates differences at *p* < 0.05; ns indicates non-significant differences.

Under the two sowing patterns, the cumulative N_2O emissions and yield-scaled N_2O emissions were always lower under N0 treatment (Figure 4). The cumulative N_2O emissions, yield-scaled N_2O emissions, loss of N fertilizer as N_2O , and N_2O emission factor were highest under N1 treatment, followed by the N2 and N3 treatments. Regression analysis showed that both the cumulative N_2O emissions and yield-scaled N_2O emissions significantly decreased as the accumulated N uptake by spring corn increased (Figure 5).



Figure 5. Relationship between the accumulation of N uptake of spring maize and cumulative N₂O emissions and yield-scaled N₂O emissions under three nitrogen application treatments (N1, N2, and N3). ** indicates significant differences at p < 0.01.

3.4. Selected Soil Physical and Chemical Properties and Their Relationships with N₂O Flux 3.4.1. Soil Moisture and Temperature

Due to the influence of precipitation, the WFPS under each treatment varied throughout the growth period (Figure 6). In the early and middle stages, i.e., in 2015 and 2016 (16 July 2015 and before 23 July 2016), the WFPS significantly increased under RFPM compared to FS, but the different sowing patterns generally had no significant effects on the WFPS in the later period. In addition, the N management strategies had no significant effects on the WFPS. Regression analysis showed that the N₂O flux increased significantly as the WFPS increased in the two growing seasons ($R^2 = 0.11$ ** and 0.048 **).



Figure 6. The effects of the sowing pattern and N management method on soil moisture (water filled pore space, WFPS) in 2015 (**a**) and 2016 (**b**). The relationship between soil moisture and N₂O flux in 2015 (**c**) and 2016 (**d**). In figures (**a**,**b**), data points represent mean values (n = 3), and the bar indicates one standard error to the mean. * represents values significant at p < 0.05; ** indicates significant differences at p < 0.01; ns represents no significant difference. The regression equations are presented in figures (**c**,**d**).

Similar to the WFPS, the soil temperature was only affected by the sowing pattern (Figure 7). Compared to FS, the soil temperature increased in the early growth period under RFPM (before 10 June 2015 and 16 June 2016), but it had no significant effect on the soil temperature in the later period. Regression analysis showed that in 2015, the N₂O flux significantly increased as the soil temperature increased ($R^2 = 0.048$ *), but no significant linear relationship was recorded in 2016 (p > 0.05).



Figure 7. The effects of sowing pattern and N management method on soil temperature in 2015 (**a**) and 2016 (**b**). The relationship between soil temperature and N₂O flux in 2015 (**c**) and 2016 (**d**). The vertical bars indicate standard errors of the mean. NS represents no significant difference. In figures (**a**,**b**), data points represent mean values (n = 3), and the bar indicates one standard error to the mean. * significant at p < 0.05, ns represents no significant difference. The regression equations are presented in figures (**c**,**d**).

3.4.2. Soil NO₃⁻-N and NH₄⁺-N Contents

The soil NO₃⁻-N contents were affected by the different sowing methods and N management strategies (Figure 8). Compared to N1, the NO₃⁻-N contents fluctuated more evidently under N1, N2, and N3 treatment. In the early stage, the NO₃⁻-N contents were higher under N1 and N3 than N2, but the soil NO₃⁻-N content clearly increased after topdressing with N2, and it was even higher than those under N1 and N3. In general, under the two sowing patterns, the mean soil NO₃⁻-N contents followed a pattern consistent with those of the different N management strategies, i.e., N3 > N2 > N1 > N0. The mean soil NO₃⁻-N contents were higher under RFPM than FS.

Similar to the NO_3^- -N contents, the NH_4^+ -N contents did not significantly vary with N0 (Figure 9). Under the two sowing patterns, the soil NH_4^+ -N contents rapidly increased after fertilization with N1, N2, and N3 and peaked about 6 days later, before decreasing rapidly and then stabilizing. However, the NH_4^+ -N content peaked again after topdressing with N2. The two-year average NH_4^+ -N contents with N0, N1, N2, and N3 were 2.5 mg kg⁻¹, 13.5 mg kg⁻¹, 15.5 mg kg⁻¹, and 15.8 mg kg⁻¹, respectively, under FS, as well as 2.5 mg kg⁻¹, 10.3 mg kg⁻¹, 12.1 mg kg⁻¹, and 13.3 mg kg⁻¹ under RFPM. In contrast to the NO_3^- -N contents, the NH_4^+ -N contents were higher under FS than RFPM.



Figure 8. The effects of the sowing pattern and N management method on soil NO_3^- -N content in 2015 (**a**,**b**) and 2016 (**c**,**d**). The histogram shows the mean values of soil NO_3^- -N content during the whole growing season under different N management strategies. In the figure, data points represent mean values (n = 3), and the bar indicates one standard error to the mean.



Figure 9. The effects of the sowing pattern and N management method on soil NH_4^+ -N content in 2015 (**a**,**b**) and 2016 (**c**,**d**). The histogram shows the mean values of soil NH_4^+ -N content during the whole growing season under different N management strategies. In the figures, data points represent mean values (n = 3), and the bar indicates one standard error to the mean.

Regression analysis showed that the N_2O flux was significantly positively correlated with the soil NO_3^- -N and NH_4^+ -N contents in 2015 and 2016 (Figure 10).



Figure 10. The relationship between soil NO₃⁻-N and soil NH₄⁺-N content and N₂O flux in 2015 (**a**,**c**) and 2016 (**b**,**d**). The regression equations are presented in figures (**c**,**d**). ** and *** represent values significant at p < 0.001 and p < 0.001, respectively.

3.5. Economic Benefits

Due to differences in grain yield and biomass, the net incomes in 2015, 2016, and 2017 were 2508.1–3409.9 US\$ ha⁻¹, 905.1–1679.2 US\$ ha⁻¹, and 1418–2020.1 US\$ ha⁻¹, respectively (Table 2). Compared to FS, the labor input and price of the plastic film increased the costs under RFPM, but RFPM increased the grain and hay output, thereby resulting in an increase in the net income of 25.96%. The total input, total revenue, and net income were consistently lower under N0 in all three years. Compared to N0, the production input increased with N1, N2, and N3, but all treatments increased the total output, and the final net income increases were 11.47%, 21.65%, and 20.87%, respectively. In general, RFPM combined with N2 or N3 led to higher net incomes.

Growing Seasons	Sowing Method	Treatments	Labor Input (US\$ ha ⁻¹)		Material Input (US\$ ha ⁻¹)			Machinery Input (US\$ ha ⁻¹)	achinery Input (S\$ ha ⁻¹) Total Input	Output (US\$ ha^{-1})		Total Output	Net Income
			Field Man- agements	Seeding, Harvesting	Plastic Sheets	Commercial Seeds	Fertilizers	Land Preparation	Grain Yield	Hay Yield	(US\$ ĥa ⁻¹)	(055 lla -)	
2015		N0	160	50	0	156.3	/	120	486.3	2669.64	324.8	2994.4	2508.1
	TC	N1	190	50	0	156.3	151.2	120	667.5	3325.00	358.3	3683.3	3015.8
	FS	N2	250	50	0	156.3	151.2	120	727.5	3405.16	374.0	3779.2	3051.7
		N3	190	50	0	156.3	226.8	120	743.1	3292.39	396.0	3688.4	2945.3
		N0	210	50	117.2	156.3	/	120	653.5	2909.40	541.3	3450.7	2797.2
	DEDM	N1	240	50	117.2	156.3	151.2	120	834.7	3325.00	597.2	3922.2	3087.5
	KFFW	N2	300	50	117.2	156.3	151.2	120	894.7	3681.25	623.4	4304.6	3409.9
		N3	240	50	117.2	156.3	226.8	120	910.3	3651.56	660.1	4311.6	3401.3
		N0	160	50	0	156.3	/	120	486.3	1079.16	212.3	1291.4	805.1
	TC	N1	190	50	0	156.3	151.2	120	667.5	1246.88	234.9	1481.8	814.3
	F5	N2	250	50	0	156.3	151.2	120	727.5	1464.86	261.4	1726.3	998.8
2016		N3	190	50	0	156.3	226.8	120	743.1	1488.25	271.2	1759.4	1016.3
2016		N0	210	50	117.2	156.3	/	120	653.5	1543.80	353.8	1897.6	1244.1
	RFPM	N1	240	50	117.2	156.3	151.2	120	834.7	1929.69	391.5	2321.2	1486.5
		N2	300	50	117.2	156.3	151.2	120	894.7	2137.50	435.7	2573.2	1678.5
		N3	240	50	117.2	156.3	226.8	120	910.3	2137.50	452.0	2589.5	1679.2
2017	FS	N0	160	50	0	156.3	/	120	486.3	1663.36	241.0	1904.3	1418.0
		N1	190	50	0	156.3	151.2	120	667.5	1690.13	285.4	1975.5	1308.0
		N2	250	50	0	156.3	151.2	120	727.5	1848.87	323.9	2172.7	1445.2
		N3	190	50	0	156.3	226.8	120	743.1	1900.41	334.1	2234.5	1491.4
		N0	210	50	117.2	156.3	/	120	653.5	1840.63	401.6	2242.3	1588.8
	DEDM	N1	240	50	117.2	156.3	151.2	120	834.7	2196.88	475.7	2672.5	1837.8
	IXI T IVI	N2	300	50	117.2	156.3	151.2	120	894.7	2375.00	539.8	2914.8	2020.1
		N3	240	50	117.2	156.3	226.8	120	910.3	2345.31	556.9	2902.2	1991.9

Table 2. The effects of sowing pattern and N management method on the economic benefits (US\$) of spring maize in 2015, 2016, and 2017.

Notes: The price per unit for urea and controlled-release urea was 0.31 US\$ kg⁻¹ and 0.47 US\$ kg⁻¹, respectively. The price per unit for grain and straw was 0.3 US\$ kg⁻¹ and 0.03 US\$ kg⁻¹, respectively. Values are given as the means of three replications.

4. Discussion

RFPM is considered to be one of the most effective sowing methods in terms of improving crop productivity in rain-fed agricultural areas [14,16]. In the present study, compared to FS, RFPM significantly improved the productivity of spring maize by promoting crop growth (Figure 2), including improvements in the grain yield, N uptake, and N use efficiency (Tables 1 and S1). These results are consistent with those obtained in previous studies [14,16,47]. We considered that the improved micro-environment under RFPM alleviated the restrictions on water and nutrient availability to crops, thereby promoting growth of the canopy and roots to enhance the absorption of water and nutrients, thus increasing the accumulated dry matter and grain yield [24,48,49].

In the Loess Plateau region, low precipitation in the early growth stage of spring maize makes it difficult to obtain a suitable water environment in the soil for N absorption by crops. Importantly, the N requirements of crops are usually greater in the middle and late growth stages; thus, the available N supply is not well synchronized when all of the urea is applied as a base fertilizer (N1) [40,49,50]. Past studies have shown that improving the synchronization of the N supply with the crop N demand will promote root growth and the root morphology [51,52] to enhance the uptake of N and water, especially in the later growth stage [53]. In the present study, N2 and N3 significantly improved the accumulated dry matter, grain yield, and N use efficiency in spring maize compared to N1 (Figure 2, Tables 1 and S1). In addition, we found that the productivity of spring maize under RFPM was highest under the N2 and N3 treatments (Tables 1 and S1), which may be due to the relationship between soil N supply and crop N demand, which was improved via split urea application and CRU [40–42].

Furthermore, N₂O is an intermediate product of microbe-mediated nitrification and denitrification processes [54,55], in which its production is determined based on physical and chemical properties, such as the soil temperature, moisture content, and mineral nitrogen content [54,56,57]. The N₂O emissions under RFPM are still controversial. Some studies have shown that thin film mulching under RFPM reduces the contact surface between soil and air to decrease N_2O emissions [9,28,29]. Yu et al. (2017) [58] used the denitrification-decomposition (DNDC) model, predicting that plastic film mulching would reduce N₂O emissions in the context of climate change. However, other studies have suggested that RFPM might promote N₂O emissions by improving the soil's hydrothermal environment [26,27]. The results obtained in the present study indicate that RFPM increased cumulative N₂O emissions by 7.89% compared to FS. In addition to improving the hydrothermal environment, the production of N_2O increased due to the promotion of nitrification and denitrification processes [59–61], and the increase in the soil's WFPS under RFPM resulted in a "piston effect" that caused the soil's pores to intensify N2O overflow [62,63]. Thus, our results showed that RFPM mainly increased cumulative N_2O emissions by increasing the N₂O flux in the early growth stage of spring maize because the N₂O flux did not significantly differ in the middle and late growth stages, a fact that we considered to be related to the changes in the soil's hydrothermal environment. In the early growth stage, RFPM significantly improved the soil hydrothermal environment due to its enhanced water collection effect and the warming effect of the plastic film [47]. However, in the later stage, the dense spring maize canopy made it difficult for solar radiation to reach the ground, thereby reducing the warming and insulation effects of the plastic film [24]. In addition, spring maize produced a larger canopy under RFPM than FS (Figure 2), which may have increased the consumption of soil water [49]; thus, RFPM did not enhance the soil's hydrothermal environment in this stage (Figures 6 and 7), resulting in no significant change in the N₂O flux.

Many previous studies have shown that the application of N fertilizer is the main direct factor related to soil N₂O emissions [9,26]. For example, Zhang et al. (2021c) [64] used the N¹⁵ tracer technique to show that N fertilizer directly provided sufficient N to N₂O producers or stimulated the mineralization of soil organic matter to promote the production of N₂O, using soil N as the substrate. Therefore, in the present study, the N₂O flux and

cumulative N₂O emissions were significantly higher under N1, N2, and N3 treatment than N0 (Figures 3 and 4). Increasing the N supply usually increases the availability of the substrate required for N₂O production [10,11], and some studies determined a significant positive correlation between the N₂O flux peak and N supply [9,65]. Therefore, compared to N1, the N₂O flux peak reduced under N2 and N3 due to the decreased N input in the base fertilizer and slow release of N, respectively (Figure 3). Previous studies also found positive correlations between the N₂O flux and soil NO₃⁻-N and NH₄⁺-N contents [9,32,66], and the same results were obtained in our study (Figure 10). Improving the crop N uptake by optimizing cultivation management measures can reduce the soil N availability and N₂O emissions [9,31], and we found that cumulative N₂O emissions significantly decreased as the N uptake increased (Figure 5), which may have been the main reason that the N2 and N3 treatments reduced the cumulative N₂O emissions (Figure 4).

Moreover, grain yield and cumulative N₂O emissions are key indicators used to measure the crop productivity and emissions of N_2O , respectively, but it is difficult to correlate these two independent indicators. Some researchers have tried to establish a relationship between crop productivity and N₂O emissions using yield-scaled N₂O emissions (ratio of cumulative N₂O emissions relative to the grain yield), which can be regarded as the environmental cost of crop production [67,68]. For example, Venterea et al. (2011) [67] found that the yield-scaled N₂O emissions were small when the remaining N (N application rate minus N uptake by crops) was negative or close to zero, but further increasing the N application rate would increase the yield-scaled N₂O emissions. Some studies also identified the field management practice with the lowest environmental cost in regional production based on this index [69–71]. Increasing demand for food and climate change require the optimization of field management practices, i.e., maximizing crop productivity while minimizing environmental costs [72–74]. In the present study, we aimed to determine whether it is possible to balance increases in the productivity of spring maize with reductions in the environmental costs using an appropriate sowing pattern and N management strategy, and our results confirmed that this balance is achievable. Compared to FS, RFPM significantly reduced yield-scaled N₂O emissions due to the increases in the grain yield (Figure 4c,d, Tables 1 and S1). In addition, we found that the optimal N management strategy under RFPM could further reduce the yield-scaled N₂O emissions and increase the grain yield, especially N3 treatment. There is no denying that labor and material inputs are the two main agricultural production costs [75]. Compared to FS, the labor and material input costs were higher under RFPM, but the net income from grain and hay outputs was much higher (Table 2). Similar results were obtained in previous studies [76,77]. In the present study, the three N application treatments all improved the final net income compared to the no N application treatment, thereby demonstrating that N fertilizer plays an important role in improving the net income. Compared to N1, the labor and material costs increased under N2 and N3, respectively, but both methods increased the final net income, as there was almost no difference in the net incomes under the N2 and N3 treatments. An increased net income is often the main reason that farmers select specific field management practices [18]. Therefore, RFPM combined with N2 or N3 is a superior field management practice from a net income perspective.

It is generally accepted that the selection of reasonable field management practices requires the comprehensive consideration of many factors, including the crop productivity, environmental costs, and economic benefits [30,47]. Based on the spring maize grain yield, N uptake, net income, yield-scaled N₂O emissions, and cumulative N₂O emissions, the radar map depicted in Figure 11 clearly shows the optimal combination of the sowing pattern and N management strategy, i.e., RFPM combined with N2 or N3. However, considering the shortage of available labor for agricultural management caused by the continuous migration of the rural labor force to cities in China, as well as the lack of suitable machinery for later topdressing, N3 is a more suitable management strategy for promotion and application than N2. Other studies have shown that CRU can lower the N input threshold compared to the normal urea [41,42]; thus, CRU could potentially further



contribute to tradeoffs between the crop productivity and environmental costs [34], and it should be investigated using RFPM in future research.

Figure 11. Radar graphs illustrating the differences in grain yield, net income, N uptake, cumulative N_2O emissions, and yield-scaled N_2O emissions between different N management strategies using FS (a) and RFPM (b).

5. Conclusions

In the present study, we found that compared to other treatments, RFPM combined with N2 or N3 promoted the growth of the spring maize canopy and increased the spring maize productivity (the grain yield, cumulative N uptake, and N use efficiency). These two combinations increased the cumulative N₂O emissions but decreased the yield-scaled N₂O emissions. In addition, compared to FS, RFPM increased the production cost, but it also increased the net income by improving the total output. More importantly, compared to N2, the use of N3 is more advantageous in terms of reducing the labor cost. Therefore, we suggest combining RFPM with N3, as it is an efficient management strategy that can increase spring maize production in the Loess Plateau region.

Supplementary Materials: The following supporting information can be downloaded at: https: //www.mdpi.com/article/10.3390/agronomy13092220/s1, Table S1: Effect of planting pattern (PP) and N management method (NM) on grain yield (GY), yield components, accumulation of N uptake (ANU), NPFP and NAUE of spring maize in 2015, 2016 and 2017.

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