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ORIGINAL PAPER

# Response of productivity and nitrogen efficiency to plastic-film mulching patterns for maize in sub-humid northeast China

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## Abstract

In the semi-humid region of northeast China, the plastic-film mulching (PFM) is essential for sustaining yields, while the yield-increase potential and nitrogen (N) use mechanism under different PFM patterns in this area remain poorly understood. A field experiment using maize (*Zea mays* L.) was conducted for two consecutive years to study the effects of different PFM patterns on soil microclimate factors, N mineralization, N loss, crop yields and N use efficiency under drip irrigation. The six treatments consisted of full ridge-furrow mulching (FM), only ridge mulching (RM), non-mulching (NM), ridge-furrow mulching without fertilization (CFM), ridge mulching without fertilization (CRM), and non-mulching without fertilization (CNM). The results showed that the PFM could obviously warm the soil throughout the growing season. Compared to NM, FM and RM obviously increased the soil temperature by 2.0–5.4 ℃ and 1.6–4.8 ℃ in the 2017 season, respectively, and by 1.9–7.8 ℃ and 1.0–5.7 ℃ in the 2018 season, respectively. Across two years, soil temperature was highest for FM followed by RM and NM. In general, FM enhanced the soil water content compared with RM, especially in the 0–50 cm profile throughout the growing season. The PFM could significantly ($p < 0.05$) promote soil N mineralization ($N_{\mathrm{min}}$). Furthermore, irrespective of fertilization, the PFM significantly ($p < 0.05$) improved plant N uptake ($N_{\mathrm{uptake}}$), grain N accumulation ($N_{\mathrm{grain}}$) and N harvest index (NHI). Averaged across years, full ridge-furrow mulching and only ridge mulching distinctly enhanced the NHI under fertilization by 6.8% and 6.1%, respectively, relative to non-mulching. Finally, PFM imposed significant influence ($p < 0.05$) on ear barren tip, 100-seed weight and grain yield. Grain yield under FM and RM were significantly promoted by 15.0% and 12.5%, respectively, compared with NM. Meanwhile, full ridge-furrow mulching could obviously increase grain yield compared to ridge mulching. In conclusion, full ridge-furrow mulching provided a more feasible water-heat environment for soil N mineralization, improving plant N uptake and reducing N loss, and thereby significantly increasing crop productivity and nitrogen use efficiency.

## Introduction

The Northeast Plain of China, a typical rain-fed region, is one of the most important grain production bases of China, where more than 50% of the cultivated area (more than 11.1 million ha) was sown for maize cultivation, and produced approximately 34% of the total national production in 2016 (National Bureau of Statistics of China 2017). The maize (*Zea mays* L.) production directly affected the food security of China. However, the soil insufficient cumulative temperature and frequent drought in April–May constitute a major bottleneck to crop production (Yu et al. 2006; Wang et al. 2015a, b; Cai et al. 2017). Consequently, plastic-film mulching (PFM) technology, confirmed to be beneficial to improve agricultural production (Gao et al. 2014; Li et al. 2015), has been introduced and considered a potential agriculture practice in this region (Sui et al. 2018).

Modification of crop microclimate by plastic-film mulching the soil surface alters soil moisture and temperature (Wang et al. 2015a, b). Generally, PFM favorably influences soil moisture regime by controlling evaporation rate (Chakraborty et al. 2008; Li et al. 2013). Meanwhile, PFM effectively increases soil temperature through preventing latent heat and sensible heat exchange in near-surface air layers (Zhao et al. 2012; Wu et al. 2016) and absorbing the long-wave re-radiation from the soil (Ghosh et al. 2006). Greater soil temperature and moisture may potentially improve soil microbial activity and communities (Ford

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et al. 2007), and thereby accelerate soil nitrogen (N) transformations (i.e., N mineralization), which in turn will affect soil N availability and ecosystem productivity (Mohapatra et al. 1998; Fang et al. 2011). Moreover, PFM stimulated the absorption of N by crops (Wang et al. 2014), and thus maximizing the benefit of N fertilizer and minimizing N loss (Liu et al. 2015; Wang and Xing 2016). Based on these principles, changing PFM patterns (i.e., partly-mulched or fully-mulched pattern) may be able to adjust soil microclimate and soil microbial communities which directly affect soil N mineralization and absorption, and ultimately increase crop yield and fertilizer utilization efficiency. Zhou et al. (2009) reported that the film fully-mulched cropping maximized the reducing soil evaporation and increasing soil temperature. In addition, Hai et al. (2015) found that plastic film covered all soil surfaces prominently stimulated N mineralization, and thus increases soil availability and uptake by maize. However, until now, relatively few attentions have been paid to soil N transformations and N balance under different PFM patterns, and the potential to further improve N efficiency by plastic-film mulching remains unknown. Moreover, previous studies also reported that the positive effects of PFM relate to soil types and climatic conditions (Haapala et al. 2014; Sui et al. 2018). So far, extensive studies about crops cultivation under PFM mainly focused on arid and semi-arid region in the Northwest China (Wang et al. 2009; Gao et al. 2014; Zhao et al. 2014). Little researches were carried out to quantify the impacts of typical PFM patterns on soil microenvironment and N transformations in these regions were characterized by black soil rich in organic matter and abundant rainfall. Therefore, the underlying yield-increase mechanism of PFM in these agricultural systems has remained unclear. Against aforementioned background, in this study, N balance method was used to investigate soil net N mineralization and apparent N loss under different PFM patterns in the Northeast Plain of China, and soil microclimate factors, residual mineral N, crop N uptake and yields were also measured. The aims of this paper were to investigate the soil microenvironment factors response to PFM patterns in sub-humid region, to assess the effects of PFM patterns on soil net N mineralization, N loss, grain yields and N use efficiency, and to explore the suitable PFM practices for maize in the northeast China.

## Materials and methods

### Experimental site

Field experiments on maize (*Zea mays* L.) under drip irrigation were conducted at the Irrigation Experiment Station of the Jilin Institute of Water Resources Technology Research (125°19′ E, 43°38′ N and altitude 216 m) in Changchun, Jilin, China. The experimental area experiences a temperate sub-humid climate with an annual mean temperature of 4.8 ℃ and an annual mean precipitation of 568 mm with more than 60% occurring between June and September (Zhao and Zhang 2011). During maize growth, rainfall and air temperature were recorded with an automatic weather station (JLC-CQ1, Licheng, China) close to the experimental field. Due to the failure of the automatic weather station, the air temperature data from 105 to 125 DAS in 2017 were missing. At three locations of the field, undisturbed soil samples were taken at three depth intervals (0–30, 30–60 and 60–90 cm) for measurement of bulk density using 100 $cm^3$ rings and filed capacity following the method by Veihmeyer and Hendrickson (1949). The particle size distribution of the soil in the experimental field was measured using a laser method (Mastersizer 2000, Maleven Instruments, Ltd., Malvern, UK), and the texture was classified as silt loam with 12.7% clay, 73.1% silt and 14.2% sand. Selected physical properties are summarized in Table 1.

### Experimental design

Field experiments were conducted from May to September in 2017 and 2018. It had six treatments (three PFM patterns with and without N fertilization), replicated three times with a randomized complete block design. The three plastic-film mulching patterns were full ridge-furrow and only ridge mulching, respectively, with 150 cm and 60 cm wide plastic film (colorless, transparent and 0.008 mm thick) and one non-mulching treatment (Fig. 1), abbreviated as FM, RM and NM, respectively. Comparatively, three N-free treatments referred to CFM, CRM, and CNM were used as control treatments.

Each experimental plot size was 8 m long and 3.6 m wide. A 50 cm wide buffer zone between adjacent plots reduced

**Table 1** Major soil properties at the Irrigation Experimental Station in Changchun, Jilin, China

| Soil depth (cm) | Particle size distribution (%) | | | Soil texture | Soil bulk density (g $cm^{-3}$) | Field capacity ($cm^3$ $cm^{-3}$) |
|---|---|---|---|---|---|---|
| | Clay | Silt | Sand | | | |
| 0–30 | 12.9 | 72.9 | 14.2 | Silt loam | 1.35 | 0.35 |
| 30–60 | 12.7 | 72.9 | 14.4 | Silt loam | 1.47 | 0.40 |
| 60–90 | 12.4 | 73.6 | 14.0 | Silt loam | 1.42 | 0.42 |

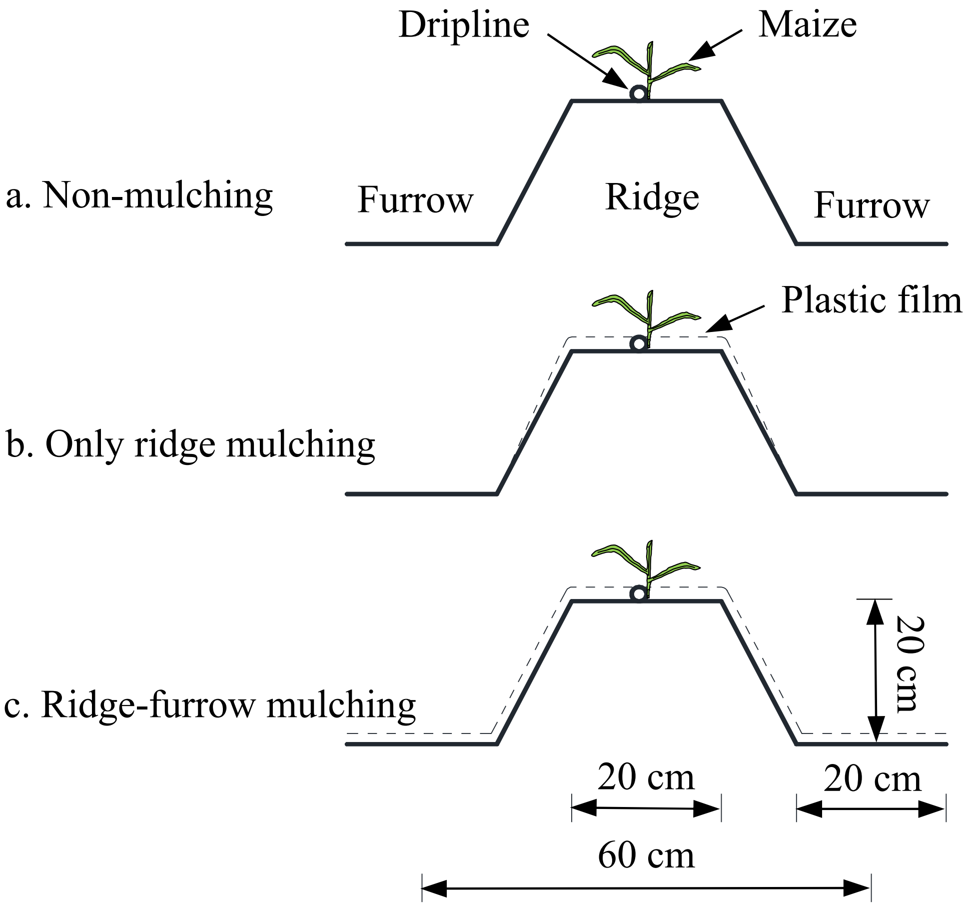


**Fig. 1** Ridge-furrow details and plastic-film mulching patterns

possible lateral exchange of water between plots. All plots were configured into a ridge-furrow pattern. The ridge was 20 cm wide, and the furrow between two ridges was 40 cm wide and 20 cm deep. For each plot, bunds with an approximate height of 20 cm were also constructed at both ends of each furrow to protect rainfall run off the plot during rainfall event. Maize was sown on 28 April in 2017 and 26 April in 2018. Each plot consisted of six maize rows and one-row maize was sown in a ridge with row spacing of 60 cm and plant spacing of 30 cm, resulting in a density of 55,555 plants per hectare.

## Irrigation and fertilization

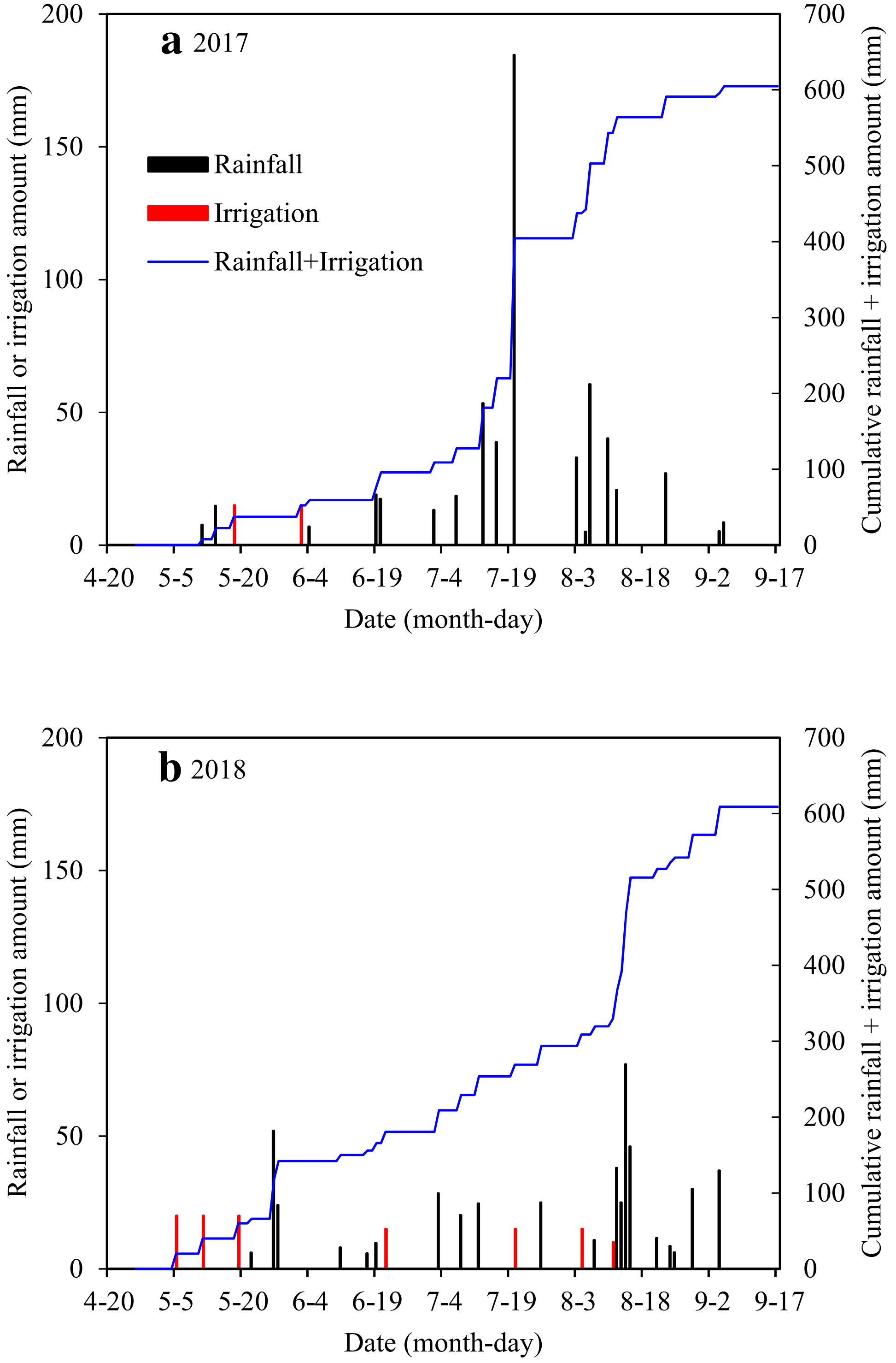
One dripline was installed within the median of each ridge to provide irrigation for each plot. The emitter spacing was 30 cm, and the nominal flow rate for each emitter was 1.38 L $h^{-1}$ at 0.1 MPa pressure. Irrigation was applied for each treatment when the soil moisture under non-mulching treatment was depleted to 65–70% of the field capacity. During the experimental seasons, the total precipitation recorded at the experimental site was 574.9 mm in 2017 and 494.1 mm in 2018. The field was irrigated 2 and 7 times in 2017 and 2018, respectively, and total irrigation depth was 30 mm in 2017 and 115 mm in 2018 (Fig. 2).

Compound fertilizers with $N:P_2O_5:K_2O$ of 28:13:14 were used for both seasons. Prior to sowing, each plot was fertilized with 239 kg $ha^{-1}$ N, 111 kg $ha^{-1}$ $P_2O_5$, 119 kg $ha^{-1}$ $K_2O$. This fertilization rate was recommended by the local agricultural extension agency. The pre-determined amount of compound fertilizers for a plot (2.88 kg) was broadcasted evenly by hand. Then, the ridges were prepared by a rotary cultivator.

## Samplings and measurements

The soil temperature at plough layer (0–30 cm) was measured with rectangular geothermometers (Xinglong Thermal Instruments, Wuqiang County, Hebei Province, China), which were placed in the middle of ridge for three treatments (i.e., FM, RM and NM). Soil temperatures were recorded at 8:00, 14:00 and 18:00 h every day. The mean daily soil temperature was calculated as the average of three daily readings for each treatment. Due to intermittent rainfall, soil temperature was not observed from 96 to 102 DAS and from 116 to 119 DAS in 2017. Soil water content was determined gravimetrically in all replications. Soil samples were collected in the middle of

**Fig. 2** Effective rainfall and irrigation during the 2017 and 2018 growing seasons



the ridge and between two maize plants, using 5-cm-diameter auger at one position in each plot. The depth interval spacing was 10 cm from 0 to 30 cm and 20 cm from 30 to 90 cm depth. Soil moisture was measured on 21 June (the end of the seeding stage), 25 July (the end of the jointing stage), 8 August (the end of the heading stage), 26 August (the end of the filling stage) and 17 September (the end of the maturity stage) in 2017 season; and June 17 (the end of the seeding stage), July 18 (the end of the jointing stage), August 4 (the end of the heading stage), August 23 (the end of the filling stage) and September 16 (the end of the maturity stage) in 2018 season. To determine the initial and residual mineral N in the 0–90 cm soil profile, soil samples were collected using auger at one location in each plot at six depths of 0–10, 10–20, 20–30, 30–50, 50–70 and 70–90 cm on 27 April and 17 September in 2017 season, and on 25 April and 18 September in 2018 season. Fresh soil samples were air-dried and then passed through a 1 mm sieve prior to measurement of $NO_3$–N and $NH_4$–N contents. Soil subsamples were extracted using 1 M $L^{-1}$ KCl solution (1:5, soil to solution ratio) and shaken for 1 h, followed by filtration and analysis for $NO_3$–N and $NH_4$–N concentrations employing an Autoanalyser (Bran + Luebbe, Norderstedt, Germany).

For each plot, two plants were selected for collecting plant samples at the end of each growth stage. The plant sample was clipped at the soil surface and oven-dried at 70 ℃ to a constant weight to measure the aboveground plant biomass. Total N content of aboveground plant sample was measured using a Kjeltec Analyzer (Kjeltec 2300, Foss, Denmark). Grain yield was harvested at the physiological maturity (on 16 September in 2017 and 17 September in 2018). Grain yield was determined from two inner rows of two equally distributed locations in each plot. At each location, 2.16 $m^2$ of plants (six plants per row) were manually harvested and grain yield was converted to a moisture content of 14%. The yield components (i.e., ear length, barren ear tip, kernel number per cob and 100-seed weight) were also measured from the harvested maize.

### Nitrogen efficiency and nitrogen balance

Nitrogen harvest index (NHI, %) as an important index to reflect internal transfer efficiency of absorbed N from vegetative plant parts to grain is generally calculated by the ratio between N uptake in grain and in whole plant:

$$\mathrm{NHI} = N_{\mathrm{grain}}/N_{\mathrm{uptake}} \times 100 \tag{1}$$

where $N_{\mathrm{grain}}$ and $N_{\mathrm{uptake}}$ are the grain and aboveground plant N accumulation (kg $ha^{-1}$), respectively (Austin and Jones, 1975; Löffler and Busch, 1982). N fertilizer agronomic efficiency (NAE, kg $kg^{-1}$) is defined as the increase in crop grain yield per unit of applied N:

$$\mathrm{NAE} = \left(Y_{\mathrm{wf}} - Y_{\mathrm{wc}}\right)/N_{\mathrm{F}} \tag{2}$$

where $Y_{\mathrm{wf}}$ and $Y_{\mathrm{wc}}$ are the grain yield with and without N application (kg $ha^{-1}$), respectively; $N_{\mathrm{F}}$ is the amount of N fertilizer applied (kg $ha^{-1}$) (Craswell and Godwin 1984). Nitrogen fertilizer use efficiency (NUE, %) is defined as the ratio of the increase in plant N accumulation that resulted from N fertilizer application to the N fertilizer rate:

$$\mathrm{NUE} = \left(N_{\mathrm{wf}} - N_{\mathrm{wc}}\right)/N_{\mathrm{F}} \times 100 \tag{3}$$

where $N_{\mathrm{wf}}$ and $N_{\mathrm{wc}}$ are the aboveground plant N accumulation with and without N application (kg $ha^{-1}$), respectively (Peng et al. 2002).

Each item for soil N budget was calculated for all treatments in two seasons. Only the 0–90 cm soil profile was considered for mineral N ($NH_4$–N + $NO_3$–N) in the N balance calculation. The components of soil nitrogen balance consisted of initial and residual soil mineral N, net N mineralization, fertilizer N, plant N uptake and apparent N loss ($N_{\mathrm{loss}}$, kg $ha^{-1}$). For each treatment, the nitrogen balance may be written as:

$$N_{\mathrm{loss}} = N_{\mathrm{input}} + N_{\mathrm{ini}} + N_{\mathrm{min}} - N_{\mathrm{uptake}} - N_{\mathrm{res}} \tag{4}$$

where $N_{\mathrm{input}}$, $N_{\mathrm{ini}}$ and $N_{\mathrm{res}}$ are $N$ application rate, initial and residual mineral N in the 0–90 cm soil profile (kg $ha^{-1}$), respectively. Assuming no apparent N loss, seasonal net N mineralization ($N_{\mathrm{min}}$, kg $ha^{-1}$) was roughly calculated by balance of N inputs and outputs in the control treatment as follows (Cabrera and Kissel 1988; Liu et al. 2003):

$$N_{\mathrm{min}} = N_{\mathrm{uptake,c}} + N_{\mathrm{res,c}} - N_{\mathrm{ini,c}} \tag{5}$$

where $N_{\mathrm{uptake,c}}$, $N_{\mathrm{res,c}}$ and $N_{\mathrm{ini,c}}$ are plant N uptake, residual and initial soil mineral N in the control treatments (kg $ha^{-1}$), respectively.

### Statistical analyses

Duncan's multiple range tests were conducted at the level of 0.05 to test the significance of soil water content, yield components, plant N uptake, nitrogen use efficiency and nitrogen balance among treatments. A two-way analysis of variance (ANOVA) was used to test whether the PFM pattern and fertilization had significant impact on maize yield and nitrogen efficiency. All the experimental data analyses were conducted with SPSS 16.0 package (SPSS 2007).

## Results and discussion

### Soil temperature

Soil temperature, directly affected by solar radiation and atmosphere temperature, is one of the most important factors affecting the crop growth (Chen et al. 2009). As shown in Fig. 3, the PFM could obviously warm the soil compared to non-mulching treatment throughout the entire growing seasons in 2017 and 2018. The daily mean soil temperature under all treatments followed a pattern similar to air temperature. Across the two seasons, soil temperature was highest for FM followed by RM and NM. Soil temperatures under FM and RM were 2.0–5.4 ℃ and 1.6–4.8 ℃ higher, respectively, than that under NM in 2017, and 1.9–7.8 ℃ and 1.0–5.7 ℃ higher, respectively, in 2018. Remarkably, compared with RM, the soil temperatures at 30 cm layer under FM were increased by 0.1–1.5 ℃ and 0.2–2.8 ℃ in

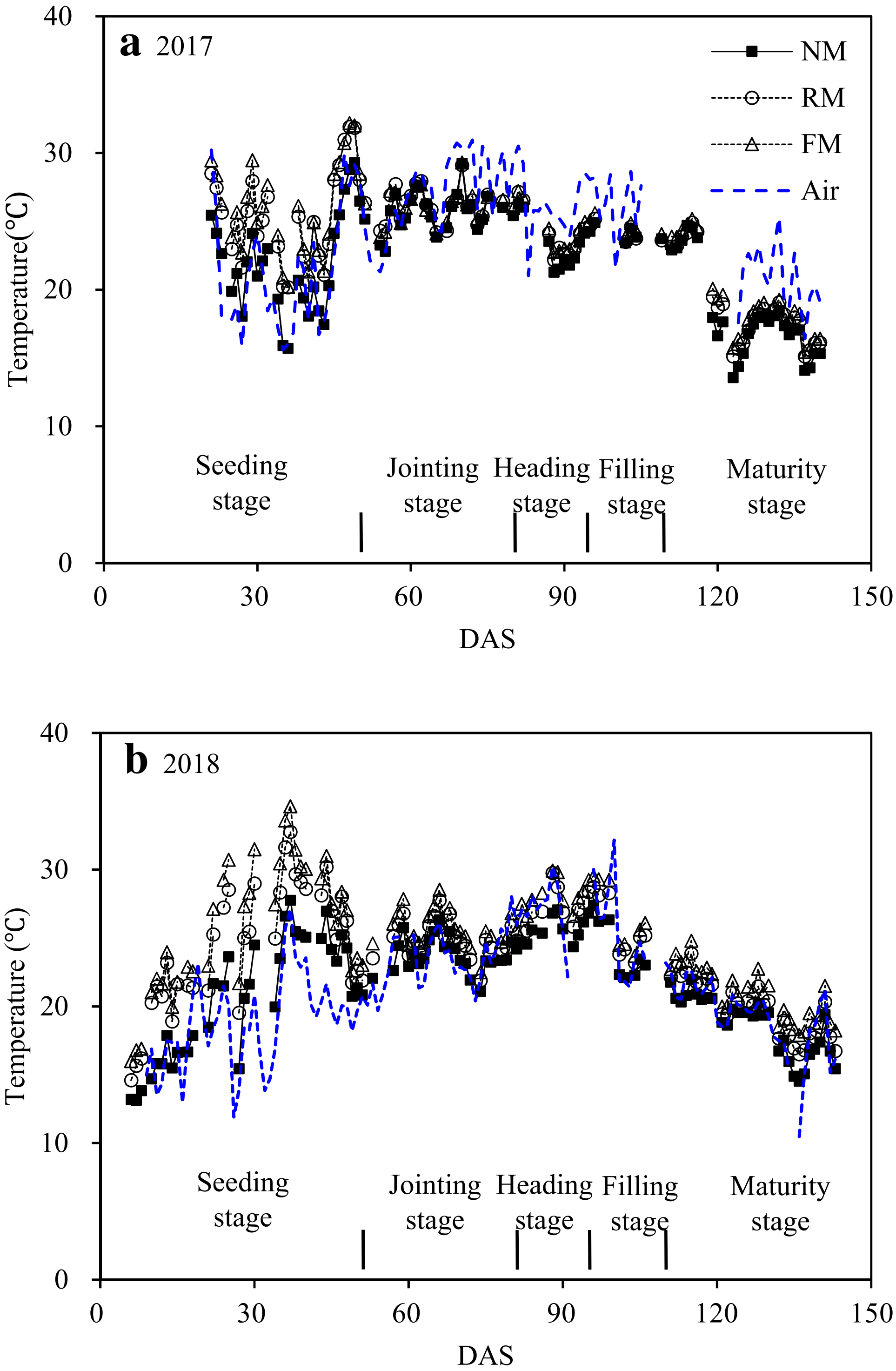


**Fig. 3** Air temperature and soil temperature (0–30 cm) of different treatments during growing seasons of maize in 2017 and 2018. *NM* plot without mulching, *RM* only ridge mulching, *FM* full ridge-furrow mulching

2017 and 2018, respectively, suggesting a better warming effect in FM treatment.

The average soil temperatures (0–30 cm) at each maize growth stage of non-mulching treatment were distinctly lower than that of mulching treatments, particularly at the beginning and late growing stage (Table 2). At the seeding stage, averaged across years, the average soil temperature under FM, RM and NM was 25.8 ℃, 24.9 ℃ and 21.4 ℃, respectively, and that under FM and RM were greatly increased by 21.1% and 16.4%, respectively, as compared to NM. After the seeding stage, although the soil temperature for non-mulching was lower than that of mulching, the difference in soil temperature among all treatments was small, which could be attributed to

**Table 2** The mean value of soil temperature (0–30 cm) at each growth stage

| Treatment | Average soil temperature (℃) | | | | |
|---|---|---|---|---|---|
| | Seeding stage | Jointing stage | Heading stage | Filling stage | Maturity stage |
| 2017 | | | | | |
| NM | 22.0 | 25.8 | 23.2 | 21.9 | 16.4 |
| RM | 25.4 | 26.2 | 23.7 | 22.4 | 17.2 |
| FM | 26.0 | 26.3 | 24.0 | 23.0 | 17.5 |
| 2018 | | | | | |
| NM | 20.7 | 24.0 | 25.5 | 21.4 | 17.7 |
| RM | 24.3 | 25.1 | 27.3 | 22.8 | 18.9 |
| FM | 25.7 | 25.9 | 28.1 | 23.6 | 19.9 |

*NM* plot without mulching, *RM* only ridge mulching, *FM* full ridge-furrow mulching

the ground covering by plants. At the maturity stage, as the air temperature drops, PFM showed a positive effect on improving soil temperature. Averaged over the two-year trial, the mean soil temperature at the maturity stage under FM, RM and NM was 18.7 ℃, 18.0 ℃ and 17.1 ℃, respectively. FM and RM increased soil temperature by 9.8% and 5.6%, respectively, relative to NM. These results indicate that the soil temperature in sub-humid region was appreciably impacted by plastic-film mulching, especially at the beginning and late growing stage, and could be enhanced through adequate management practices.

## Soil moisture

The effect of PFM patterns on soil moisture was studied for two consecutive years (Table 3). The non-mulching treatment generally had a higher soil water content than PFM treatments in 0–70 cm soil layer before maturity stage in 2017 and in 0–50 cm soil layer across the growing season in 2018. The differences in two experimental years can be attributed to the fact that the precipitation in 2017 (574.9 mm) was substantially higher than in 2018 (494.1 mm) and concentrated mostly in the summer months. In addition, the possible reason for low soil moisture content of mulching in deep soil layers was that better soil

**Table 3** Soil moisture content (0–70 cm) for different plastic-film mulching patterns at the end of each growth stage during 2017 and 2018

| Year | Soil depth (cm) | Treatment | Soil moisture content (%) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Seeding stage | Jointing stage | Heading stage | Filling stage | Maturity stage |
| 2017 | 0–30 | NM | 32.7 ± 0.6a | 33.3 ± 1.4a | 34.6 ± 0.2a | 36.0 ± 1.2a | 27.5 ± 0.2a |
| | | RM | 31.2 ± 1.9a | 32.6 ± 0.2a | 34.6 ± 1.1a | 32.8 ± 0.1b | 29.8 ± 2.0b |
| | | FM | 31.4 ± 1.2a | 34.0 ± 0.8a | 35.4 ± 3.5a | 32.5 ± 0.3b | 29.9 ± 0.2b |
| | 30–50 | NM | 38.8 ± 0.2a | 40.9 ± 1.7a | 41.8 ± 1.4a | 41.1 ± 1.8a | 33.7 ± 0.8a |
| | | RM | 35.7 ± 1.7b | 39.5 ± 1.4a | 41.3 ± 0.8a | 35.4 ± 0.6b | 35.2 ± 0.7b |
| | | FM | 36.4 ± 0.4b | 39.7 ± 1.4a | 41.3 ± 2.1a | 37.3 ± 2.5b | 34.7 ± 0.1b |
| | 50–70 | NM | 37.6 ± 0.1a | 39.2 ± 1.7a | 38.6 ± 2.1a | 40.1 ± 1.7a | 33.1 ± 1.2a |
| | | RM | 33.1 ± 1.8b | 37.8 ± 1.9a | 37.4 ± 1.1a | 35.4 ± 0.1b | 33.5 ± 1.0a |
| | | FM | 34.3 ± 0.4b | 37.7 ± 0.8a | 38.4 ± 1.2a | 37.8 ± 1.5ab | 32.9 ± 1.1a |
| 2018 | 0–30 | NM | 31.0 ± 0.2a | 30.5 ± 1.7a | 25.5 ± 1.9a | 33.6 ± 1.9a | 33.7 ± 0.8a |
| | | RM | 29.9 ± 2.5a | 30.1 ± 0.6a | 23.6 ± 3.0a | 33.2 ± 1.0a | 34.1 ± 0.9a |
| | | FM | 29.9 ± 2.6a | 30.2 ± 1.7a | 25.4 ± 1.4a | 33.6 ± 1.2a | 33.5 ± 1.1a |
| | 30–50 | NM | 36.4 ± 1.3a | 36.5 ± 1.4a | 30.8 ± 0.3a | 39.8 ± 2.3a | 39.9 ± 2.0a |
| | | RM | 34.9 ± 1.5a | 35.6 ± 1.1a | 30.0 ± 2.6a | 38.4 ± 1.8a | 39.7 ± 1.5a |
| | | FM | 35.9 ± 0.1a | 35.6 ± 1.5a | 30.8 ± 0.5a | 38.7 ± 0.3a | 39.6 ± 1.1a |
| | 50–70 | NM | 35.0 ± 0.3a | 32.9 ± 2.4a | 31.8 ± 1.1a | 38.9 ± 1.8a | 39.2 ± 2.8a |
| | | RM | 35.6 ± 0.7a | 34.1 ± 1.6a | 31.2 ± 1.8a | 39.1 ± 1.6a | 40.1 ± 1.6a |
| | | FM | 34.8 ± 0.9a | 34.7 ± 0.8a | 30.3 ± 1.2a | 38.4 ± 0.8a | 38.7 ± 2.0a |

Treatments with the same letter in each column are not significantly different at $p < 0.05$

*NM* plot without mulching, *RM* only ridge mulching, *FM* full ridge-furrow mulching hydrothermal conditions under PFM treatments resulted in better individual plant development, which exploited greater deep soil water (Jia et al. 2006; Bu et al. 2013). Throughout the growing season, although no significant differences were found between FM and RM at each soil layer in both years, the soil moistures under FM were generally higher than that under RM in the 0–70 cm profile in 2017 and in 0–50 cm profile in 2018 before the maturity stage. In the sub-humid northeast China, the plastic-film mulching reduced the amount of evaporation in maize field by reducing the net radiation under canopy, and finally improved water use efficiency in maize field with drip irrigation (Zhang et al. 2018). Therefore, full plastic-film mulching with larger mulching area would reduce more net radiation under canopy, thus reducing soil evaporation and creating more feasible environment of soil moisture (Li et al. 2013; Zribi et al. 2015). At the maturity stage, PFM significantly ($p < 0.05$) affected soil water content in the upper 50 cm layer in 2017. Compared to NM, FM and RM could markedly promote the soil moisture content by 1.0–2.4% and 1.5–2.3%, respectively. However, due to frequent rainfalls, similar effect of PFM in increasing soil moisture was not found at maturity stage in 2018.

## Soil nitrogen balance

For the aim of sustainable land use, considering soil nitrogen balance is an effective way to avoid negative effects on field ecosystem, particularly in high-yielding areas. Thus, the nitrogen budgets were calculated for each growing season and the results are described in Table 4. Mulching generally affects soil fertility through increase in the soil N mineralization. The PFM significantly ($p < 0.05$) promoted $N_{\mathrm{min}}$, while there was no significant difference between ridge-furrow and ridge mulching treatments. The $N_{\mathrm{min}}$ (26.4–69.4 kg ha$^{-1}$) in our experiment was an important input from the high-fertility soil, especially in the first trial year. In both years, the highest $N_{\mathrm{min}}$ (69.4 and 26.8 kg ha$^{-1}$) was observed in CFM and the lowest was found in CNM. This is likely due to the favorable soil hydrothermal conditions under ridge-furrow full mulching, which could greatly promote soil N mineralization through stimulating the activities of soil heterotrophic microorganisms (Mary et al. 1996; Ford et al. 2007). Meanwhile, at normal fertilization level (239 kg N ha$^{-1}$), PFM could decrease the residual mineral N in the soil. For example, the FM and RM treatments significantly reduced $N_{\mathrm{res}}$ by 37.0% and 29.9%, respectively, relative to NM in the 2017.

**Table 4** Nitrogen budgets (kg ha$^{-1}$) under different treatments in 2017 and 2018 growing seasons

| Treatment | $N_{\mathrm{ini}}$ | $N_{\mathrm{input}}$ | $N_{\mathrm{uptake}}$ | $N_{\mathrm{res}}$ | $N_{\mathrm{min}}$ | $N_{loss}$ |
|---|---|---|---|---|---|---|
| 2017 | | | | | | |
| NM | 164.8 | 239 | 327.6 ± 12.7b | 148.5 ± 42.3a | – | − 78.0 ± 43.7b |
| RM | 164.8 | 239 | 368.5 ± 4.9a | 104.1 ± 27.2b | – | − 27.9 ± 23.6ab |
| FM | 164.8 | 239 | 380.5 ± 28.4a | 93.5 ± 6.4b | – | − 0.80 ± 31.3a |
| CNM | 164.8 | 0 | 96.2 ± 28.6d | 62.8 ± 4.1b | − 5.6 ± 30.1b | – |
| CRM | 164.8 | 0 | 113.8 ± 12.7 cd | 91.8 ± 10.5b | 40.9 ± 23.3a | – |
| CFM | 164.8 | 0 | 139.9 ± 18.2c | 94.2 ± 7.6b | 69.4 ± 17.8a | – |
| ANOVA (*p* values) | | | | | | |
| Mulching pattern | – | – | **(0.004) | NS | *(0.025) | NS |
| Fertilization | – | – | ***(0.000) | **(0.008) | – | – |
| 2018 | | | | | | |
| NM | 151.7 | 239 | 219.3 ± 9.1b | 58.3 ± 6.4ab | – | 101.3 ± 7.3a |
| RM | 151.7 | 239 | 271.3 ± 19.6a | 65.3 ± 7.8a | – | 80.4 ± 21.6a |
| FM | 151.7 | 239 | 274.2 ± 19.0a | 51.6 ± 4.7b | – | 91.5 ± 21.3a |
| CNM | 101.6 | 0 | 60.6 ± 16.9d | 29.3 ± 2.6c | − 11.6 ± 15.2b | – |
| CRM | 101.6 | 0 | 97.3 ± 16.2c | 30.6 ± 8.0c | 26.4 ± 13.1a | – |
| CFM | 101.6 | 0 | 96.9 ± 15.0c | 31.4 ± 5.1c | 26.8 ± 14.6a | – |
| ANOVA (*p* values) | | | | | | |
| Mulching pattern | – | – | **(0.001) | NS | *(0.026) | NS |
| Fertilization | – | – | ***(0.000) | ***(0.000) | – | – |

Treatments with the same letter in each column are not significantly different at $p < 0.05$

*NS* indicates no significance

*NM* plot without mulching, *RM* only ridge mulching, *FM* full ridge-furrow mulching, *CNM* no mulching and no fertilizing, *CRM* ridge mulching and no fertilizing, *CFM* ridge and furrow mulching and no fertilizing, $N_{ini}$ initial mineral N, $N_{input}$ N application, $N_{uptake}$ aboveground plant N accumulation, $N_{res}$ residual mineral N, $N_{min}$ net N mineralization, $N_{loss}$ N apparent loss

*, ** and *** indicates significance at $p < 0.05$, 0.01 and 0.001, respectively

In addition, the PFM patterns also had impact on the soil N loss. Compared to NM, FM and RM decreased $N_{loss}$ by 9.7% and 20.6% in the 2018 season. These results indicated that the PFM, especially full ridge-furrow mulching, could distinctly reduce the soil N remnant and loss, and improve the soil N mineralization by managing soil heat and water status.

## Nitrogen use efficiency

Improving N efficiency is fundamental in crop production to increase crop yield and reduce agricultural costs, as well as environmental pollution (Fageria 2014). The N efficiency and plant N uptakes of maize under different PFM patterns are compared in Table 5. The PFM significantly ($p < 0.05$) affected plant N uptake ($N_{uptake}$), grain N accumulation ($N_{grain}$) and then N harvest index (NHI), while there were insignificant differences between full ridge-furrow and ridge mulching treatments. Plastic-film mulching treatments generally produced markedly high $N_{uptake}$ and $N_{grain}$ compared to non-mulching. For example, averaged across years, relative to NM, FM and RM enhanced the aboveground plant N accumulation by 19.7% and 16.9%, respectively, and enhanced the grain N accumulation by 31.0% and 26.9%, respectively. In addition, although no significant difference was found between FM and RM, the $N_{uptake}$ and $N_{grain}$ under FM were slightly higher, by 2.8% and 4.1%, respectively, than those under RM. The N harvest index, indicating the efficiency with crop utilizing the acquired N for grain production, is closely related to crop plant N uptake and grain N uptake (Liu et al. 2002; Fageria and Baligar 2003). In our experiments, averaged the two seasons, the NHI under FM and RM were distinctly improved by 6.8% and 6.1%, respectively, when compared to NM. Under non-fertilization, it was enhanced by 11.9% and 12.0% for CFM and CRM compared to CNM. The high NHI, indicating an increased partitioning of N to grain (Bulman and Smith 1994), reduced the loss caused by the ineffective accumulation of N in the leaves or stems and promoted the efficient N cycle in maize plants. Our results strengthened the precious finding that PFM significantly increases maize N uptake compared with non-mulching, thereby affecting N utilization efficiency (Dong et al. 2019).

In two years, PFM typically advanced the efficiency of maize nitrogen use. Averaged the cropping years, the values of NUE under NM, RM and FM were 81.4%, 89.0% and 90.4%, respectively, followed the trend of FM > RM > NM.

**Table 5** Nitrogen use of different treatments in physiological maturity

| Treatment | $N_{grain}$ (kg ha$^{-1}$) | $N_{uptake}$ (kg ha$^{-1}$) | NHI (%) | NUE (%) | NAE (kg kg$^{-1}$) |
|---|---|---|---|---|---|
| 2107 | | | | | |
| NM | 230.5 ± 13.0b | 327.6 ± 12.7b | 70.3 ± 1.2b | 96.5 ± 5.3b | 30.5 ± 3.9a |
| RM | 283.5 ± 1.1a | 368.5 ± 4.9a | 76.9 ± 1.0a | 105.3 ± 0.3a | 31.8 ± 3.2a |
| FM | 295.7 ± 9.4a | 380.5 ± 28.4a | 77.9 ± 5.3a | 106.6 ± 5.6a | 32.3 ± 2.6a |
| CNM | 62.3 ± 19.7d | 96.2 ± 28.6d | 64.5 ± 1.2c | – | – |
| CRM | 83.7 ± 8.1cd | 113.8 ± 12.7cd | 73.6 ± 1.1ab | – | – |
| CFM | 103.9 ± 19.0c | 139.9 ± 18.2c | 73.9 ± 4.0ab | – | – |
| ANOVA (*p* values) | | | | | |
| Mulching pattern | ***(0.000) | **(0.004) | ***(0.000) | NS | NS |
| Fertilization | ***(0.000) | ***(0.000) | **(0.007) | – | – |
| 2018 | | | | | |
| NM | 166.3 ± 19.9b | 219.3 ± 9.1b | 75.6 ± 6.3a | 66.4 ± 3.8a | 32.5 ± 2.4a |
| RM | 220.2 ± 13.6a | 271.3 ± 19.6a | 81.2 ± 3.3a | 72.7 ± 8.2a | 33.7 ± 2.9a |
| FM | 224.2 ± 24.1a | 274.2 ± 19.0a | 81.5 ± 3.4a | 74.1 ± 7.9a | 35.7 ± 2.5a |
| CNM | 36.31 ± 12.1d | 60.6 ± 16.9d | 59.2 ± 3.5b | – | – |
| CRM | 72.33 ± 14.5c | 97.3 ± 16.2c | 74.0 ± 3.6a | – | – |
| CFM | 71.17 ± 9.6c | 96.9 ± 15.0c | 73.6 ± 5.3a | – | – |
| ANOVA (*p* values) | | | | | |
| Mulching pattern | ***(0.000) | **(0.001) | **(0.002) | NS | NS |
| Fertilization | ***(0.000) | ***(0.000) | ***(0.000) | – | – |

NM: plot without mulching; RM: only ridge mulching; FM: full ridge-furrow mulching; CNM: no mulching and no fertilizing; CRM: ridge mulching and no fertilizing; CFM: ridge and furrow mulching and no fertilizing; $N_{grain}$: grain N accumulation; $N_{uptake}$: aboveground plant N accumulation; NHI: N harvest index; NUE: N fertilizer use efficiency; NAE: N fertilizer agronomic efficiency

Treatments with the same letter in each column are not significantly different at $p < 0.05$

NS indicates no significance

*, ** and *** indicates significance at $p < 0.05$, 0.01 and 0.001, respectively

These indicated that the PFM patterns can effectively promote the fertilizer N use efficiency of maize. Uniformly, mulching also clearly improved the N fertilizer agronomic efficiency. The highest NAE in 2107 and 2018 was achieved both in FM followed by RM and NM. The annual NAE averaged across years under FM and RM (34.0 kg kg$^{-1}$ and 32.7 kg kg$^{-1}$) was enhanced by 7.9% and 3.8%, respectively, when compared to NM (31.5 kg kg$^{-1}$). The fertilizer N agronomic efficiency is defined as the grain productivity per unit of N application. In our experiment, PFM improved the productivity of N fertilizer, and especially ridge-furrow full mulching maximized the efficiency of N fertilizer among the three PFM patterns. Moreover, the ANOVA results also showed that the PFM patterns and fertilization significantly ($p < 0.01$) affected the NHI, $N_{\text{uptake}}$ and $N_{\text{grain}}$, but no significant effects on NUE and NAE.

## Yield and yield components

PFM under fertilization imposed significant ($p < 0.05$) effects on ear barren tip, 100-seed weight and grain yield, while the differences between full ridge-furrow and only ridge mulching treatments were not statistically significant over the two years (Table 6). Compared to NM, FM and RM significantly increased 100-seed weight by 9.2% and 8.6%, respectively. On the contrary, the highest ear barren tips of maize, 2.1 cm in 2017 and 0.8 cm in 2018, were recorded both in NM. Moreover, FM clearly increased maize yield over the 2-year trial. Averaged over the cropping years, the grain yield was highest for FM followed by RM and NM, because of the highest number of 100-seed weight and lowest ear barren tip. Grain yields for FM and RM were greatly increased, by 15.0% and 12.5%, respectively, as compared with NM. The low yield of NM could probably attribute to the insufficient accumulation of temperature in soil resulted from low air temperature at the early stage of maize growth (Fig. 3). However, PFM treatments, especially FM treatment, can efficiently meet the requirements of water, heat and nutrients for crop growth by changing soil hydrothermal conditions in the root zone (Liu and Chen 1992; Quezada et al. 1995; Chen and Guo 1998), and then significantly affect crop yield (Ravi and Lourduraj 1996; Huang et al. 1999). In both years, no significant differences in ear length and

**Table 6** Yield and the yield components of maize under different treatments in 2017 and 2018

| Treatment | Ear length (cm) | Ear barren tip (cm) | Kernel number per cob | 100-seed weight (g) | Grain yield (t ha$^{-1}$) |
|---|---|---|---|---|---|
| 2017 | | | | | |
| NM | 25.0 ± 1.2a | 2.1 ± 0.4b | 735 ± 34a | 35.3 ± 1.3b | 13.8 ± 1.0b |
| RM | 23.8 ± 0.6a | 0.9 ± 0.2a | 769 ± 29a | 37.8 ± 2.0a | 15.5 ± 0.8a |
| FM | 23.6 ± 0.6a | 0.9 ± 0.1a | 777 ± 16a | 37.8 ± 1.9a | 15.5 ± 1.0a |
| CNM | 14.6 ± 2.1b | 2.4 ± 0.4bc | 374 ± 70b | 24.1 ± 0.9c | 5.3 ± 0.9c |
| CRM | 18.0 ± 0.4c | 2.8 ± 0.1c | 492 ± 16c | 25.2 ± 1.4d | 6.3 ± 0.3c |
| CFM | 17.9 ± 0.2c | 2.4 ± 0.1bc | 510 ± 11c | 26.4 ± 2.1d | 6.9 ± 0.4c |
| ANOVA (*p* values) | | | | | |
| Mulching pattern | NS | **(0.004) | **(0.005) | *(0.034) | **(0.005) |
| Fertilization | ***(0.000) | ***0.000 | ***0.000 | ***0.000 | ***0.000 |
| 2018 | | | | | |
| NM | 22 ± 0.6a | 0.8 ± 0.1b | 684 ± 14.1a | 34.3 ± 1.5b | 12.9 ± 0.6b |
| RM | 21.7 ± 0.8a | 0.3 ± 0.2a | 700 ± 43.2a | 37.8 ± 1.1a | 14.9 ± 0.8a |
| FM | 22.2 ± 0.3a | 0.3 ± 0.0a | 731 ± 0.77a | 38.2 ± 1.5a | 15.2 ± 0.6a |
| CNM | 11.5 ± 2.1b | 2.3 ± 0.2c | 310 ± 87.4b | 25.8 ± 1.3c | 3.8 ± 0.9c |
| CRM | 14.0 ± 0.4c | 2.0 ± 0.0d | 431 ± 18.5c | 23.3 ± 0.5d | 5.2 ± 0.1d |
| CFM | 14.3 ± 0.8c | 1.8 ± 0.2d | 450 ± 34.7c | 22.6 ± 1.5d | 5.3 ± 0.1d |
| ANOVA (*p* values) | | | | | |
| Mulching pattern | NS | **(0.007) | **(0.008) | NS | **(0.001) |
| Fertilization | ***(0.000) | ***(0.000) | ***(0.000) | ***(0.000) | ***(0.000) |

Treatments with the same letter in each column are not significantly different at $p < 0.05$

*NS* indicates no significance

*NM* plot without mulching, *RM* only ridge mulching, *FM* full ridge-furrow mulching, *CNM* no mulching and no fertilizing, *CRM* ridge mulching and no fertilizing, *CFM* ridge and furrow mulching and no fertilizing

*, ** and *** indicates significance at $p < 0.05$, 0.01 and 0.001, respectively

cob kernel number were found between with and without mulching treatments.

Under no fertilization, mulching significantly ($p < 0.05$) affected the maize yield and its components in both years, except ear barren tip and grain yield in 2017. The cob kernel number, ear length and 100-seed weight under mulching were significantly higher than those under non-mulching. The PFM obviously increased the maize yield relative to non-mulching. In 2018, the maize yield was significantly ($p < 0.05$) higher for CFM and CRM than for CNM. Averaged across years, compared with CNM, CFM and CRM increased the grain yield by 34.1% and 26.4%, respectively. Notably, the grain yield for CFM was markedly higher by 7.7% than that for CRM. Meanwhile, the ANOVA results revealed that PFM pattern significantly affected grain yield, kernel number and ear barren tip in both years at a significance level of $p < 0.01$. These results were in agreement with other studies which reported the great positive effects of PFM on crop production (Quezada et al. 1995; Ravi and Lourduraj 1996; Li et al. 1999).

As shown in Table 6, the ANOVA results also revealed that fertilization significantly ($p < 0.001$) affected maize yield and the yield components. Averaging the PFM patterns, N fertilizer substantially increased maize yield, 100-seed weight, ear length and cob kernel number, while obviously decreased ear barren tip, compared to no fertilization treatment over the 2-year trial.

## Conclusion

2-year field experiments of maize were conducted from 2017 to 2018 to evaluate the effects of PFM patterns on soil hydrothermal status, crop yield and nitrogen use efficiency. The following conclusions were supported by this study:

1. In the sub-humid region of northeast China, the PFM patterns could appreciably improve soil temperature, especially at the beginning and late growing stage. Throughout the growing season, soil moisture of full ridge-furrow mulching was generally higher than that of only ridge mulching due to effectively retain moisture in the soil by restraining the soil evaporation.
2. The PFM significantly ($p < 0.05$) promoted soil N mineralization, and could decrease residual mineral N in the soil and N apparent loss. Generally, the full ridge-furrow mulching distinctly reduced the soil N remnant and loss, and improve the soil N mineralization by managing soil heat and water status.
3. The PFM significantly ($p < 0.05$) increased aboveground plant N accumulation and grain N accumulation, thereby significantly ($p < 0.05$) increased the N harvest index compared with non-mulching. PFM improved the productivity of N fertilizer, and the efficiency of N fertilizer was maximized under full ridge-furrow mulching. Meanwhile, the PFM, especially full ridge-furrow mulching, could significantly ($p < 0.05$) increase maize yield.

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## Compliance with ethical standards

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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