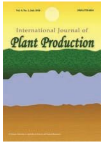

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Root-shoot regulation and yield of mulched drip irrigated maize on sandy soil

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Abstract

Sandy fields have been reclaimed to exploit the grain production potential in northwest China. A 2-year statistically replicated field study was conducted to determine the effects of mulched drip irrigation on soil water, soil nitrate, shoot root growth and yields of maize on a sandy field in the Hetao Irrigation District. Treatments included border irrigation (BI), fully mulched drip irrigation (FMDI) and partially mulched drip irrigation (PMDI). Low frequency fertigation and high frequency fertigation were applied in 2014 and 2015, respectively. The results showed that high frequency mulched drip irrigation (MDI) maintained soil moisture and NO_3^--N at suitable levels and improved soil water uniformity (C_{us}). Soil NO_3^--N was adequate for the FMDI treatment of both high and low frequency fertigations, but it was insufficient for the PMDI treatment under low frequency fertigation. Soil water and C_{us} regulated root−shoot via leaf areas and surface root areas were described well by the ratio of root surface area to leaf area ($S_{r/l}$). Higher C_{us} tended to cause a lower $S_{r/l}$. Compared with the BI treatment, a higher yield and harvest index (HI) was obtained under the MDI treatments primarily due to the high number of grains per spike. The FMDI and PMDI treatments resulted in no yield differences under high frequency fertigation. Therefore, high frequency PMDI management with irrigation amounts based on the reference evapotranspiration after the jointing stage were recommended in the sandy maize field based on economic considerations. Under low frequency fertigation, the FMDI treatment was recommended for a higher yield, which was attributable to the higher dry matter of the vegetative organs and maintaining higher levels of soil NO_3^--N in the upper sand layer when compared to the PMDI treatment.

Keywords: Soil water uniformity; Harvest index; Mulched drip irrigation; Shoot-root regulation; Sand-layered soil.

Abbreviations: FMDI, full mulched drip irrigation; PMDI, partial mulched drip irrigation; BI, border irrigation; C_{us}, soil moisture distribution uniformity; DAS, days after sowing; A_l, leaf area; SA_r, root surface area; M_l, dry matter of leaves; M_r, dry matter of roots; $M_{r/l}$, dry matter ratio of root to leaf; $S_{r/l}$, ratio of root surface area to leaf area; HGW, hundred gain weight; HI, harvest index; DM, dry matter; BE, beneath the emitters; ME, midway between the emitters.

Introduction

Sandy fields are typically characterized by high rates of soil water percolation and crop yield reductions (El-Hendawy et al., 2010). In sandy fields, extensive irrigation is generally applied to prevent yield reductions. However, this practice has been shown to result in low water use efficiency and substantial non-point pollution of the within the field drainage (Guo et al., 2014).

Drip irrigation can precisely supply water and fertilizer to the root zone, which enables the utilization of barren lands (Silber et al., 2003). Mulching is also widely used to decrease evaporation for a high evaporation-precipitation ratio. However, research has demonstrated that mulched drip irrigation (MDI) may cause premature senility and crop yield decreases in poorly aerated soil (Hu et al., 2009) that may be partially attributable to excessive shoot-to-root biomass ratios (Mai and Tian, 2012).

Li et al. (2007) reported that the root distribution was restricted to the wetted zone. It has also been shown that the wetted volume and NO_3^--N concentrations (Gorska et al., 2008) in the root zone may regulate shoot and root growth. Kang et al. (2000) employed the Christiansen uniformity coefficient (C_{us}) to evaluate the soil water distribution and analyzed the influence of alternate partial root-zone irrigation on crop yields and its water use efficiency.

Compared with partial plastic film mulch, Li et al. (2010) found that full plastic film mulch led to higher quantities of soil water storage within the 0−200 cm soil depth from the sowing to jointing stage, but displayed lower quantities of soil water storage (0−200 cm) from the jointing stage to the filling stage. Full plastic film mulch more profoundly enhances crop establishment (Chalker-Scott, 2007) and the amount of nitrogen accumulation in the maize kernel (Zhang et al., 2011) that may result in a higher hundred-grain weight (Kunzová and Hejcman, 2009) than the value when the corn is grown under a partial plastic film mulch (Ramakrishna et al., 2016).

The Hetao Irrigation District (40°19–41°18N, 106°20–109°19E) is one of the three largest irrigation districts in China. Sandy fields are common in this region and the maize yield production has characteristically been poor. Within the district, over 2000 mm water is annually irrigated to maintain maize growth. The objectives of this study were: (i) to observe the soil moisture and nitrate distribution under mulched drip irrigation in a sandy field, (ii) to seek if C_{us} can be used to evaluate the regulation of root and shoot under mulched drip irrigation and (iii) to determine the more efficient mulching method under different irrigation scenarios.

Materials and Methods

Site and climatic conditions

The experiment was conducted in 2014 and 2015 at the Shuguang Irrigation Research Station in the Hetao Irrigation District, western Inner Mongolia Autonomous Region, China (40°43N, 107°13E, 1042 m asl). This region is characterized with an arid continental climate with an average annual rainfall of 135.0 mm concentrated between June and September. The annual mean pan evaporation exceeds 2000 mm. The annual mean air temperature is 9.1 ºC with monthly averages that range from 23.8 ºC in July to -10.1 ºC in January. The average air temperature was 19.9 and 20.2 ºC and the total precipitation was 84.0 and 14.6 mm during growth period in 2014 and 2015, respectively. The main physical and chemical properties of the 0–120 cm soil layer are listed in Table 1.

Table 1. Physical and chemical properties of the 0-120 cm soil in 20 cm soil depth intervals at the study site.

Depth[a] (cm)	BD ($g\ cm^{-3}$)	FMC (%)	OM ($g\ kg^{-1}$)	NO_3^- ($mg\ kg^{-1}$)	NH_4^+ ($mg\ kg^{-1}$)	AP ($mg\ kg^{-1}$)	Particle size distribution (%)			Soil texture
							clay	silt	sand	
0-20	1.4	32.16	7.3	7.9	8.0	33.2	20.0	47.8	32.2	Silty loam
20-40	1.4	34.22	6.7	5.7	13.8	21.5	23.0	53.8	23.2	Silty loam
40-60	1.4	30.8	6.3	3.5	5.4	12.7	23.1	47.2	29.7	Silty loam
60-90	1.5	23.53	3.0	1.4	3.1	4.0	2.04	3.66	94.3	sand
90-120	1.4	32.2	5.3	3.8	6.2	7.3	15.3	35.4	49.3	Silty loam

[a] BD, bulk density; FMC, field moisture capacity; OM, organic matter; AP, available phosphorus.

Experimental design and field management

This experiment used a completely randomized block design with three replicates. Each plot was 4 m wide by 12 m long with 8 plant rows. Three treatments were implemented: border irrigation (BI; flooding in bordered plots), fully mulched drip irrigation (FMDI) where the plots were completely mulched and partially mulched drip irrigation (PMDI) where the plots were partially mulched with a plastic film of a 60 cm width. In the BI treatment, two planting rows were covered by plastic film mulch with a width of 60 cm (Figure 1). In the FMDI and PMDI treatments, one irrigation drip lateral was positioned at the center of two adjacent crop rows that were fully mulched with plastic film or partially mulched with plastic film at a width of 60 cm (Figure 1). In all treatments, the clear plastic film was 0.008-mm-thick polyethylene and the mulched area indices were 1.0, 0.6 and 0.6 in the FMDI, PMDI and BI treatments, respectively. Two rows of maize seed were sown on both sides of drip tapes with a 15-cm distance for the narrow rows. The wide rows and narrow rows were measured as 70 cm and 30 cm, respectively (Figure 1).

The drip irrigation systems were placed before being covered with plastic mulch and consisted of a control unit and distribution lines. Drip tapes (Ø = 16 mm) with emitters spaced at 30 cm and delivering water with flow rates of 1.4 $l\ h^{-1}$ were used. The irrigation for the BI treatment was applied using a water belt with a water meter. Low frequency irrigation was applied in 2014 and the maize suffered severe water stress. A higher single irrigation amount could keep soil moisture under low frequency irrigation conditions (Howell et al., 1997), but it easily causes substantial percolation below the root zone between the irrigation events on sandy soils, which has low soil-water storage capacity. As a result, high frequency irrigation was applied during the 2015 maize season. The irrigation and fertilization events are listed in Table 2. The irrigation amount in the mulched drip irrigation (MDI) treatments was set at 60% of the local irrigation during 2014 and it was based on evapotranspiration (ET) during 2015. ET was calculated using an E_{20} pan (Wang et al., 2015). The irrigation amount was 300 mm for the BI treatments during the two years and is in accordance with the recommended irrigation amount in this irrigation district (Huo et al., 2012) and 180 mm and 346.1 mm for mulch drip irrigation in 2014 and 2015 respectively. There were 4 irrigation events for the BI treatment over both years, according to the local irrigation regime used for both years. In the MDI treatments, irrigation was applied 9 and 20 times in 2014 and 2015 respectively. The total N application rate was 300 kg N ha^{-1} for all treatments in both years. 420 kg ha^{-1} of ammonium phosphate (200 kg P_2O_5 ha^{-1}) was spread as a base fertilizer before mulching in both years. The N was broadcast at levels of 150 kg N/ha as a base fertilizer in both years, in the form of urea (75 kg N ha^{-1}) and ammonium phosphate (75 kg N ha^{-1}). The remaining 150 kg N ha^{-1} (urea) was evenly applied with irrigation after the six-leave (V6) stage.

The plots were manually covered with a clear plastic film on 22 April 2014 and 26 April 2015. The maize cultivar "Ximeng 6" was planted on 24 April and 28 April in 2014 and 2015, respectively. Seeds were sown hole-by-hole using a hole-sowing machine at a 5-cm depth with a planting density of 66,600 plants ha^{-1} and immediately followed by mulching.

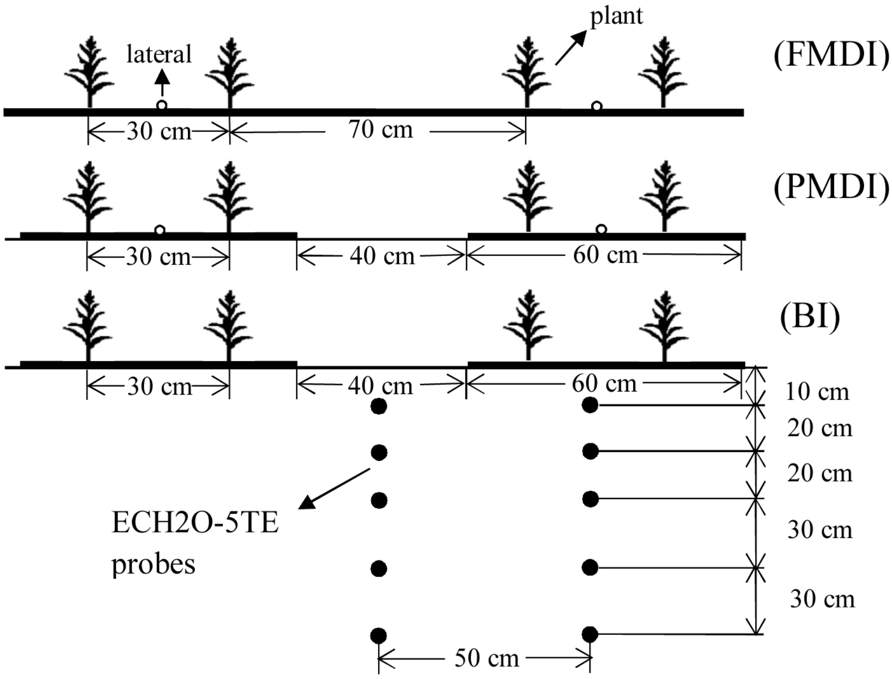

Figure 1. Diagram shows the mulching and planting methods in this study for the border irrigation (BI), full mulched drip irrigation (FMDI) and the partial mulched drip irrigation (PMDI) treatments. The bold lines represent the mulched zones. The locations of the drip irrigation laterals and the ECH_2O-5TE soil moisture probes are represented by open circles and closed circles, respectively.

Table 2. Irrigation and fertilization events after sowing the maize crop for the border irrigation treatment (BI) and the mulched irrigation (MDI) treatments during 2014 and 2015.The MDI treatments consist of the full mulched drip irrigation (FMDI) treatment and the partial mulched drip irrigation (PMDI) treatment.

Treatment	2014				2015			
	Irrigation amounts (mm)	Irrigation times	N application rate (kg ha^{-1})	N application times	Irrigation amounts mm	Irrigation times	N application rate (kg ha^{-1})	N application times
MDI	180	9	150	4	346	20	150	16
BI	300	4	150	4	300	4	150	4

Samplings and measurements

In the BI treatment, the soil water contents were measured at the 1−3 days before and 3-5 days after each irrigation (depending on local rainfall events), using a 54 mm (diameter) steel core sampling tube that was manually driven to a 100-cm depth at two horizontal locations (beneath the planting row and midway between the planting rows. The soil cores were weighed wet and dried at 105 ºC for 48 h to determine the gravimetric soil water content measurement. The volumetric soil water content was calculated by multiplying the soil bulk density times the gravimetric soil water content. In the MDI treatments, using real-time monitoring, the volumetric soil water content was measured hourly at 10, 30, 50, 80 and 110 cm soil depths at two locations (beneath the emitters (BE) and midway between the emitters (ME)) to record profiled soil moisture. The soil temperature was measured hourly for the 20-, 40-, 60-, 100- and 120-cm layers at the same locations as the soil water content. Both the soil water content and the soil temperature were measured using ECH_2O-5TE (Decagon Devices, Inc., Pullman, WA, USA) probes beneath the emitters (BE) and midway between the emitters (ME) and recorded by Em50 data loggers (Decagon Devices, Inc., Pullman, WA, USA). The probes were calibrated and tested according to the instruction manual before being inserted into soil profile. The soil NO_3^- concentrations were measured in soil samples taken at 0.1 m intervals to a depth of 1 m, at the same horizontal distances from the laterals used for the soil moisture measurements. The soil samples were extracted with 1 M KCl (10 g of soil: 100 mL of KCl), oscillated, filtered and analysed using an AA3 Continuous Flow Analytical System (Bao, 2000).

The root length and root surface area were measured at the milk-ripe stage in 2015. The root material was sampled by washing roots from soil blocks of 0.15 m length by 0.10 m width by 0.1 height excavated from each plot. In the vertical direction, sampling was conducted at 10-cm intervals to the depth at which the roots were no longer visible. The rinsed roots were scanned with a root scanner (EPSON Perfection V700) and analysed using WinRHIZOPro software to obtain root length density (RLD). The individual leaf area was determined by leaf length × leaf width and measured with a ruler.

To determine the total dry matter above the ground level at harvest stage, six plants were labelled 21 days after planting in each plot. The dry matter (DM) was determined after oven drying at 65 ºC to a constant weight, with leaves, stems and ears separated. Grain yield was determined by hand harvesting the two adjacent centre rows in each plot at maturity. The grains were sun-dried for 4–5 days and weighed after threshing. Then, the kernel number per ear was counted and the grain yield of maize was established while considering a 15% water content within the sun-dried grain. The grain water content (%) after being sun-dried was determined using the constant weight after oven drying at 65 ºC which was divided into the sun-dried grain weight.

Calculations and statistical analysis.

The Christiansen uniformity coefficient of the soil water content (C_{us}) was used to evaluate the uniformity of irrigated water distribution according to Kang et al. (2000):

$$C_{us} = 1 - \frac{\overline{\Delta\theta}}{\bar{\theta}} \quad (1)$$

$$\overline{\Delta\theta} = \frac{\sum_1^N \left|\theta_i - \bar{\theta}\right|}{N} \quad (2)$$

where C_{us} is the uniformity soil water coefficient, ranging between 0 (very low uniformity) and 1 (very high uniformity). $\overline{\theta}$ is the average soil water content ($m^3 \cdot m^{-3}$) and $\overline{\Delta\theta}$ ($m^3 \cdot m^{-3}$) is the average difference of the measured water content (θ_i) and N is the total number of samples. The C_{us} calculation time step was determined before or after irrigation events. Before the jointing stage, C_{us} was calculated at 70 days after sowing (DAS) in 2014 and at 52 and 57 DAS in 2015. After the jointing stage, the C_{us} was calculated at 85, 100, 114, 126, 138 DAS in 2014 and at 74, 79, 103, 109, 117 and 126 DAS in 2015.

The harvest index (HI) was determined as the ratio of the corn grain yield to the aboveground dry matter. The data were analysed using the ANOVA procedure with the SPSS statistical package. Multiple comparisons of the mean annual values were performed using Duncan's multiple range test. In all analyses, a P-value < 0.05 was considered statistically significant.

Results

Soil moisture and uniformity coefficient

The $\theta_{a\text{-}b}$ notation is used for a clear description on the spatial distribution of the soil water within the profile (BE and ME). The "a" designates the soil depth (10 cm, 50 cm, 80 cm, 100 cm) and the "b" designates the horizontal sampling distance (0 cm or 50 cm).

1) Soil moisture in MDI treatments in 2014

In 2014, beneath the emitters (BE), the $\theta_{10\text{-}0}$, $\theta_{80\text{-}0}$ for the FMDI and PMDI treatments displayed no significant differences (Figure 2a, c). The $\theta_{50\text{-}0}$ under the FMDI treatment substantially decreased from 50 DAS and was lower than under the PMDI treatment from 57 DAS (Figure 2b). At the location midway between the emitters (ME), a sharp and slight $\theta_{10\text{-}50}$ decrease occurred for the PMDI and FMDI treatments after 84 DAS (Figure 2a). The soil moisture of the FMDI treatment was higher than the PMDI treatment at the 10-cm soil depth while it was lower than the PMDI treatment at the 50-cm soil depth (Figure 2a, b). The soil moisture at 100 cm increased moderately with fluctuations in terms of field capacity from 84 DAS (Figure 2d), which may be related with to the groundwater (Sophocleous, 1991) as in Figure 3.

2) Soil moisture in MDI treatments in 2015

Because of the frequent fertigation after the jointing stage in 2015, $\theta_{10\text{-}0}$ remained steady during the growth period beneath the emitters (Figure 2e). However, $\theta_{50\text{-}0}$ under the FMDI and PMDI treatments decreased sharply 50 DAS (Figure 2f). Between the emitters, $\theta_{10\text{-}50}$ showed no differences with $\theta_{10\text{-}0}$ in the FMDI treatments while $\theta_{10\text{-}50}$ showed significant differences with $\theta_{10\text{-}0}$ in the PMDI treatments (Figure 2e). The $\theta_{50\text{-}50}$ under the FMDI and PMDI treatments decreased sharply in 2015 (Figure 2f). However, $\theta_{50\text{-}50}$ under the FMDI treatment increased steadily up to two weeks after frequent irrigation and increased rapidly during the later period of frequent irrigation. The sand layer presented a high moisture (0.16 to 0.21 cm^3 cm^{-3}) (Figure 2g) due to the autumn irrigation of 250 mm applied during October in 2014 to reduce soil salinity, which raised the water table to the 0.6-m soil depth and caused a high sand layer moisture.

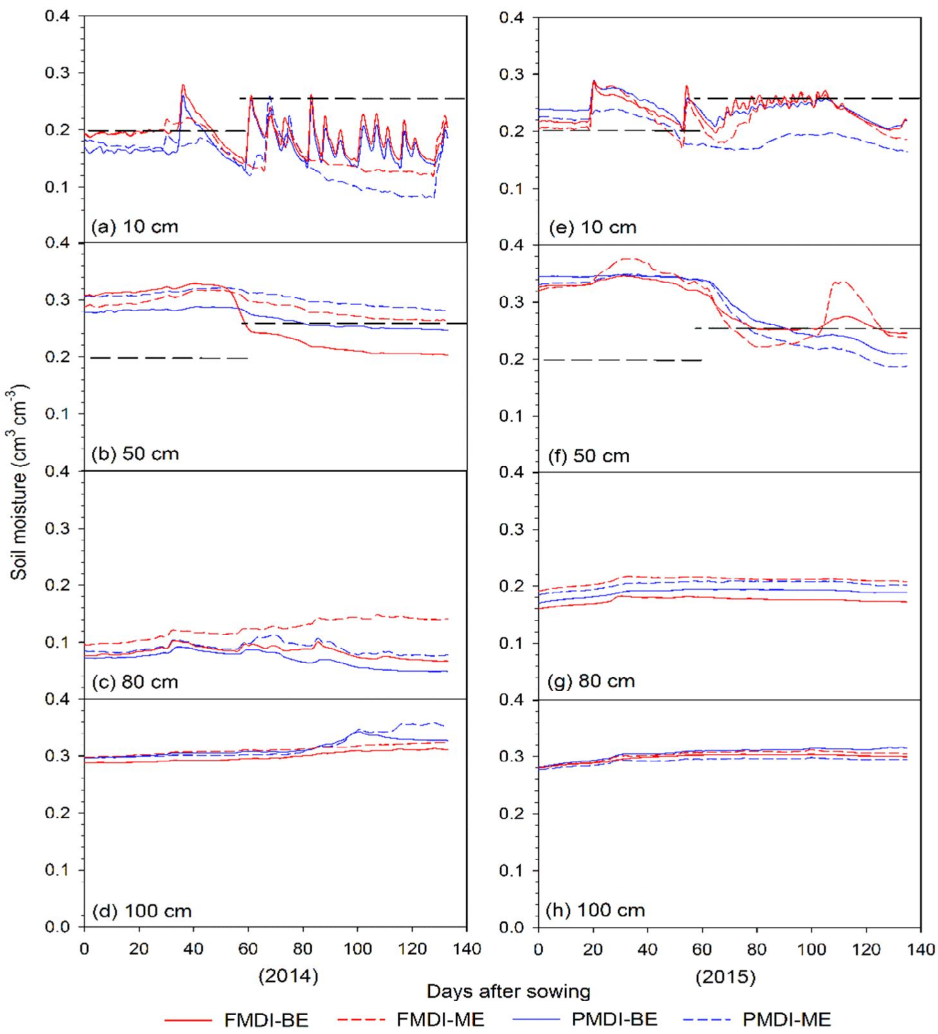

Figure 2. Soil moisture at the 10, 50, 80 and 100 cm soil depths beneath the drip emitters (BE) and midway between the drip emitters (ME) for the full mulched drip irrigation (FMDI) and partial mulched drip irrigation (PMDI) treatments. Graphs (a), (b), (c) and (d) display results for 2014 and graphs (e), (f), (g) and (h) display results for 2015. The long dashed line represents the water stress level before (0.2 $cm^3\ cm^{-3}$) and after (0.26 $cm^3\ cm^{-3}$) the jointing stage for maize (Ma et al., 2014).

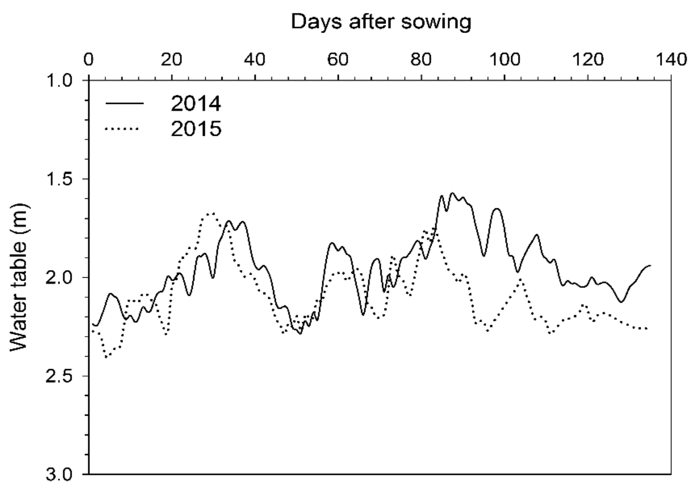

Figure 3. Depth of the water table following the sowing of the maize crop in 2014 and 2015.

3) Soil moisture and uniformity coefficient in BI and MDI treatments

The average soil water content above the sand layer at the 60-cm soil depth under the BI treatment fluctuated more widely after irrigation and rainfall events than under the mulched drip irrigation treatments (Figure 4a, b). The soil moisture did not meet the water requirements for maize during reproductive stage according to the local irrigation scheduling in 2015 (Figure 4b). Irrigation improved the C_{us} in the BI and MDI treatments (C_{us} > 0.8) in this study (Figure 4c, d). Besides, the C_{us} of the BI treatment showed a drastic change during arid weather conditions, but did not occur for the MDI treatments (Figure 4c, d). In the MDI treatments, the C_{us} of the FMDI treatment was higher than the value for the PMDI treatment.

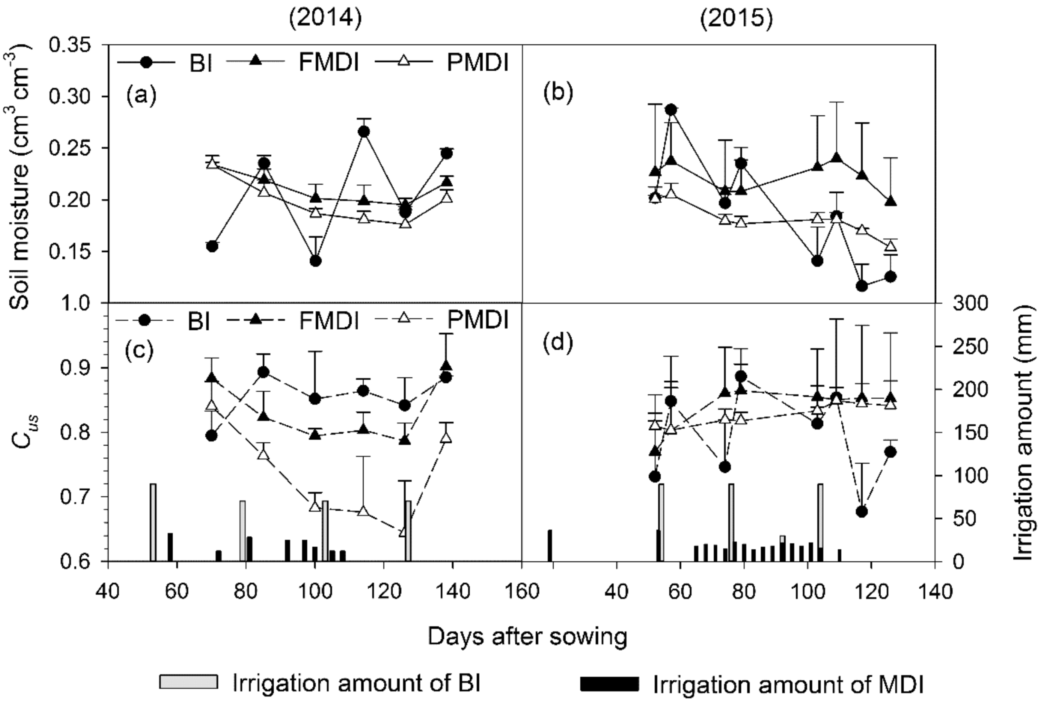

Figure 4. Changes in the average soil moisture and moisture uniformity (C_{us}) for the border irrigation (BI), full mulched drip irrigation (FMDI) and the partial mulched drip irrigation (PMDI) treatments during the days after sowing the maize crop. Graphs (a) and (c) show the average soil moisture and C_{us} in 2014 and graphs (b) and (d) show the average soil moisture and C_{us} in 2015. The bar graphs indicate the irrigation amounts for the BI treatment and the mulched drip irrigation (MDI) treatments.

Soil nitrate under mulched drip irrigation

1) Soil nitrate under mulched drip irrigation during 2014

During the V6 stage, the concentrations of soil NO_3^--N decreased from the surface soil to the underlying soil (Figure 5a). The soil NO_3^--N concentrations at the 10- and 50-cm depths for the FMDI treatments were higher than the values for the PMDI treatments, respectively (Figure 5a). This outcome implied that full mulching may have effectively maintained soil NO_3^--N concentrations within the sand layer. The soil NO_3^--N concentrations beneath the emitters were higher than the values for the point midway between the emitters. At the silking and milk stages, the soil NO_3^--N concentrations were low and showed no significant differences between the BE and ME. In the sand layer, the NO_3^-- concentrations remained between 5 and 15 mg/kg for the growth season (Figure 5a, b, c). It was found that soil NO_3^- deficits occurred (soil NO_3^--N concentrations below 15 mg kg^{-1}) under low frequent fertigation conditions, especially for the PMDI treatment (Figure 5a, b, c).

2) Soil nitrate under mulched drip irrigation in 2015

The soil NO_3^- concentrations at the V6 stage (Figure 5d) displayed similar results with the values displayed during 2014 (Figure 5a). During the silking stage, the differences in the soil NO_3^--N concentrations were predominantly at the 10-cm soil depth. The soil NO_3^--N concentrations for the FMDI treatment were lower than the values observed for the PMDI treatments with no differences between the BE and ME locations (Figure 5e). The soil NO_3^--N concentrations beneath the emitters were lower than the point midway between the emitters at the 10-cm soil depth for the PMDI treatments (Figure 5e). During the milk stage, the soil NO_3^--N concentrations were obviously enhanced. At the 10-cm soil depth, the soil NO_3^--N concentrations beneath the emitters were lower than the point midway between the emitters for the FMDI and PMDI treatments. It was shown that soil NO_3^--N concentrations at the 10-cm depth in both MDI treatments and at the 50-cm soil depth for the FMDI treatment were very high (exceeding 50 mg kg^{-1}), which is a value regarded as luxurious for crop growth. It was indicated that high frequency MDI may have a substantial potential for saving fertilizer, especially for the FMDI treatments.

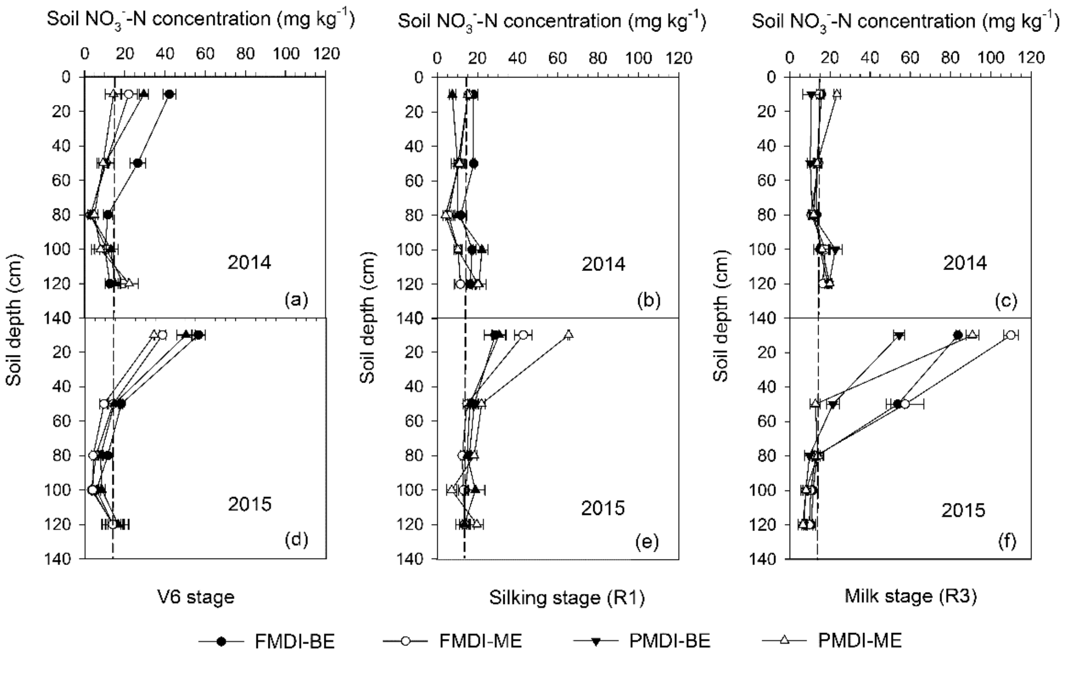

Figure 5. Comparison of the soil NO_3^--N concentrations of the 0-120 cm soil depths (in 20-cm intervals) at three maize plant growth stages (V6, silking and milk stage). Graphs (a), (b) and (c) display the soil NO_3^--N concentrations in 2014, while graphs (d), (e) and (f) display the soil NO_3^--N concentrations in 2015. Positional abbreviations used are as follows: BE = beneath the drip emitters and ME = the point midway between drip emitters.

Root length density and shoot/root regulation analysis based on soil water status

The root length density (RLD) typically decreases exponentially with increasing soil depth. However, in the BI treatment, the maximum RLD was found at the 10–20 cm soil depth instead of the 0–10 cm soil depth when wide rows were used (Figure 6a, d). The results indicated that the extent of lateral root growth at the 10-20 cm and 20-30 cm soil depths was greater for the BI (51.7%) and PMDI (44.4%) treatments than for the FMDI treatment in this sand-layered field (Figure 6b, c, d).

In order to investigate the regulation of shoot/root ratios under mulched drip irrigation, the following quantitative variables for 2015 were plotted in a scatter diagram (Figure 7): soil moisture, C_{us}, leaf area (A_l), root surface area (SA_r), ratio of root surface area to leaf area ($S_{r/l}$), dry matter of leaf (M_l), dry matter of root (M_r) and dry matter ratio of root to leaf ($M_{r/l}$). To analyse the relationships between the eight factors mentioned above: the highest value of each factor among the three treatments (BI, FMDI and PMDI) was set to "1", then the ratio (scores from 0-1) of each factor in all the treatments was calculated and plotted in the scatter diagram. The FMDI treatment has greater soil moisture levels than the other two treatments which were approximately equivalent. The FMDI and PMDI treatments had greater values of C_{us} than the BI treatment. The BI treatment when compared with the FMDI and PMDI treatments had higher values of M_r, $M_{r/l}$, SA_r and $S_{r/l}$. When comparing the FMDI and PMDI treatments, the FMDI treatment had slightly higher values of M_r, $M_{r/l}$ and A_l when compared to the PMDI treatment. The PMDI treatment had slightly higher values of SA_r and $S_{r/l}$ than the FMDI treatments. The FMDI and PMDI treatments had approximately equivalent values for M_l. From the orders of the factors marked with arrows (Figure 7), it can be included that the C_{us} regulated $S_{r/l}$ via A_l and SA_r (Figure 7).

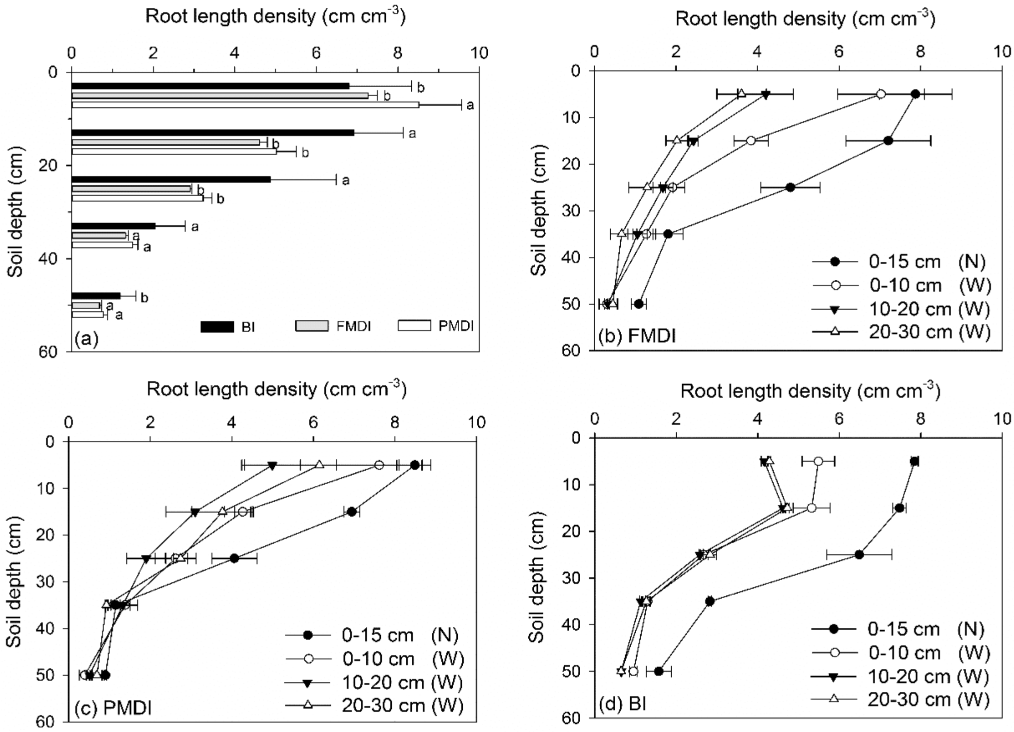

Figure 6. Root length density (RLD) at the 0-60 cm soil layers in 2015 at the maize milk-ripe stage in the border irrigation (BI), full mulched drip irrigation (FMDI) and partial mulched drip irrigation (PMDI) treatments. Positional abbreviations are as follows: "N" = distance (cm) from drip tapes in narrow rows and "W" = distance (cm) from drip tapes in wide rows.

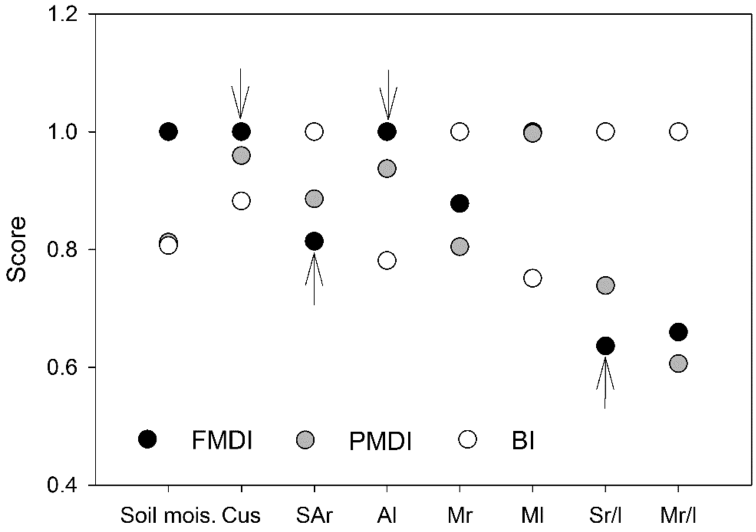

Figure 7. Scores (ratios of values divide the maximum value for each factor) of the soil moisture and plant growth parameters in 2015 determined at the milk-ripe stage in the border irrigation (BI), full mulched drip irrigation (FMDI) and partial mulched drip irrigation (FMDI) treatments. Soil and plant growth parameters are as follows: C_{us} = soil water distribution uniformity, A_l = leaf area, M_l = dry matter of leaves, SA_r = surface area of root, M_r = dry matter of root, $M_{r/l}$ = dry matter ratio of root to leaf and $S_{r/l}$ = ratio of root surface area to leaf area.

Dry matter, yield and harvest index

Frequent fertigation resulted in higher DM values under the MDI treatments than the BI treatment in both years (Table 3). The DM values of the FMDI and PMDI treatments were 16.0% and 6.3% higher than the BI treatment in 2014, respectively and were 52.5% and 41.3% higher than the BI treatment in 2015, respectively. No significant differences of the DM values were showed between the FMDI and PMDI treatments. Under low frequency irrigation in 2014, the yields between the PMDI and BI treatments showed no differences. However, the yields of the FMDI and PMDI treatments were 189.9% and 172.0% higher, respectively, than the BI treatment under high frequency irrigation in 2015. The higher yields for the MDI treatments in 2015 were reflected in higher values of the harvest index (HI) and hundred gain weight (HGW) compared to the BI treatments.

Table 3. Dry matter, yield, hundred grain weight (HGW) and harvest index (HI) for the border irrigation (BI), full mulched drip irrigation (FMDI) and partial mulched drip irrigation (PMDI) treatments in 2014 and 2015.

Year	Treatment	Dry matter (g)	Yield (kg ha^{-1})	HGW (g)	HI
	BI	410.1b[a]	10279.6b	34.1a	0.44a
2014	FMDI	475.6a	14412.0a	32.6a	0.48a
	PMDI	435.9ab	11358.1b	30.7a	0.46a
	BI	279.5b	6046.6b	27.5 b	0.29b
2015	FMDI	426.1a	17530.3a	34.4 a	0.62a
	PMDI	395.0a	16444.4a	33.9 a	0.63a

[a] Different letters in the same column indicate significant difference ($P < 0.05$).

Discussion

Soil moisture and nitrate

In 2014, beneath the emitters, the earlier and more sharply soil moisture decrease in root zone under the FMDI treatment was attributed to the faster growth rate and higher leaf area index. It was thought that part of the difference was attributable to the better thermal conditions of the surface soil under the FMDI treatment which was confirmed in our previous study (Qi et al., 2016). A more rapid θ_{10-50} decrease under the PMDI treatment than the FMDI treatment occurred 84 DAS (Figure 2a) that may be partially attributable to the combined action of soil evaporation and the rapid root uptake of soil moisture (Figure 6a, c) that typically occurs during the maize jointing and silking stages. The surface wetted radius has been shown to be less than 30 cm for the emitter used in this study (Zhou et al., 2017), so, as anticipated the surface soil moisture of the zone 30 cm away from the drip laterals showed weak responses to irrigation (Figure 2a). In addition, ponding on the soil surface under the mulched cover was observed for the PMDI treatment and has previously been shown to be caused by the soil surface obstruction restricting lateral movement of the irrigation water (Li et al., 2007). The lower soil moisture at the 10-cm depth midway between the emitters was because irrigation water has been shown not to reach this zone under low irrigation frequency (Zhou et al., 2017), while, the higher soil moisture at the 50-cm depth midway between emitters may be attributed greater lateral water distribution with soil depth and less root distribution in the soil midway between the emitters (Figure 7). Compared with 2014, a more rapid soil moisture decrease was documented above the sand layer 50 DAS during 2015 that may be ascribed to the high evapotranspiration, which was exasperated by the infrequent rainfall (Allen et al., 1998) in 2015. Frequent irrigation enhanced the soil moisture midway between the emitters and eliminated soil moisture differences between the BE and ME. Frequent irrigation events constantly occurred so the "initial soil moisture" increased continuously, thus the wetted surface radius gradually become larger (Kandelous and Sĭmůnek, 2010) and after a period of time, the irrigation water would reach the zone midway between emitters. As a result, the more rapid soil moisture increase at the 50-cm depth in the FMDI treatment 94 DAS may also be ascribed to the overlap of the wetting zones.

The sharp decrease in soil moisture and C_{us} above the 0-60 cm sand layer under the BI treatment was because irrigation water was infiltrated from the no-mulched zone, where soil moisture was high but there was nothing on the soil surface to impede evaporation. After irrigation, soil evaporation would be expected to occur at averaged daily values of 2.4 mm with a range from 0.8 mm to 6.1 mm that would effectively remove soil water from the 0-15 cm depth for the bare soil between the mulch strips.

Beneath the emitters, the soil NO_3^- concentrations substantially decreased under the MDI treatments in 2014. In 2015, the soil NO_3^- concentrations began to steadily increase 80 DAS and, would be available for plant uptake during the important periods (R1-R3) for maize grain production (Figure 5). This outcome confirmed that frequent fertilization by fertigation is recommended, particularly in sandy fields. The more rapid increase in NO_3^- concentrations under the FMDI treatment than the PMDI treatment during the late growing stage was perhaps due to less root length density (Figure 7) (Coelho and Or 1999). At the middle of the plant rows, the more rapid decrease under the PMDI treatment until 70 DAS may be caused by the more extensive lateral root distribution than under the FMDI treatment. Compared with the FMDI treatment, the earlier rebound and higher levels of soil NO_3^- concentrations under the PMDI treatment in 2015 was due to the upward shift of NO_3^- coupling with the upward flux of soil water caused by evaporation which at date would have an averaged daily value of 1.5 mm ranging from 0.2 mm to 3.3 mm that would extract water from the 0-15 cm soil depth. Additionally, denitrification may have occurred under the FMDI treatment at high soil NO_3^- concentrations in an anoxic soil environment (Mahmood et al., 2005).

Shoot/root regulation and crop yield

Previous studies have shown that root growth may be limited by poor soil aeration (Hu et al., 2009) or wetted soil zones (Li et al., 2007). In our study, the BI and PMDI treatments displayed a more lateral extent of root growth than the FMDI treatment (Figure 6c, d) which might be attributed to good soil aeration. Different from the MDI treatments, the maximum RLD at the 10-20 cm soil depth (Figure 6a) in the BI treatments may be attributable to a drastic reduction of soil moisture at the 0-10 cm depth (Eapen et al., 2005) (Figure 4a). The C_{us} regulated $S_{r/l}$ via the "area form" values such as A_l and SA_r (Figure 7) was mainly because the growth of vegetative organs, such as leaf and root, is a continuous process that simultaneous new tissue production and old tissue decay (Taylor and Klepper 1974). The old leaf or root plays fewer roles of photosynthesis or soil water and nutrient uptake, respectively. However, the leaf area excludes the impact of yellow leaves and the fine root is closely related with RLD and often work well on soil water and nutrient uptake (Hund et al., 2009).

It was interesting that the FMDI treatment obtained higher yields with less roots in 2015 (Figure 6a). More root proliferation needs more carbon costs during water and nitrogen capture by competing plants aboveground when soil water and nitrate was limited (Robinson, 2001), which led to a lower dry matter in the PMDI and BI treatments. Remobilizing the N assimilated in the vegetative organs (Hirel et al., 2007) may play an important role for grain filling in the FMDI treatments because of its higher DM (Table 3) and the earlier arrival of the reproductive stage in the form of leaf senescence (Luo et al., 2013), which results in higher HI. Besides, the FMDI treatment could more effectively maintain NO_3^--N above the sand layer than the PMDI treatment (Figure 5a), which would extend the duration of the grain filling stage (Jorge, 1995) and may be another reason for a higher yield in terms of a higher HGW than the PMDI treatment (Table 3). Compared with the BI treatment, the higher HI and yields in the MDI treatments were not caused by the higher HGW (Table 3) in this study. Instead, an increased number of grains per spike was responsible for the higher yields under the MDI treatment. In 2015, drought (precipitation was only 14.6 mm) and spider mites affected the entire Hetao Irrigation District, which resulted in poor pollination and substantially decreased yields and dry biomass in the BI treatments.

Conclusions

Soil water content and uniformity (C_{us}) under border irrigation (BI) decreased sharply after the jointing stage of spring maize on a sandy soil and was not able to satisfy the soil water requirements for maize. However, high-frequency mulched drip irrigation (MDI) could maintain soil moisture and improved the C_{us} in a rainless environment. Soil NO_3^- was adequate for maize production under the FMDI treatment of both high and low frequency fertigation, while it was insufficient for the PMDI treatment of low frequency fertigation.

The dry matter production under BI was lower than that of the MDI treatments, particularly under the sparse rainfall conditions. However, the BI and PMDI treatments exhibited better root architecture. The root–shoot regulation by the soil water and NO_3^- was via the leaf area and $S_{r/l}$ showed a better description for root–shoot regulation. The yields in the MDI treatments were higher than under the BI treatments which was attributable to a higher number of grains per spike and resulted in a greater HI. No difference of yield showed between FMDI and PMDI under high-frequency condition. However, yield in FMDI was higher than PMDI under low-frequency condition.

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