Journal of Integrative Agriculture 2021, 20(12): 3127–3142

Available online at www.sciencedirect.com

ScienceDirect

RESEARCH ARTICLE

Drip irrigation incorporating water conservation measures: Effects on soil water–nitrogen utilization, root traits and grain production of spring maize in semi-arid areas

WU Yang[1, 2], BIAN Shao-feng[1], LIU Zhi-ming[1], WANG Li-chun[1], WANG Yong-jun[1], XU Wen-hua[3], ZHOU Yu[4]

[1] *Jilin Academy of Agricultural Sciences, Changchun 130033, P.R.China*
[2] *Jiujiang University, Jiujiang 332005, P.R.China*
[3] *Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, P.R.China*
[4] *Chongqing Academy of Agricultural Sciences, Yongchuan 402160, P.R.China*

Abstract
The Northeast Plain is the largest maize production area in China, and drip irrigation has recently been proposed to cope with the effects of frequent droughts and to improve water use efficiency (WUE). In order to develop an efficient and environmentally friendly irrigation system, drip irrigation experiments were conducted in 2016–2018 incorporating different soil water conservation measures as follows: (1) drip irrigation under plastic film mulch (PI), (2) drip irrigation under biodegradable film mulch (BI), (3) drip irrigation incorporating straw returning (SI), and (4) drip irrigation with the tape buried at a shallow soil depth (OI); with furrow irrigation (FI) used as the control. The results showed that PI and BI gave the highest maize yield, as well as the highest WUE and nitrogen use efficiency (NUE) because of the higher root length density (RLD) and better heat conditions during the vegetative stage. But compared with BI, PI consumed more soil water in the 20–60 and 60–100 cm soil layers, and accelerated the progress of root and leaf senescence due to a larger root system in the top 0–20 cm soil layer and a higher soil temperature during the reproductive stage. SI was effective in improving soil water and nitrate contents, and promoted RLD in deeper soil layers, thereby maintaining higher physiological activity during the reproductive stage. FI resulted in higher nitrate levels in the deep 60–100 cm soil layer, which increased the risk of nitrogen losses by leaching compared with the drip irrigation treatments. RLD in the 0–20 cm soil layer was highly positively correlated with yield, WUE and NUE (P<0.001), but it was negatively correlated with root nitrogen use efficiency (NRE) (P<0.05), and the correlation was weaker in deeper soil layers. We concluded that BI had advantages in water–nitrogen utilization and yield stability response to drought stress, and thus is recommended for environmentally friendly and sustainable maize production in Northeast China.

Keywords: drip irrigation, root, water use efficiency, nitrogen use efficiency, maize

Received 25 March, 2020 Accepted 1 July, 2020
WU Yang, E-mail: yangwu15@126.com; Correspondence WANG Yong-jun, Tel: +86-431-87063941, E-mail: yjwang2004@126.com

doi: 10.1016/S2095-3119(20)63314-7

1. Introduction

Irrigation is one of the most effective ways to improve and stabilize crop yields. Irrigated farmland occupies 16% of the total agricultural acreage, contributing 40% of total agricultural production (Kang *et al*. 2016). The issue of global warming has been known since the 1980s, and the water crisis is increasingly acute and accompanied by frequent droughts, economic and demographic growth. Agricultural production consumes the largest amount of fresh water; i.e., 69% in the world, and over 90% in the countries with scarce water resources (FAO 2014). Therefore, improving crop production with reduced irrigation through the development of water-saving agricultural strategies is critically important to prevent and relieve future water shortages.

The effective management of irrigation includes reasonable irrigation scheduling and efficient irrigation patterns. Irrigation scheduling, which includes irrigation amount, irrigation time and irrigation frequency, varies widely and is related to climatic conditions, crop species and soil properties. Thus, irrigation scheduling is a major concern and has been studied broadly for different crops and regions (Soltani *et al*. 2001; Patanè *et al*. 2011). Surface irrigation has the longest history and is still the most widely used type of irrigation worldwide. In China, furrow irrigation and border irrigation are associated with lower costs, inaccuracy, and low irrigation water use efficiency (IWUE), and account for 97% of the total area under irrigation. In contrast, new irrigation patterns such as drip irrigation, sprinkle irrigation and infiltrating irrigation can achieve higher IWUE and significantly reduce water use by 30–100% compared to traditional surface irrigation (Albaji *et al*. 2010; Liu *et al*. 2014). In northern China, drip irrigation has been vigorously promoted to conserve scarce water resources. Most notably, drip irrigation under plastic film mulch (PI) was developed and has been used in Northwest China for cotton since the late 1990s, and it has been promoted in Northeast China for maize since 2012 (Xue *et al*. 2017).

PI represents the effective incorporation of "water conservation technology" and "water-saving irrigation technology", and has significant advantages in reducing wasteful evaporation, promoting crop growth and increasing yields and water use efficiency (WUE) in either arid (Mai *et al*. 2012; Li X Y *et al*. 2017; Zhou *et al*. 2018), semi-arid (Jayakumar *et al*. 2017) or semi-humid areas (Liu *et al*. 2018). PI changes the soil water infiltration and distribution features, and it especially improves irrigation uniformity and soil water stability in the top and middle soil layers (Wang *et al*. 2014; Zhou *et al*. 2018). Moreover, PI has been recognized as an effective irrigation method to promote nitrogen absorption and utilization, and it can maintain a high soil nitrate content and minimize seasonal nitrate leaching (Wang *et al*. 2014; Sui *et al*. 2018). PI has been shown to improve the soil water content and soil temperature in the top soil layer (Li X Y *et al*. 2017; Sui *et al*. 2018). However, increased soil water content and temperatures in the top soil layer obstructs root elongation into the deeper soil layers, i.e., 90% of the roots are in the 0–40 cm soil layer for plants grown under the PI system, which further influences the physiological function of root absorption (Jha *et al*. 2017). Many studies have also reported that PI advances the growth and development of plants, which influences leaf photosynthesis, nitrogen accumulation and yield during the reproductive growth stage (Mai and Tian 2012; Karandish and Shahnazari 2016). It has been demonstrated that PI has significant effects on "soil–root–plant" interactions. However, plant senescence, the spatio–temporal distributions of soil water, soil nitrate, and root systems, and their relationships with yield, WUE, and nitrogen use efficiency (NUE) are unclear at present.

There are some challenges for implementation, however, as the increasing application of PI has brought not only economic benefits, but also the serious problem of plastic film pollution in recent years (Yan *et al*. 2014; Wu *et al*. 2017). Thus, drip irrigation combined with environmental soil water conservation measures, such as biodegradable film mulching (Wang *et al*. 2019), straw returning (Zhou *et al*. 2019), as well as buried drip irrigation/subsurface drip irrigation (Mo *et al*. 2017) have received increasing attention, and were proven to be beneficial for improving crop yields and WUE. However, there is still a lack of comparative study on water–nitrogen utilization between PI and the different soil pollution–reducing drip irrigation measures thus far.

The Northeast Plain is the most important grain production area in China, accounting for 34% of total maize production. In this study, a 3-year field experiment consisting of five treatments was conducted in this area: (1) drip irrigation under plastic film mulch (PI); (2) drip irrigation under biodegradable film mulch (BI); (3) drip irrigation incorporating straw returning (SI); (4) drip irrigation with the tape buried at a shallow soil depth (OI); and (5) furrow irrigation (FI). The main objectives were to quantify (1) soil "water–nitrate–root" interactions in different growth zones, (2) root and leaf senescence processes, (3) soil water and nitrate utilization, and (4) maize yield and economic benefits. We anticipate that the results of this study will help to stabilize maize production by providing an efficient and environmentally friendly irrigation management system for semi-arid areas.

2. Materials and methods

2.1. Site description

The experiment was conducted from 2016–2018 at the farm research station of Jilin Academy of Agricultural Sciences located in Taonan City, Jilin Province, China (45°33´N, 122°78´E, 156.8 m a.s.l.). Over the past 35 years, the annual mean sunshine duration was 2 817.2 h, the annual mean pan evaporation was 1 928 mm, the frost-free season was 140 days, the annual mean temperature was 6.0°C, and the annual mean precipitation was 419.7 mm. Because of the low amount of rainfall, a crop yield cannot be guaranteed without irrigation in this area. The precipitation and air temperature distributions during the experimental period are shown in Fig. 1. The soil was heavy clay and details of the soil properties are described in Table 1.

2.2. Experimental design

Four drip irrigation treatments that incorporate water conservation measures were set as follows: (1) drip irrigation under plastic film mulch (PI), (2) drip irrigation under biodegradable film mulch (BI), (3) drip irrigation incorporating straw returning (SI), and (4) drip irrigation with the tape buried at a shallow soil depth (OI). In addition, traditional furrow irrigation (FI) was used as the control. The experiment employed a completely randomized design with three replicates, and each plot area measured 170 m^2 (8.5 m×20 m). Plastic film (polyethylene clear film, 0.9 m wide×0.008 mm thick; produced by Jilin Difu Agricultural Technology Co., Ltd., Jilin, China) and biodegradable film (polylactic clear film, 0.9 m wide×0.008 mm thick; produced by Jilin Difu Agricultural Technology Co., Ltd., Jilin, China) were used to cover the surfaces of the planting ridges. Varying levels of damage to the biodegradable film were observed in August, and the film was completely degraded after crop harvest. For the SI treatment, maize straw produced in the identical plot areas was cut to lengths of ~10 cm and then returned to the soil at a depth of 20 cm using a deep soil tillage machine (produced by Jilin Province Kangda Agricultural Machinery Co., Ltd., Jilin, China). In the OI and SI treatments, the drip tape was buried at a shallow soil depth of 5–10 cm to prevent evaporation of the irrigation water. The maize cultivar Fumin 985 (dent type) was sown at a rate of 77 000 plants ha^{-1}, and an alternating planting of broad and narrow rows was used in this experiment (a popular planting strategy in Northeast China, which favors the utilization of light energy). A planting schematic diagram for the different treatments is shown in Fig. 2. Fertilizer consisting of 210 kg ha^{-1} nitrogen, 105 kg ha^{-1} phosphorus pentoxide, and 90 kg ha^{-1} potassium oxide was applied one time before sowing. The irrigation regime used depended on the regional climate and production conditions, and included 55 mm water before sowing, and 40, 30 and 20 mm at the jointing, tasseling and filling stages, respectively. The drip irrigation tape was 16 mm in width with an emitter spacing of 30 cm, and the flow rate of the emitter was 3 L h^{-1} at a working pressure of 0.1 MPa. The irrigation rate was recorded using a precise water meter. The fertilization and irrigation management practices were the same for each treatment. The maize seeds were sown on May 4, May 1 and May 6 in the 2016, 2017 and 2018 planting seasons, respectively. The relative maturity for the PI treatment was 1–3 and 7–10 days advanced compared with BI and the other non-mulched treatments, respectively. All crops were harvested on October 30, October 28 and October 30 in 2016, 2017 and 2018, respectively.

2.3. Sampling and measurement

Soil water and nitrate contents At the tasseling and maturity stages, the soil was sampled to a depth of 100 cm. The details of the sampling method are shown in Fig. 2. The terms "I-zone", "R-zone" and "N-zone" are defined as 0–20, 20–30 and 30–65 cm horizontal distance away

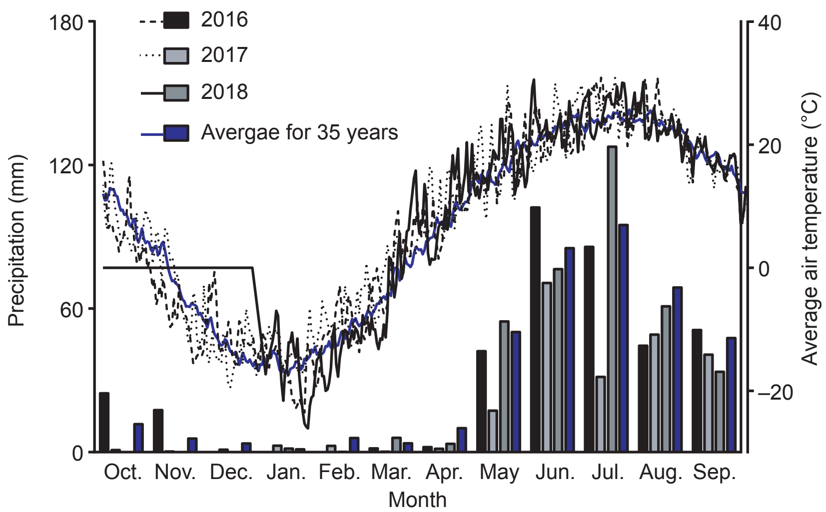

Fig. 1 Precipitation and air temperature distribution for the 2016–2018 growing seasons at the experimental site, Taonan City, Jilin Province, China.

Table 1 Soil properties at the Taonan Experimental Site of Jilin Province, China at 0–100 cm depths

Soil layer	0–20 cm	20–40 cm	40–60 cm	60–100 cm
Mechanical composition (%)				
2–0.02 mm (clay loam)	34.96	23.13	18.57	18.83
0.02–0.002 mm (clay)	37.93	31.98	34.30	35.38
<0.002 mm (clay)	27.10	44.71	47.17	45.79
Physical and chemical properties				
Available N (mg kg^{-1})	69.50	51.40	44.40	36.40
Available P (mg kg^{-1})	30.90	22.80	15.40	10.90
Available K (mg kg^{-1})	139.30	85.10	72.10	65.30
Organic matter (g kg^{-1})	13.14	10.38	6.58	5.05
Bulk density (g cm^{-3})	1.40	1.50	1.58	1.68
Field capacity (weight %)	20.44	22.04	23.70	25.05
Wilting point (weight %)	10.0	10.90	12.70	14.15

from the drip irrigation tape/irrigation furrow, according to the morphological features of the roots in practice. The soil samples were obtained using a 100/50 mm-diameter steel core-sampling drill at three locations for each plot. A portion of each sample was used to measure soil water content, and the remaining soil was used to measure soil nitrate content. Soil water was measured by drying the soil to a constant weight at 105°C and weighing. The fresh soil samples used for analyzing soil nitrate were extracted by shaking in a 2-mol L^{-1} KCl solution (Li *et al*. 2016), and the soil nitrate content was measured using an AA3 continuous flow analyzer (SEAL Analytical Ltd., Germany).

Soil water storage was calculated using eq. (1):

$$SW=\sum_i^n h_i \times \rho_i \times b_i \times 10/100 \quad (1)$$

where SW (mm) is the soil water storage, h_i (cm) is the soil layer depth, ρ_i (g cm^{-3}) is the soil bulk density in the different soil layers, b_i is the percentage of soil moisture by weight, n is the number of soil layers, and i=10, 20, 40, …, 100.

The field evapotranspiration rate was calculated using the soil water balance eq. (2):

$$ET=P+\Delta SW+I+C-D-R \quad (2)$$

where ET (mm) is the total evapotranspiration, P (mm) is the precipitation during a specific growth period, ΔSW (mm) is the difference in soil water storage between two specific growth periods, and the soil water storage here used the average value from the different sampling locations in the 100 cm soil layer, I (mm) is the irrigation amount during the growth period, C is the upward flow into the root zone, D is the downward drainage out of the root zone, and R is the surface runoff. At the experimental site, the groundwater table was located at a depth of about 120 m below the surface, so the upward flow into the root zone was negligible. Runoff was never observed because the experimental field was flat and drainage was assumed to be insignificant over a depth of 100 cm.

Water use efficiency (WUE) was calculated as the ratio of the grain yield relative to the ET rate during the entire growth period. The irrigation water use efficiency (IWUE) was the grain yield divided by the total irrigation amount (Jha *et al*. 2017).

Soil temperature The soil temperature was measured using an EasyLog USB data logger (Lascar Electronics Ltd., V7.2). For each plot, one logger was installed in the soil between planting rows at a depth of 10 cm. The temperature data were automatically recorded every hour during the entire growing period. The daily mean soil temperature (DT) was calculated as the average of 12 intra-day readings. The sum of the DT above the base temperature for maize (10°C) was identified as the accumulated soil temperature (AST) during specific stages of growth.

Root traits and nitrogen utilization Three maize plants in each plot were sampled to measure biomass, plant nitrogen uptake and root length at both tasseling and maturity stages. The root sampling method was the same for soil water and soil nitrate contents. The root samples were carefully washed and the non-root contaminants were carefully removed. The fresh roots were scanned with an Epson Perfection V700 scanner and the root lengths were analyzed with WinRHIZO (Regent Instruments Inc., Canada) (Liu *et al*. 2017). The maize plant samples (roots and aboveground parts) were then dried to constant weights in an oven at 65°C to calculate the dry weights. Root length density (RLD) was calculated by dividing the root length by the sampling core volume in the different soil layers. After weighing, the dry samples were ground to pass through a 1-mm sieve and the nitrogen concentration was measured using the micro-Kjeldahl method (CN61M/KDY-9820; Beijing, China) (Li G H *et al*. 2017). Plant nitrogen uptake was calculated as the product of plant nitrogen concentration and dry matter weight. The nitrogen use efficiency (NUE) was calculated as the ratio of yield relative to nitrogen uptake in the whole plant at maturity. The root nitrogen use efficiency (NRE) was calculated from the nitrogen uptake of the whole plant divided by the root mass at maturity (Fu *et al*. 2017).

Physiological parameters Three plants were harvested

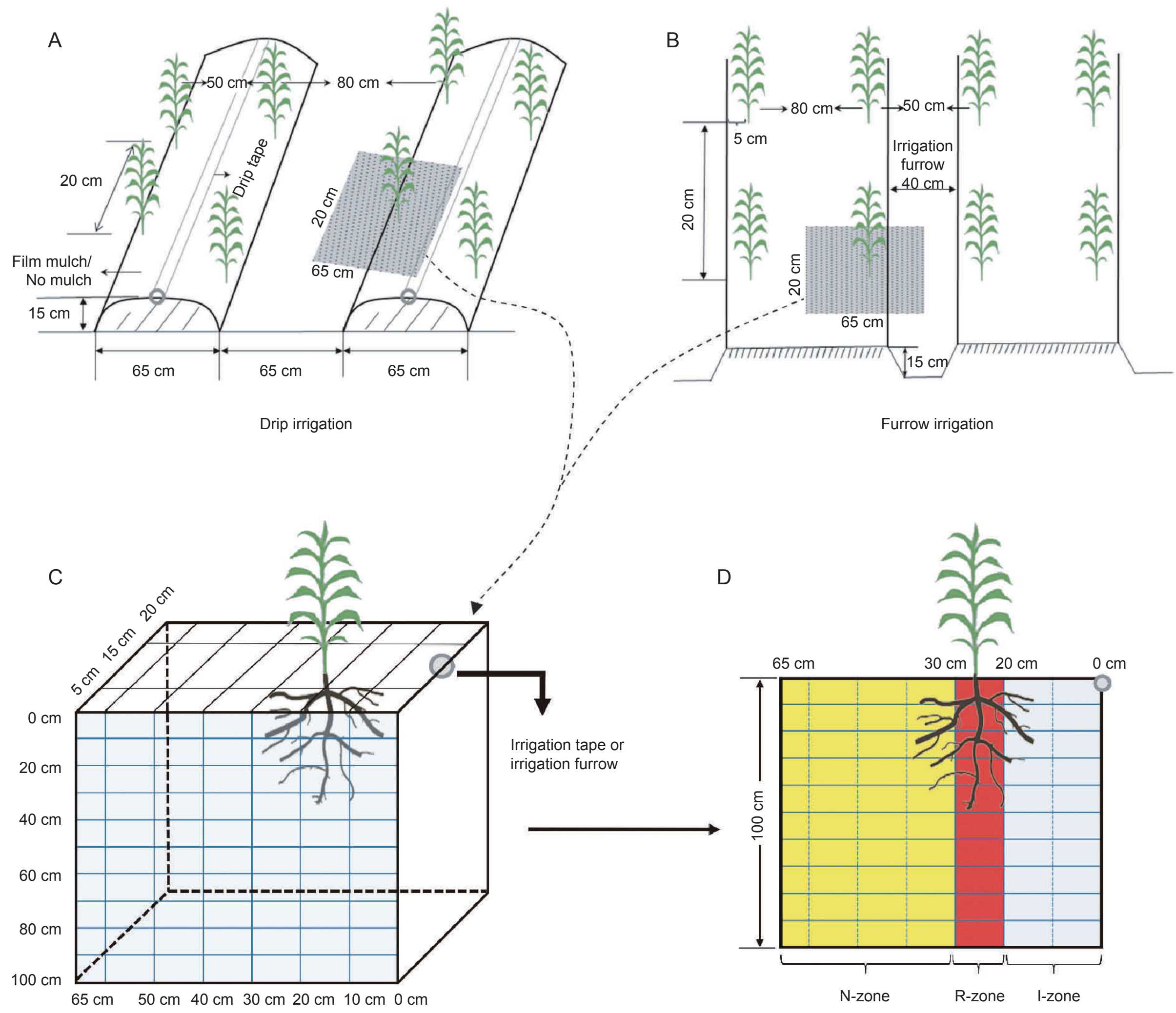

Fig. 2 Schematic diagram of the field layout and the sampling method.

from each plot at the tasseling, milk (about 25 days from tasseling), and dent (about 55 days from tasseling) stages. The ear-leaf and roots in the 0–20, 20–40 and 40–60 cm soil layers were used for measurements. At a given stage, samples were collected for all treatments on the same day. The activities of superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and nitrate reductase (NR) and the concentration of malondialdehyde (MDA) were determined using an enzyme-linked immunosorbent assay (ELISA) kit (Beijin Solarbio Technology Ltd., China) following the manufacturer's instructions. The SOD activity was measured by monitoring the inhibition of the photochemical reduction of nitroblue tetrazolium (NBT) at 560 nm. CAT and POD activities were measured by monitoring the changes in absorbance at 240 and 470 nm, respectively. CAT activity was expressed as a decrease in the OD_{240} of 0.1 per minute, while the POD activity was expressed as an increase in the OD_{470} of 0.1 per minute. The MDA concentration was measured at 532 nm and corrected by subtracting the absorbance at 600 nm. NR activity was calculated as the reduction of 1 μg NO_2^- per hour (Chen *et al*. 2004; Tang *et al*. 2010). Plant nitrate content was determined by the colorimetric analysis of nitrosalicylic acid as described by Gao *et al*. (2006).

Yield Four representative, undamaged lines were selected from each plot, and 15 random plants in each line were harvested. The numbers of seeds per ear and the seed weight (14% standard water content) were determined to calculate the yield.

2.4. Statistical analyses

Data were subjected to analysis of variance (ANOVA) using SPSS 18.0. Multiple comparisons were conducted using the least significant difference (LSD) method. Pearson correlation coefficients were also calculated using SPSS.

3. Results

3.1. Yield

The PI treatment resulted in a significant yield improvement compared with SI, OI and FI (P<0.05), especially during the 2017 drought year. In the three years of the experiment (2016–2018), PI increased the yield by 5.40–7.95%, 21.91–29.53%, 30.17–40.80%, and 33.04–43.10% compared with BI, SI, OI, and FI, respectively (Table 2). There was also no significant difference between PI and BI for yield in the different years (P>0.05).

3.2. Soil water

The soil water content was higher closer to the I-zone, whereas the soil water content in the R-zone was the lowest due to crop consumption for growth (Fig. 3). Less rainfall occurred from June to July of 2017 (89.7 mm lower than the 35-year average), which obviously lowered the soil water content at the tasseling stage. SI had a positive effect on conserving soil water, while PI extracted more soil water, especially from the 20–60 and 60–100 cm soil layers. No significant differences were found between PI and BI for soil water in the 0–60 cm soil layer (P<0.05), but PI reduced the soil water content in the 60–100 cm soil layer by 8.34–10.65% and 6.70–9.03% compared to BI at the tasseling and maturity stages, respectively.

3.3. Soil temperature

Both PI and BI increased soil temperature compared with SI, OI and FI, and the warming effects mainly occurred during the maize vegetative stage. The accumulated soil temperature for the PI treatment was 6.56–7.41%, 14.49–17.57%, 13.63–16.38%, and 14.07–17.17% higher, respectively, than those for BI, SI, OI, and FI during the vegetative stage. Due to the degradation of the biodegradable film, BI had no significant influence on soil temperature during the reproductive stage. In contrast, PI increased the accumulated soil temperature by 8.12–10.07%, 10.68–12.89%, 9.64–11.81%, and 10.42–11.51% compared with the BI, SI, OI, and FI treatments, respectively, during the reproductive stage (Fig. 4).

3.4. Soil nitrate

Much of the soil nitrate was absorbed by the roots in the R-zone and 0–20 cm soil layer (Fig. 5). The soil nitrate content in the 60–100 cm soil layer was increased due to the frequent rainfall from the tasseling to maturity stages. PI and BI decreased the soil nitrate content in the 0–100 cm soil layer, while SI improved the soil nitrate content in the 0–60 cm soil layer at the tasseling and maturity stages. PI and BI significantly reduced nitrate residues in the deep soil layer. Compared with SI, OI and FI, the soil nitrate content in the 60–100 cm soil layer was decreased by 20.74–25.12%, 16.77–22.99% and 22.17–28.87%, respectively in the PI treatment (P>0.05), and these same values for BI were 13.77–19.94%, 9.45–17.66% and 15.33–23.94%, respectively (P>0.05), at maturity.

3.5. Root length density (RLD)

RLD in the different zones was rated as follows: R-zone>I-zone>N-zone (Fig. 6). The PI treatment mainly increased the RLD in the 0–20 cm soil layer, and it was 33.31–45.76%, 76.06–79.72%, 120.78–147.50%, and 116.90–137.79% higher at tasseling, and 25.48–39.16%, 51.48–56.24%, 94.59–118.11%, and 87.43–112.14% higher at maturity, compared with BI, SI, OI, and FI, respectively. BI and SI increased RLD in the 20–60 and 60–100 cm soil layers. The RLD in the 20–100 cm layer for the BI treatment was increased by 23.47–26.76%, 43.72–47.75% and 24.53–30.64% at tasseling and by 28.89–32.67%, 40.00–43.71% and 21.13–24.46% at maturity, compared with PI, OI and FI, respectively, and the same values for SI were 20.74–28.96%, 41.38–50.11% and 23.59–30.06%, and 32.47–40.95%, 43.74–53.09% and 23.83–32.46%, respectively. There was no significant difference between FI and OI for RLD in the 0–20 cm soil layer, but RLD in the 20–100 cm layer for FI was increased by 12.71–15.41% and 15.47–16.08% compared with OI at the tasseling and maturity stages, respectively.

3.6. Plant senescence

Maize plants enter into senescence progress from the tasseling stage. The differences in leaf and root protective enzyme activities and MDA contents among different treatments were more obvious over time (Fig. 7). PI significantly reduced the protective enzyme activities (SOD, CAT and POD) and increased the MDA content, especially in leaves and roots, for the deeper 40–60 cm soil layer (P<0.05) compared with the other treatments. Both PI and BI accelerated the rate of senescence in roots and leaves, whereas plants in the SI treatment maintained higher physiological activity during the reproductive stage. No significant difference was found between OI and FI with respect to the rate of plant senescence (P>0.05).

3.7. ET and WUE

Higher soil water consumption in the PI treatment led to higher ET (Fig. 8). In particular, PI accelerated growth

Table 2 Grain yield, soil water use efficiency, and nitrogen use efficiency for the different irrigation treatments[1)]

Year	Treatment[2)]	Yield (t ha^{-1})	WUE (kg mm^{-3})	IWUE (kg mm^{-3})	NUE (g g^{-1})	NRE (mg g^{-1})
2016	PI	12.65±0.57 a	3.17±0.14 a	8.73±0.39 a	31.93±1.44 a	164.82±8.53 b
	BI	11.86±0.59 a	3.10±0.15 a	8.18±0.40 a	31.04±1.53 ab	170.17±9.80 ab
	SI	10.27±0.58 b	2.84±0.16 b	7.09±0.41 b	28.44±1.63 bc	176.95±9.74 ab
	OI	9.49±0.41 bc	2.55±0.11 c	6.54±0.29 bc	28.58±1.25 bc	182.04±8.01 a
	FI	9.23±0.48 c	2.46±0.13 c	6.36±0.33 c	27.80±1.45 c	172.80±7.08 ab
2017	PI	12.42±0.59 a	3.81±0.18 a	8.57±0.41 a	37.03±1.77 a	158.81±7.50 b
	BI	11.51±0.53 a	3.73±0.17 a	7.94±0.36 a	36.57±1.67 a	166.36±8.36 ab
	SI	9.59±0.49 b	3.36±0.17 b	6.61±0.34 b	32.05±1.63 b	174.45±9.50 ab
	OI	8.82±0.35 bc	2.98±0.13 c	6.08±0.24 bc	32.32±1.30 b	178.74±9.09 a
	FI	8.68±0.34 c	2.90±0.12 c	5.99±0.24 c	31.59±1.25 b	169.43±10.06 ab
2018	PI	13.64±0.64 a	3.15±0.15 a	9.41±0.59 a	31.83±1.49 a	172.36±6.83 b
	BI	12.95±0.77 a	3.09±0.18 ab	8.93±0.59 a	31.10±1.85 ab	177.75±7.54 ab
	SI	11.19±0.51 b	2.83±0.13 bc	7.72±0.59 b	29.63±1.36 ab	180.37±8.24 ab
	OI	10.48±0.58 bc	2.58±0.14 cd	7.23±0.59 bc	29.38±1.62 b	188.72±9.79 a
	FI	10.26±0.48 c	2.50±0.12 d	7.07±0.59 c	28.95±1.34 b	179.98±7.85 ab

[1)] WUE, soil water use efficiency; IWUE, irrigation water use efficiency; NUE, nitrogen use efficiency; NRE, root nitrogen use efficiency.
[2)] PI and BI, drip irrigation under plastic film mulch and biodegradable film mulch, respectively; SI, drip irrigation incorporating straw returning; OI, drip irrigation with the tape buried at a shallow soil depth; FI, furrow irrigation.
Values are given as the mean±standard deviation (n=3). Different lowercase letters indicate significant differences at P<0.05.

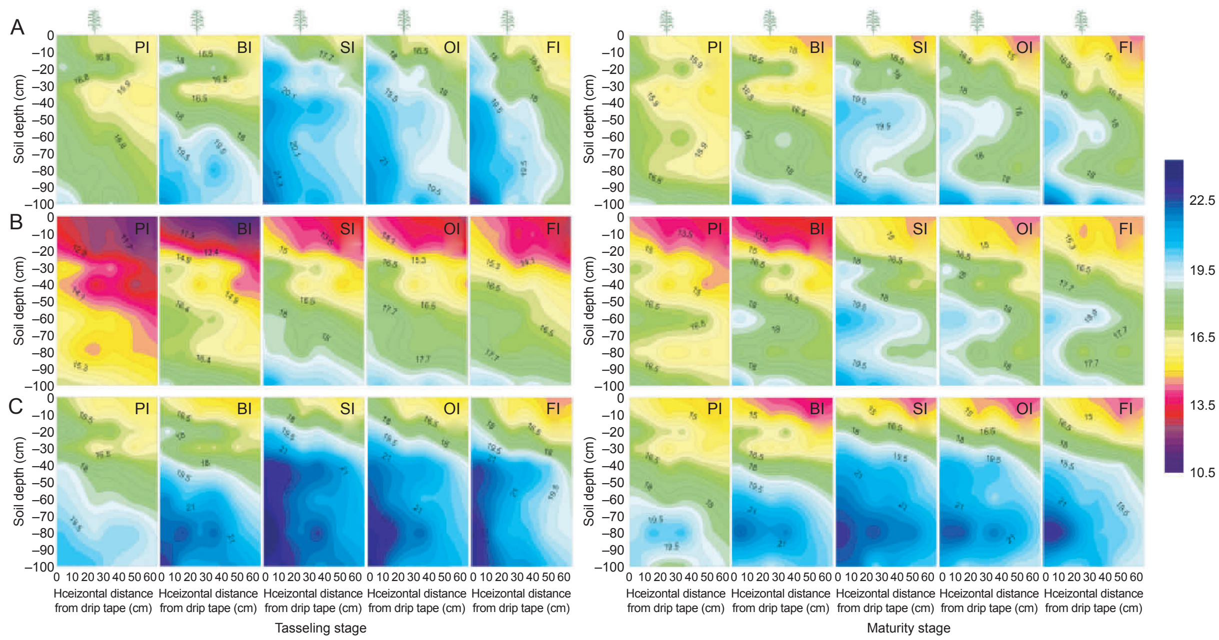

Fig. 3 Soil water content at the tasseling and maturity stages. A, B and C represent the 2016, 2017 and 2018 seasons, respectively. PI and BI represent drip irrigation under plastic film mulch and biodegradable film mulch, respectively; SI, drip irrigation incorporating straw returning; OI, drip irrigation with the tape buried to a shallow soil depth; FI, furrow irrigation.

in maize from sowing to tasseling, and the ET during the vegetative stage was 6.94–10.60%, 15.93–24.38%, 11.80–19.83%, and 9.60–16.00% higher for PI compared with BI, SI, OI, and FI, respectively. However, PI decreased ET during the reproductive stage, which contributed to the relatively advanced maturity. The order of increasing WUE for the five different treatments was as follows: PI>BI>SI>OI>FI. The WUE for PI was increased by 1.83–2.18%, 11.34–13.34%, 22.17–27.96%, and 26.00–31.29% compared with the BI, SI, OI, and FI treatments, respectively. We also found no significant differences between PI and BI, or OI and FI for WUE (P>0.05) (Table 2).

3.8. Plant NR activity, nitrate content and NUE

The SI treatment showed the highest NR activities and nitrate contents in both the roots and leaves during the reproductive stage. In contrast, PI significantly reduced

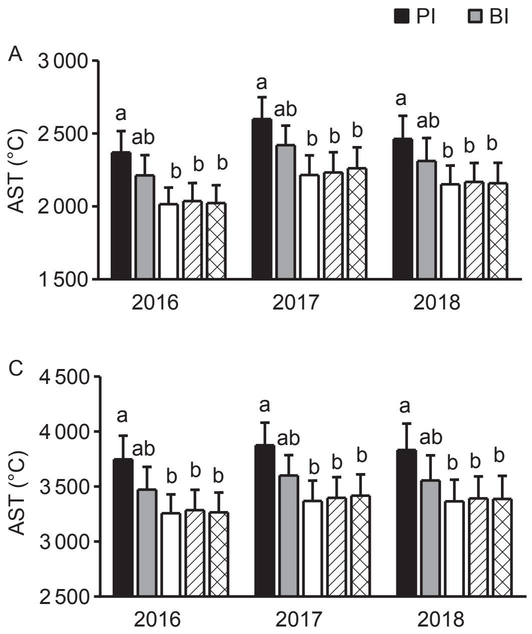

Fig. 4 Accumulated soil temperature (AST) for the different irrigation treatments. A, B and C represent the vegetative stage, the reproductive stage, and the entire maize growth period, respectively. PI and BI, drip irrigation under plastic film mulch and biodegradable film mulch, respectively; SI, drip irrigation incorporating straw returning; OI, drip irrigation with the tape buried at a shallow soil depth; FI, furrow irrigation. Values are given as the mean±standard deviation (n=3). Different lowercase letters indicate significant differences at P<0.05.

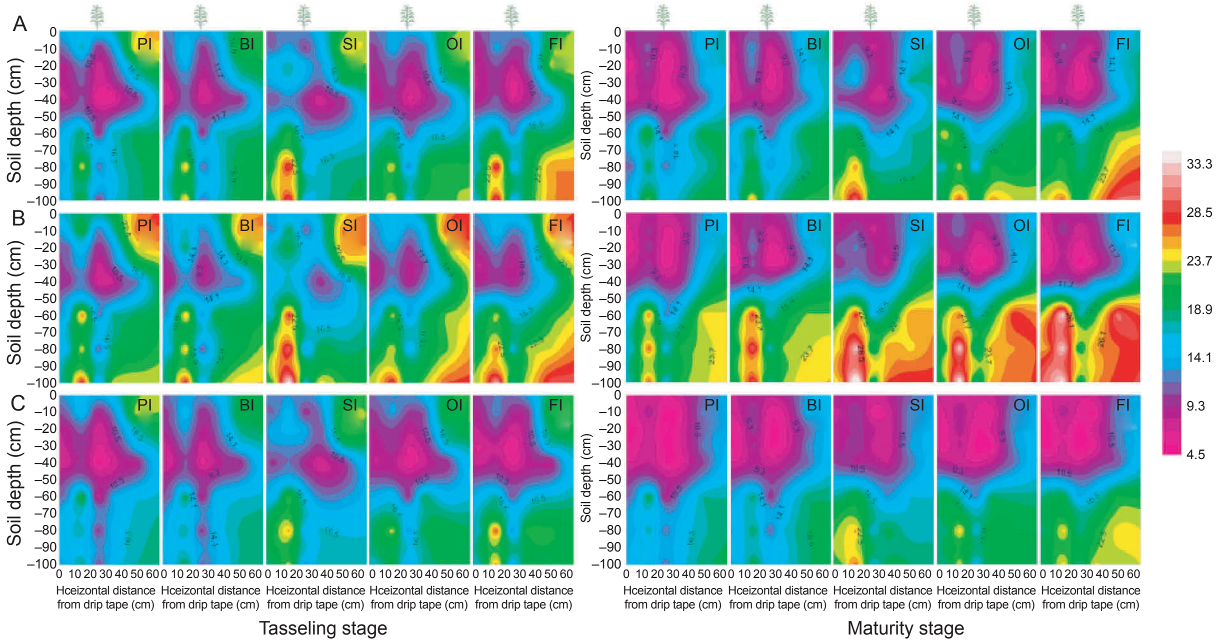

Fig. 5 Soil nitrate content at the tasseling and maturity stages. A, B and C represent 2016, 2017 and 2018, respectively. PI and BI, drip irrigation under plastic film mulch and biodegradable film mulch, respectively; SI, drip irrigation incorporating straw returning; OI, drip irrigation with the tape buried to a shallow soil depth; FI, furrow irrigation.

NR activity and nitrate content compared with the other treatments (P<0.05) (Fig. 9). The order of increasing nitrogen uptake for the above ground plant parts was as follows: PI>BI>SI>OI>FI, and the order was PI>BI>SI>FI>OI for the roots (Fig. 10). PI increased NUE by 1.26–2.35%, 7.41–15.54%, 8.34–14.59%, and 9.96–17.21% compared with BI, SI, OI, and FI, respectively, whereas PI decreased NRE by 3.04–4.54%, 4.44–8.97%, 8.67–11.15%, and 4.23–6.27%, respectively. We found no significant differences between PI and BI, or OI and FI, for either N uptake amount, NUE or NRE (P>0.05) (Table 2).

3.9. Relationships between RLD and soil water–nitrogen utilization

In the I- and R-zones, RLD showed significantly negative

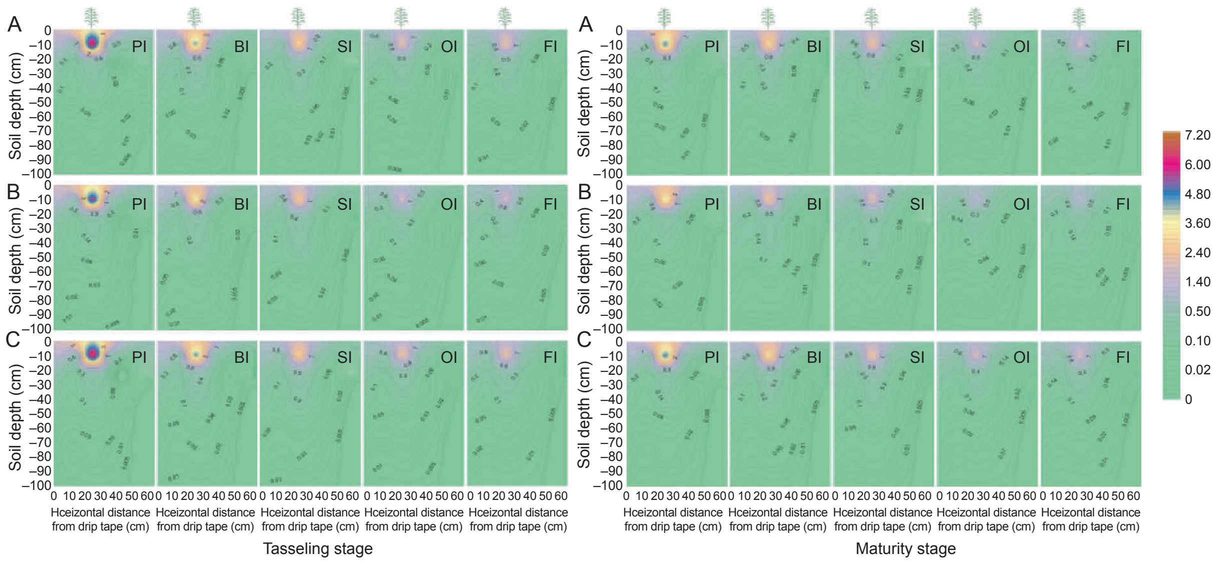

Fig. 6 Root length density (RLD) at the tasseling and maturity stages. A, B and C represent 2016, 2017 and 2018, respectively. PI and BI, drip irrigation under plastic film mulch and biodegradable film mulch, respectively; SI, drip irrigation incorporating straw returning; OI, drip irrigation with the tape buried at a shallow soil depth; FI, furrow irrigation.

correlations with soil water and soil nitrate contents in the 0–20 and 0–100 cm soil layers (P<0.05), and the soil water content was highly positively correlated with soil nitrate content in the 60–100 and 0–100 cm soil layers (P<0.001). Fewer roots were distributed in the N-zone, and thus the correlations between RLD, soil water content and soil nitrate content were weaker compared with the I- and R-zones (Fig. 11). The RLD in the 0–20 cm soil layer was highly positively correlated with yield, WUE and NUE (P<0.001), but the correlations were weaker in the 20–60 and 60–100 cm soil layers. In the I- and R-zones, the RLD was significantly negatively correlated with NRE (P<0.05), which was mainly reflected in the 0–20 cm soil layer (Fig. 12).

4. Discussion

4.1. Soil water and temperature

Plastic film mulch can promote crop vegetative growth and increase production due to a better hydrothermal environment in the top soil layer in northern China. However, increased water consumption in the deep soil layers under the plastic film mulch could cause an imbalance, resulting in unsustainable utilization of soil water for crop production (Zhang *et al*. 2011; Zhao *et al*. 2012). Accordingly, plants in the PI treatment consumed more soil water, especially in the 20–60 and 60–100 cm soil layers, which led to significantly higher ET during the vegetative growth stage in this study. In particular, less rainfall occurred during the tasseling stage in 2017, and the soil water content in the 0–100 soil layer for the PI treatment in the R-zone was 59.4–64.6% of the field water capacity, compared to 57.9–71.4%, 67.0–76.9%, 65.2–74.8%, and 63.6–73.4% for the BI, SI, OI, and FI treatments, respectively, at the tasseling stage. Although the soil water in the PI treatment was restored at maturity and contributed to reduced water consumption, even with supplemental irrigation and rainfall during the reproductive stage there is still a concern that the lower water availability of PI could increase the risk of yield failure during a critical drought year without irrigation. Because plants in the PI treatment showed a weak resistance to drought, we also agreed that PI needs sufficient water storage in the deeper soil layers to promote the downward growth of maize roots and sustain a high yield (Luo *et al*. 2012). Both PI and BI achieved the highest WUE and IWUE due to the high yield, and there were no significant differences between PI and BI for water use efficiency. Returning crop straw to the field has been advocated in northern China in recent years because it has a positive effect on retaining soil water by improving soil physical and chemical properties (Wang X J *et al*. 2018; Zhang *et al*. 2018). The results of the present study show that SI improved soil water content and reduced ET during the maize growth stage, and also effectively increased WUE compared with OI and FI.

In the study area, the average temperature during the maize growth period is 20.3°C, and thus the heat is also an issue in maize production (Wang *et al*. 2015). Similar to the results of Wang *et al*. (2011), Wu *et al*. (2017) and Zhou *et al*. (2016), we found that both plastic film and biodegradable film can increase soil temperature, and

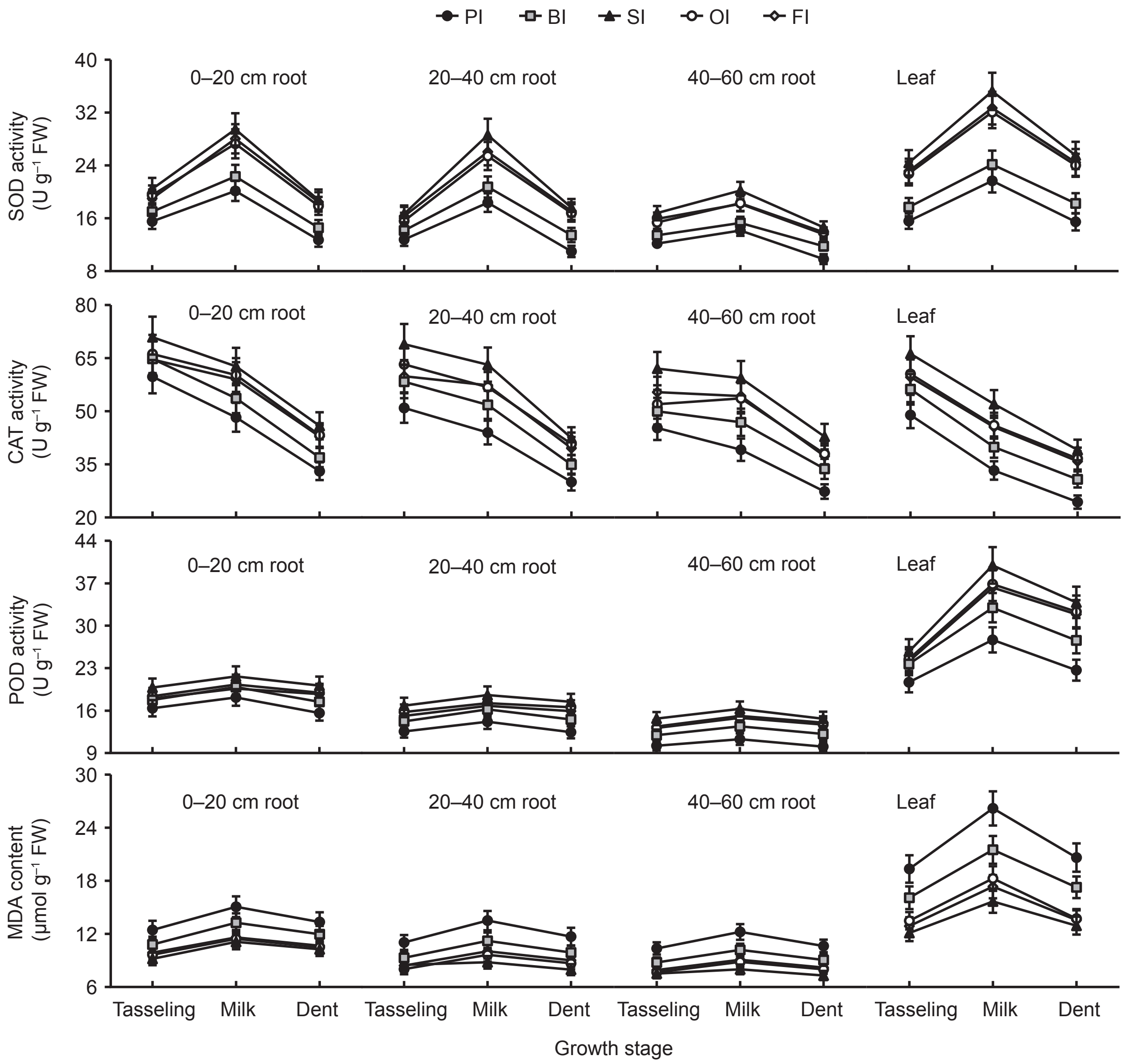

Fig. 7 Average protective enzyme activities (superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD)) and malondialdehyde (MDA) content from 2016 to 2018. PI and BI represent drip irrigation under plastic film mulch and biodegradable film mulch, respectively; SI, drip irrigation incorporating straw returning; OI, drip irrigation with the tape buried at a shallow soil depth; FI, furrow irrigation. Values are given as the mean±standard deviation (*n*=3).

both PI and BI mainly increased soil temperature during the maize vegetative stage. While the positive effects of BI on soil temperature as well as yield were less pronounced compared with PI, SI and OI had no significant effects on soil temperature compared with FI, which limited the effects of yield improvement compared with the film mulch treatments.

4.2. Nitrogen utilization

In spite of the management of nitrogen fertilizer, different irrigation methods can significantly affect soil nitrate distribution and crop nitrogen use efficiency. The plant nitrate content is closely related to nitrogen uptake and utilization, and increasing the external nitrate concentration can increase nitrate uptake. NR is considered to be a limiting factor for nitrate assimilation and has a large impact on nitrate accumulation in plants, but NR is not necessarily correlated with nitrogen uptake (Chen *et al*. 2004; Taghavi and Babalar 2007). In the present study, although PI and BI decreased the NR activities and nitrate contents in the roots and leaves during the reproductive stage due to the advanced senescence, these two treatments significantly increased nitrogen uptake in the above-ground parts and roots. The NUE was also increased compared with SI, OI and FI due to higher yield, and these results are similar to those reported by Sui *et al*. (2018), Wang *et al*. (2014) and

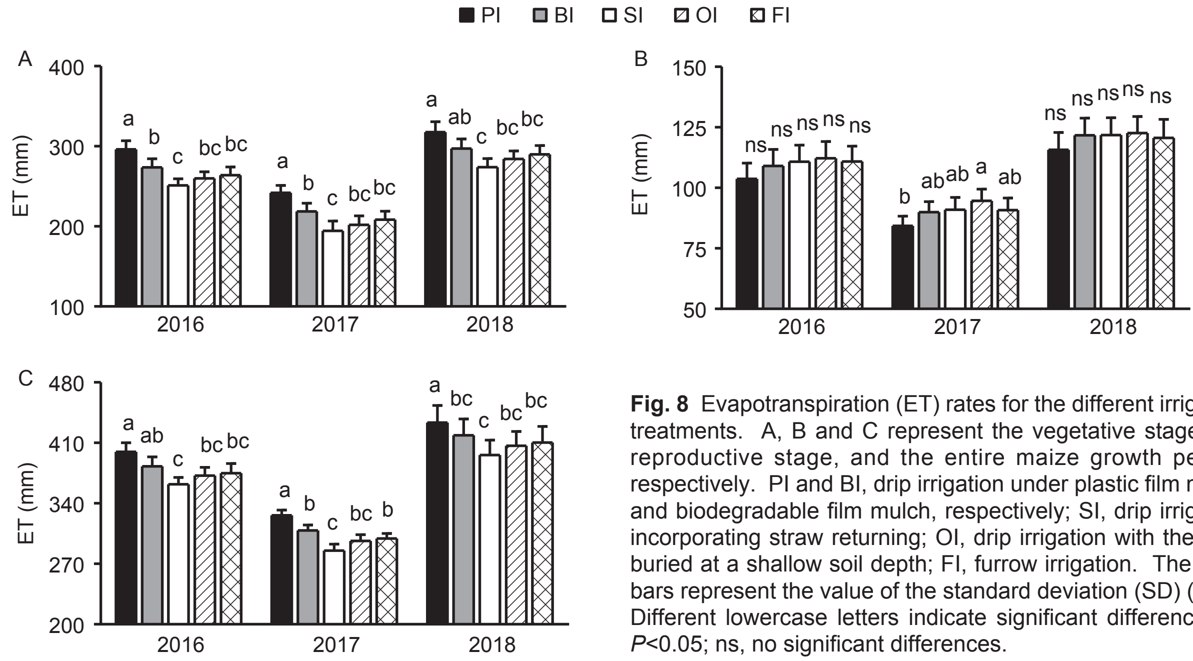

Fig. 8 Evapotranspiration (ET) rates for the different irrigation treatments. A, B and C represent the vegetative stage, the reproductive stage, and the entire maize growth period, respectively. PI and BI, drip irrigation under plastic film mulch and biodegradable film mulch, respectively; SI, drip irrigation incorporating straw returning; OI, drip irrigation with the tape buried at a shallow soil depth; FI, furrow irrigation. The error bars represent the value of the standard deviation (SD) (n=3). Different lowercase letters indicate significant differences at P<0.05; ns, no significant differences.

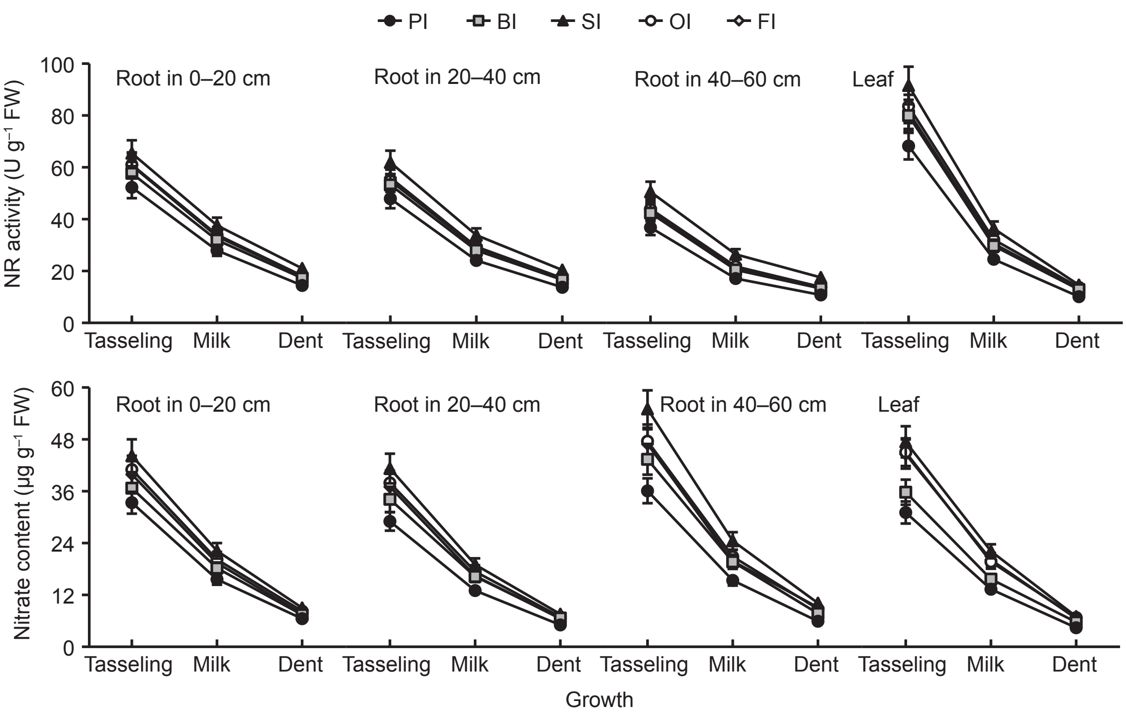

Fig. 9 Average nitrate reductase (NR) activity and nitrate content in maize roots from 2016 to 2018. PI and BI, drip irrigation under plastic film mulch and biodegradable film mulch, respectively; SI, drip irrigation incorporating straw returning; OI, drip irrigation with the tape buried at a shallow soil depth; FI, furrow irrigation. The error bars represent the value of the SD (n=3).

Zhou *et al*. (2016). Root nitrogen use efficiency (NRE) describes the root contribution to nitrogen accumulation by the shoot (Fu *et al*. 2017). PI and BI decreased NRE in view of the larger root biomass, but the complex physiological mechanisms behind this result should be further investigated. Drip irrigation improved irrigation uniformity, which in turn decreased nitrate leaching during the growth seasons (Wang *et al*. 2014). We found that soil water content was positively correlated with soil nitrate content. Plants in the PI and BI treatments extracted more

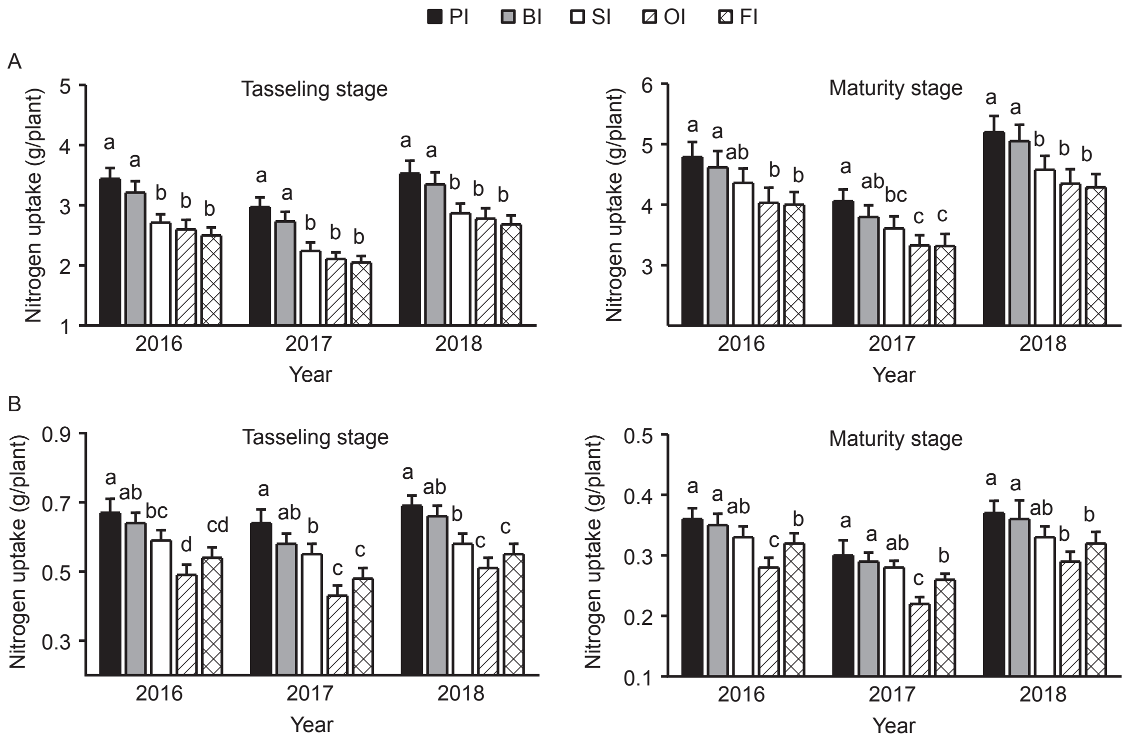

Fig. 10 Nitrogen uptake for the different irrigation treatments. A and B represent the above-ground maize plant parts and the roots, respectively. PI and BI, drip irrigation under plastic film mulch and biodegradable film mulch, respectively; SI, drip irrigation incorporating straw returning; OI, drip irrigation with the tape buried at a shallow soil depth; FI, furrow irrigation. The error bars represent the value of the SD (n=3). Different lowercase letters indicate significant differences at P<0.05.

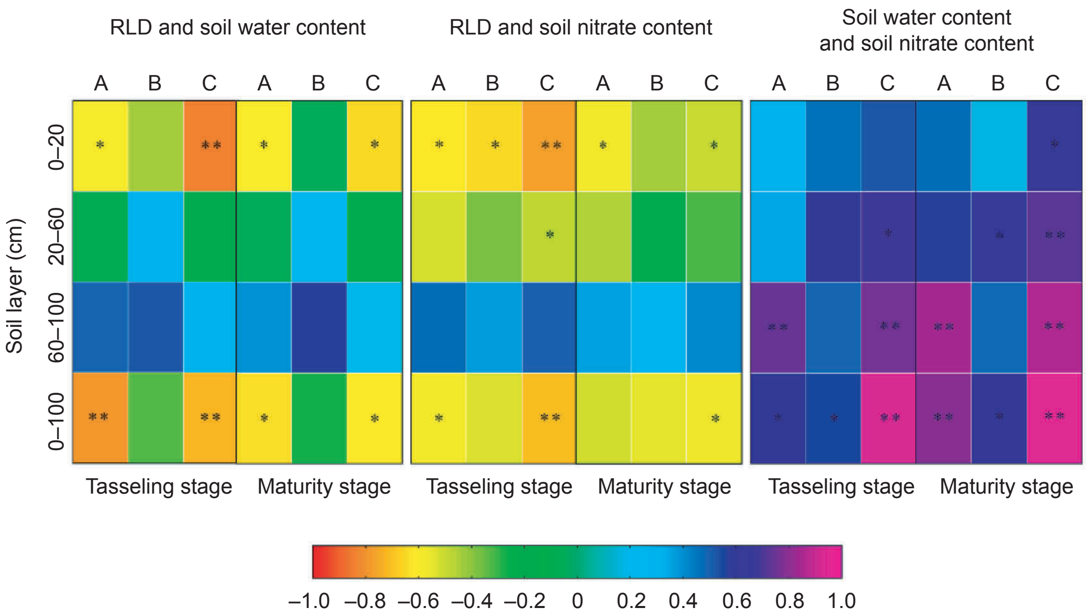

Fig. 11 Relationships between root length density (RLD) and soil water, RLD and soil nitrate, soil water and soil nitrate. A, B and C represent the I-, N- and R-zones, respectively. *, P<0.05; **, P<0.01.

nitrate and water from the I- and R-zones for maize growth, which reduced nitrate residue in the 60–100 cm soil layer at maturity. Gai *et al*. (2018) reported that soil nitrogen surplus was enhanced by returning crop straw to the field, which increased the risk of nitrate leaching. In our study, the SI treatment improved the soil nitrate content considerably

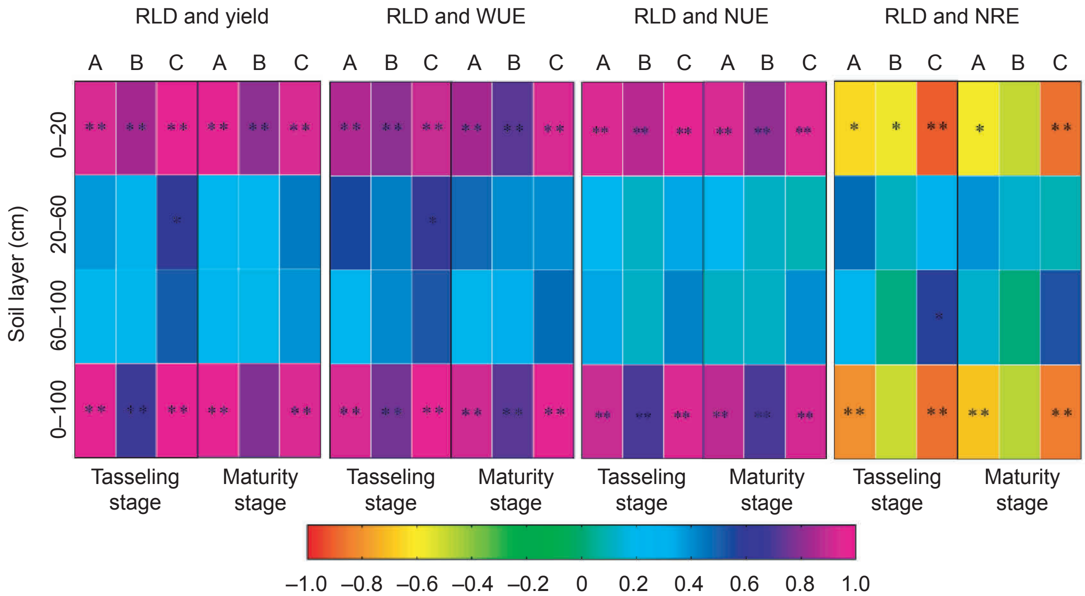

Fig. 12 Relationships between higher root length density (RLD) and yield, RLD and water use efficiency (WUE), RLD and nitrogen use efficiency (NUE), and RLD and root nitrogen use efficiency (NRE). A, B, and C represent the I-, N- and R-zones, respectively. *, *P*<0.05; **, *P*<0.01.

in the 0–60 cm soil layer in the I- and R-zones, where the straw and root biomass of maize are concentrated. But considering the higher RLD that is distributed in the deep soil in the SI treatment, the nitrate content in the 60–100 cm soil layer was not obviously increased compared to OI. Also, reduced nitrogen application is suggested for SI in case of nitrogen surplus and nitrate leaching out of the measurement range. In contrast to drip irrigation, increased irrigation water accompanied with nitrate under furrow irrigation (FI) percolated to the deep soil layers (Hassanli *et al*. 2009; Wang *et al*. 2010) and FI increased the soil nitrate content in the 60–100 cm soil layer by 1.84–7.82 and 6.94–8.26% compared with SI and OI at maturity, respectively, which increased the risk of nitrogen losses.

4.3. Root and plant senescence progression

RLD is strongly associated with crop growth and yield, and it affects water-nitrogen distribution and use efficiency (Jha *et al*. 2017; Li X Y *et al*. 2017). Drip irrigation is a localized irrigation system, and root growth under drip irrigation tends to concentrate water and fertilizer, which restricts the roots to a shallow soil depth (Sampathkumar *et al*. 2012). In the present study, the roots were mainly concentrated in the 0–20 cm soil layers for the I- and R-zones, where the RLD was significantly negatively correlated with soil water and soil nitrate contents (*P*<0.05). Our results agree with those of a previous study, showing that drip irrigation accompanied with film mulching promotes root growth (Wang J W *et al*. 2018). Both PI and BI significantly improved RLD in the 0–20 cm soil layer compared with SI, OI and FI, while plants in the BI treatment had higher RLD in the 20–100 cm soil layer compared with PI. Returning crop straw to the soil is beneficial to soil structure, the water–nitrogen environment and root growth (Zhang *et al*. 2017; An *et al*. 2018), and our results showed that SI significantly increased RLD in the 20–100 cm soil layer compared with OI and FI. Annual crops show gradual senescence after anthesis, during which higher activities of protective antioxidative enzymes, referring to SOD, POD and CAT, are beneficial for alleviating membrane lipid peroxidation with the end product of MDA, and provides the physiological basis for yield formation. PI significantly accelerated maize root and leaf senescence due to the higher soil temperature during the reproductive stage (Mai and Tian 2012). Furthermore, larger root system in the upper 0–20 cm soil layer and vigorous vegetative growth in the PI treatment may also lead to imbalanced development in maize, which decreases plant physiological activity and the leaf and root nitrate contents during the reproductive stage (Fig. 13) (Karandish and Shahnazari 2016; Yang *et al*. 2016). Also, SI increased protective enzyme activities and decreased the MDA content during the reproductive stage, which significantly delayed senescence in contrast to PI.

Reasonable water–nitrogen application to increase crop production by enhancing root growth in deep soil layers has been proposed recently for drip irrigation systems (Luo *et al*. 2012; Chilundo *et al*. 2017). However, the soil at our study site was heavy clay, and the RLD in the 0–60 cm soil layer accounted for more than 95% of the RLD in the different irrigation treatments; furthermore, we found that the RLD in the 0–20 cm soil layer was highly positively correlated with yield, WUE and NUE ($P<0.001$). RLD in the top soil layer was negatively correlated with NRE ($P<0.05$), and the correlations were weaker in the 20–60 and 60–100 cm soil layers. Thus, we conclude that RLD in the top soil layer (0–20 cm) is highly important to maize yield and resource use efficiency in the Northeast China Plain in drip irrigation systems. Also, we found that larger root systems were not necessarily better for the improvement of nitrogen use efficiency in roots. The BI treatment promoted root growth in the middle and deep soil layers (20–60 and 60–100 cm), which had an advantage in terms of resistance to senescence, drought and lodging for sustaining maize production compared with PI (Yu *et al*. 2015; Bian *et al*. 2016). Thus, future studies should focus on ways to improve root activity in the top soil layer and the ability of drip irrigation systems that employ plastic/biodegradable film mulches (PI/BI) to prevent early senescence.

5. Conclusion

In Northeast China, root length density in the 0–20 cm soil layer was highly positively correlated with maize yield and water and nitrogen use efficiency, while the positive effects were weaker in the 20–60 and 60–100 cm soil layers for the drip irrigation systems. Drip irrigation incorporating either plastic film or biodegradable film mulch had positive effects on increasing soil temperature, promoting root development and improving the utilization efficiency of soil water–nitrogen, which gave the highest maize yield benefits when compared with drip irrigation incorporating straw returning or tradition furrow irrigation. A drip irrigation system incorporating biodegradable film mulch benefited yield stability by reducing soil water consumption and slowing the progression of maize leaf and root senescence, and it was more environmentally friendly in comparison to a drip irrigation system that used plastic film mulch.

Acknowledgements

This work was supported by the National Key Research and Development Program of China (2016YFD0300103), the Science and Technology Project of Education Department of Jiangxi Province, China (GJJ190933), the Jiangxi Youth Science Foundation Project, China (20202BABL215003), the Innovation Engineering Plan Project of Jilin Province, China (CXGC2018ZY019), and the Chongqing Science and Technology Commission Project, China (cstc2018jxjl80008).

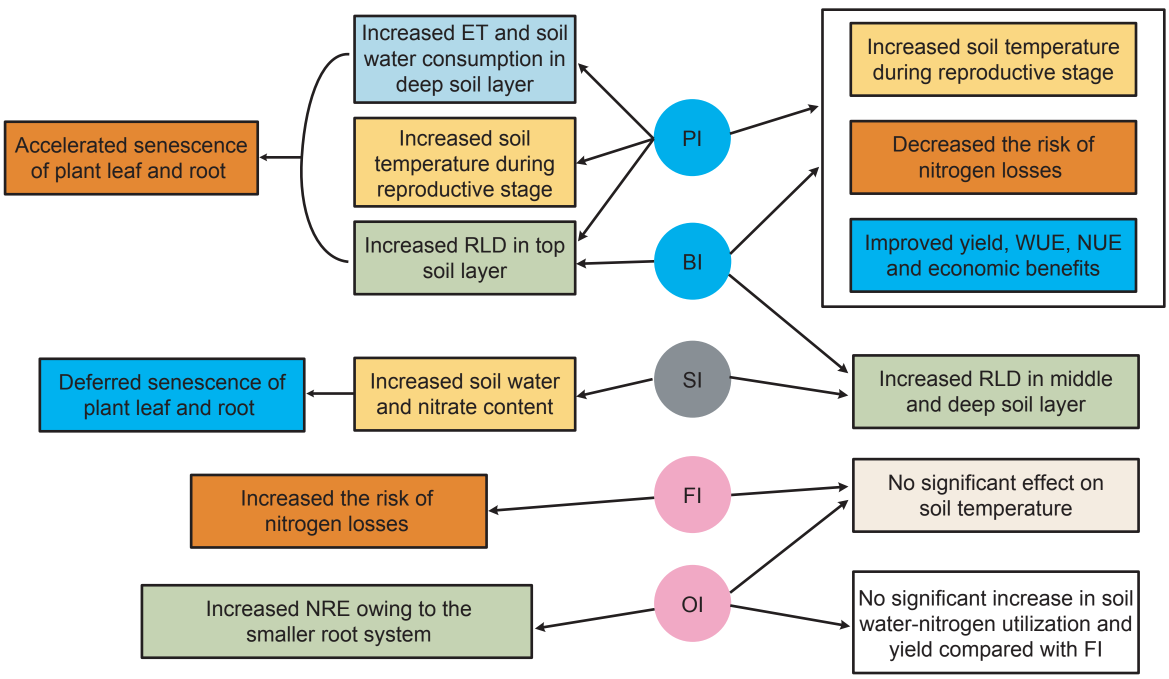

Fig. 13 Processes employed by the different irrigation systems. PI and BI, drip irrigation under plastic film mulch and biodegradable film mulch, respectively; SI, drip irrigation incorporating straw returning; FI, furrow irrigation; OI, drip irrigation with the tape buried at a shallow soil depth. ET, total evapotranspiration; RLD, root length density; NRE, root nitrogen use efficiency; WUE, water use efficiency; NUE, nitrogen use efficiency.

Declaration of competing interest

The authors declare that they have no conflict of interest.

References

Albaji M, Shahnazari A, Behzad M, Naseri A, Boroomand-Nasab S, Golabi M. 2010. Comparison of different irrigation methods based on the parametric evaluation approach in Dosalegh plain: Iran. *Agricultural Water Management*, **97**, 1093–1098.

An J P, Li C F, Qi H, Sui P X, Zhang W K, Tian P, You D B, Mri N, Xing J. 2018. Effects of straw strip returning on spring maize yield, soil moisture, nitrogen contents and root distribution in Northeast China. *Acta Agronomica Sinica*, **44**, 774–782. (in Chinese)

Bian D H, Jia G P, Cai L J, Ma Z Y, Eneji A E, Cui Y H. 2016. Effects of tillage practices on root characteristics and root lodging resistance of maize. *Field Crops Research*, **185**, 89–96.

Chen B M, Wang Z H, Li S X, Wang G X, Song H X, Wang X H. 2004. Effects of nitrate supply on plant growth, nitrate accumulation, metabolic nitrate concentration and nitrate reductase activity in three leafy vegetables. *Plant Science*, **167**, 635–643.

Chilundo M, Joel A, Wesström I, Brito R, Messing I. 2017. Response of maize root growth to irrigation and nitrogen management strategies in semi-arid loamy sandy soil. *Field Crops Research*, **200**, 143–162.

FAO (Food and Agriculture Organization of the United Nations). 2014. FAOSTAT. http://www.fao.org/faostat

Fu F B, Li F S, Kang S Z. 2017. Alternate partial root-zone drip irrigation improves water and nitrogen use efficiencies of sweet-waxy maize with nitrogen fertigation. *Scientific Reports*, **7**, 1–10.

Gai X P, Liu H B, Zhai L M, Yang B, Ren T Z, Wang H Y, Wu S X, Lei Q L. 2018. Effects of long-term additional application of organic manure or straw incorporation on soil nitrogen leaching risk. *Scientia Agricultura Sinica*, **51**, 2336–2347. (in Chinese)

Gao J F, 2006. *Experiment Guidance for Plant Physiology*. Beijing Higher Education Press, China. (in Chinese)

Hassanli A M, Ebrahimizadeh M A, Beecham S. 2009. The effects of irrigation methods with effluent and irrigation scheduling on water use efficiency and corn yields in an and region. *Agricultural Water Management*, **96**, 93–99.

Jayakumar M, Janapriya S, Surendran U. 2017. Effect of drip fertigation and polythene mulching on growth and productivity of coconut (*Cocos nucifera* L.) water, nutrient use efficiency and economic benefits. *Agricultural Water Management*, **182**, 87–93.

Jha S K, Gao Y, Liu H, Huang Z D, Wang G S, Liang Y P, Duan A W. 2017. Root development and water uptake in winter wheat under different irrigation methods and scheduling for North China. *Agricultural Water Management*, **182**, 139–150.

Karandish F, Shahnazari A. 2016. Soil temperature and maize nitrogen uptake improvement under partial root-zone drying irrigation. *Pedosphere*, **26**, 872–886.

Kang S Z, Hao X M, Du T S, Tong L, Su X L, Lu H N, Li X L, Huo Z H, Li S, Ding R S. 2016. Improving agricultural water productivity to ensure food security in China under changing environment: from research to practice. *Agricultural Water Management*, **179**, 5–17.

Li G H, Zhao B, Dong S T, Zhang J W, Liu P, Vyn T J. 2017. Impact of controlled release urea on maize yield and nitrogen use efficiency under different water conditions. *PLoS ONE*, **12**, e0181774.

Li X Y, Šimůnek J, Shi H B, Yan J W, Peng Z Y, Gong X W. 2017. Spatial distribution of soil water, soil temperature, and plant roots in a drip-irrigated intercropping field with plastic mulch. *European Journal of Agronomy*, **83**, 47–56.

Li Y, Liu H J, Huang G H, Zhang R H, Yang H Y. 2016. Nitrate nitrogen accumulation and leaching pattern at a winter wheat: summer maize cropping field in the North China Plain. *Environmental Earth Sciences*, **75**, 1–12.

Liu F, Wu G H, Zhang M Y, Qiang W. 2014. Corn production: A subsurface drip irrigation approach. *Applied Mechanics and Materials*, **666**, 375–378.

Liu Y, Yang H S, Li J S, Li Y F, Yan H J. 2018. Estimation of irrigation requirements for drip-irrigated maize in a sub-humid climate. *Journal of Integrative Agriculture*, **17**, 677–692.

Liu Z, Zhu K L, Dong S T, Liu P, Zhao B, Zhang J W. 2017. Effects of integrated agronomic practices management on root growth and development of summer maize. *European Journal of Agronomy*, **84**, 140–151.

Luo H H, Zhang H Z, Zhang Y L, Zhang W F. 2012. Effects of water storage in deeper soil layers on the root growth, root distribution and economic yield of cotton in arid area with drip irrigation under mulch. *Chinese Journal of Applied Ecology*, **23**, 395–402. (in Chinese)

Mai W X, Tian C Y. 2012. The possible mechanism of cotton premature senescence under drip irrigation below mulch film — From the perspective of growth and nutrient. *Plant Nutrition and Fertilizer Science*, **18**, 132–138. (in Chinese)

Mo Y, Li G Y, Wang D. 2017. A sowing method for subsurface drip irrigation that increases the emergence rate, yield, and water use efficiency in spring corn. *Agricultural Water Management*, **179**, 288–295.

Patanè C, Tringali S, Sortino O. 2011. Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions, *Scientia Horticulturae*, **129**, 590–596.

Sampathkumar T, Pandian B J, Mahimairaja S. 2012. Soil moisture distribution and root characters as influenced by deficit irrigation through drip system in cotton–maize cropping sequence. *Agricultural Water Management*, **103**, 43–53.

Soltani A, Khooie F R, Ghassemi-Golezani K, Moghaddam M. 2001. A simulation study of chickpea crop response to limited irrigation in a semiarid environment. *Agricultural Water Management*, **49**, 225–237.

Sui J, Wang J D, Gong S H, Xu D, Zhang Y Q, Qin Q M. 2018. Assessment of maize yield-increasing potential

and optimum N level under mulched drip irrigation in the Northeast of China. *Field Crops Research*, **215**, 132–139.
Taghavi T S, Babalar M. 2007. The effect of nitrate and plant size on nitrate uptake and *in vitro* nitrate reductase activity in strawberry (*Fragaria×ananassa cv*. Selva). *Scientia Horticulturae*, **112**, 393–398.
Tang B, Xu S Z, Zou X L, Zheng Y L, Qiu F Z. 2010. Changes of antioxidative enzymes and lipid peroxidation in leaves and roots of waterlogging-tolerant and waterlogging-sensitive maize genotypes at seedling stage. *Agricultural Sciences in China*, **9**, 651–661.
Wang J W, Niu W Q, Guo L L, Liu L, Li Y, Dyck M. 2018. Drip irrigation with film mulch improves soil alkaline phosphatase and phosphorus uptake. *Agricultural Water Management*, **201**, 258–267.
Wang M, Wang H X, Han Q F, Li R, Zhang R, Gu Z K, Yang B P. 2011. Effects of different mulching materials on soil water, temperature, and corn growth. *Acta Agronomica Sinica*, **37**, 1249–1258. (in Chinese)
Wang Q, Li F R, Zhao L, Zhang E, Shi S L, Zhao W Z, Song W X, Vance M M. 2010. Effects of irrigation and nitrogen application rates on nitrate nitrogen distribution and fertilizer nitrogen loss, wheat yield and nitrogen uptake on a recently reclaimed sandy farmland. *Plant and Soil*, **337**, 325–339.
Wang X J, Jia Z K, Liang L Y, Zhao Y F, Yang B P, Ding R X, Wang J P, Nie J F. 2018. Changes in soil characteristics and maize yield under straw returning system in dryland farming. *Field Crops Research*, **218**, 11–17.
Wang X K, Li Z B, Xing Y Y. 2015. Effects of mulching and nitrogen on soil temperature, water content, nitrate-N content and maize yield in the Loess Plateau of China. *Agricultural Water Management*, **161**, 53–64.
Wang Z, Li J, Li Y. 2014. Effects of drip irrigation system uniformity and nitrogen applied on deep percolation and nitrate leaching during growing seasons of spring maize in semi-humid region. *Irrigation Science*, **32**, 221–236.
Wang Z H, Wu Q, Fan B H, Zhang J Z, Li W H, Zheng X R, Lin H, Guo L. 2019. Testing biodegradable films as alternatives to plastic films in enhancing cotton (*Gossypium hirsutum* L.) yield under mulched drip irrigation. *Soil and Tillage Research*, **192**, 196–205.
Wu Q, Wang Z H, Zheng X R, Zhang J Z, Li W H. 2017. Effects of biodegradation film mulching on soil temperature, moisture and yield of cotton under drip irrigation in typical oasis area. *Transations of the Chinese Society of Agricultural Engineering*, **33**, 135–143. (in Chinese)
Xue X X, Mai W X, Zhao Z Y, Zhang K, Tian C Y. 2017. Optimized nitrogen fertilizer application enhances absorption of soil nitrogen and yield of castor with drip irrigation under mulch film. *Industrial Crops and Products*, **95**, 156–162.
Yan C R, Liu E K, Shu F, Liu Q, Liu S, He W Q. 2014. Review of agricultural plastic mulching and its residual pollution and prevention measures in China. *Journal of Agricultural Resources and Environment*, **31**, 95–102. (in Chinese)
Yang R, Tian C Y, Mai W X. 2016. Characteristics of root development in cotton suffering presenility under drip irrigation and film mulch in Xinjiang Autonomous Region. *Journal of Plant Nutrition and Soil Science*, **22**, 1384–1392. (in Chinese)
Yu P, Li X X, White P J, Li C J. 2015. A large and deep root system underlies high nitrogen-use efficiency in maize production. *PLoS ONE*, **10**, e0126293.
Zhang C, Mu P, Shang J M. 2018. Effects of continuous returning corn straw on soil chemical properties, enzyme activities and yield trait. *Research of Soil and Water Conservation*, **25**, 92–98. (in Chinese)
Zhang G J, Pu X Z, Zhang P P, Zhang W F. 2017. Effects of stubble returning to soil and fertilization on soil nitrogen availability and root biomass of cotton in arid region. *Scientia Agricultura Sinica*, **50**, 2624–2634. (in Chinese)
Zhang S, Li P, Yang X, Wang Z, Chen X. 2011. Effects of tillage and plastic mulch on soil water, growth and yield of spring-sown maize. *Soil and Tillage Research*, **112**, 92–97.
Zhao H, Xiong Y C, Li F M, Wang R Y, Qiang S C, Yao T F, Mo F. 2012. Plastic film mulch for half growing-season maximized WUE and yield of potato *via* moisture-temperature improvement in a semi-arid agroecosystem. *Agricultural Water Management*, **104**, 68–78.
Zhou B Y, Ma D, Sun X F, Ding Z S, Li C F, Ma W, Zhao M. 2019. Straw mulching under a drip irrigation system improves maize grain yield and water use efficiency. *Crop Science*, **59**, 2806–2819.
Zhou C M, Li Y N, Gu X N, Yin M H, Zhao X. 2016. Effects of biodegradable film mulching planting patterns on soil nutrient and nitrogen use efficiency of summer maize. *Transactions of the Chinese Society for Agricultural Machinery*, **47**, 133–142. (in Chinese)
Zhou L F, He J Q, Qi Z J, Dyck M, Zou Y F, Zhang T B, Feng H. 2018. Effects of lateral spacing for drip irrigation and mulching on the distributions of soil water and nitrate, maize yield, and water use efficiency. *Agricultural Water Management*, **199**, 190–200.

Executive Editor-in-Chief LI Shao-kun
Managing Editor WANG Ning