Research Findings

Field day at the experimental site. Mr. Dali Wu explaining to Prof. Guohua Mi, researchers and farmers the results and conclusions of his work. Photo by E. Sokolowski.

Enhancing Maize Productivity via Drip Irrigation and Drip Fertigation on a Sandy Soil in Northeast China

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Abstract

In northeast China, maize (*Zea mays* L.) is the major crop, but water levels can become extremely low in the sandy soils on which it is grown. Fertilizer application via side-dressing is difficult and fertilizer use efficiency on sandy soils is low. Drip fertigation is a way to meet the water and nutrient demands of crop growth by dissolving fertilizers in water and delivering them through a drip irrigation system to the root zone. Field experiments were conducted from 2012-2015 to study the effect of drip irrigation and drip fertigation on yield formation and water use efficiency of maize. Three treatments were carried out: conventional (CK), under which all fertilizers were applied as basal fertilizer and the field was not irrigated; drip irrigation (DI), under which all fertilizers were applied as basal fertilizer and the field was irrigated by the drip irrigation system; and surface drip fertigation (DF), under which fertilizers were applied as a basal application plus top dressing, applied during the maize growth period via a drip irrigation system. The results indicate that DI improved soil moisture, increased dry matter accumulation, and increased maize yield in dry years (2014 and 2015) but not in wet years, with no effect on water productivity in both situations. Compared to DI, DF further improved maize growth and increased both

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grain yield and water productivity under years of regular rainfall (2012) and dry years (2014 and 2015). In 2013, when heavy rain events occurred during the growth season, both DI and DF showed no effect on maize growth or grain yield. These results suggest that DF is useful for increasing maize grain yield and water productivity under unstable seasonal precipitation patterns in northeast China.

Keywords: Climate change; drought; water productivity; *Zea mays*.

Introduction

Rain-fed maize is the major crop in northeast China, where drought is frequent in spring and/or summer seasons and is the most crop limiting climate factor (Zhao and Yang, 2009; Dong *et al*., 2011; Lu *et al*., 2014). Precipitation varies widely between seasons and years. The increasing pressure on food security in China necessitates a significant increase in maize production in this region, which in turn is largely dependent on the expansion of irrigated land. The efficiency of drip irrigation has been proved in many crops and therefore should be considered as a major irrigation method, especially in sandy soils where greater economic benefits may be obtained (Sogbedji *et al*., 2000; Bhardwaj *et al*., 2007; Fanish *et al*., 2011). Drip irrigation is mostly applied in fruit and vegetable crops, and in cotton (Lamm, 2016). Some studies have shown that drip irrigation increases yield and water use efficiency of onion, tomato, dry chili pepper, and potatoes compared to traditional furrow irrigation (Hebbar *et al*., 2004; Rajput and Patel, 2006; Kundu and Sarkar, 2009; Lamm, 2016). There is also growing interest in applying drip irrigation to lower-value field crops such as cotton and maize (Lamm *et al*., 2007).

Fertilizer application in the region is very common and often excessive, and, due to dry weather and labor limitations, farmers typically apply the entire seasonal fertilizer dose before or during seed sowing (Gao *et al*., 2008). Excessive nutrient application not only reduces fertilizer efficiency, but also increases soil nutrient loss and results in environmental pollution (Zhang, 2008; Zhang *et al*., 2011; Chen *et al*., 2013). Drip fertigation provides solutions to these problems, enabling water and nutrients supply directly to the root zone and at an amount adjusted to the dynamic plant requirements (Bar-Yosef *et al*., 1989; Bar-Yosef, 1999). Therefore, this approach provides a promising way to a simultaneous increase in maize productivity as well as fertilizer and water use efficiencies (Camp, 1998; Pablo *et al*., 2007; Fanish *et al*., 2011).

Nevertheless, the effect of drip irrigation and drip fertigation on maize production is unclear under the soil conditions and climate of northeast China. This study aims to compare the effects of drip irrigation and drip fertigation on maize productivity, and fertilizer and water use efficiency under different weather conditions on a sandy soil, and understand the relative contribution of water and fertilizer management on maize productivity.

Materials and methods

Location and weather

Field experiments were conducted in Lishu, Jilin province, China (43º21′48”N, 124º05′01”E). The region is under a sub-humid, warm, temperate and continental monsoon climate with an annual mean temperature of 11.6ºC. The annual average (1986-2013) rainfall during the maize growing season is 467mm, with significant fluctuations. During the four experimental years (2012-2015), the rainfall during maize growth season was 431, 550, 342, and 304 mm, respectively (Fig. 1). As a whole, rainfall was adequate and rain distribution was uniform in 2012. Heavy rainfall occurred at grain filling stage in 2013, resulting in a 3-day flooding (Fig. 2A). 2014 and 2015 were dry years (Fig. 2B). Experiments were carried out on a sandy soil with a bulk density of 1.6-1.8 g cm^{-3} in 0-200 cm soil depth.

Field design and experimental treatments

The field experiment was conducted using a randomized complete block design with three irrigation/fertilization treatments in four replications. The treatments were applied as follows: (1) conventional (CK), under which all fertilizers were applied as basal fertilizer and the field was not irrigated; (2) drip irrigation (DI), under which all fertilizers were applied as basal fertilizer and the field was irrigated via drip irrigation; (3) drip fertigation (DF), under which fertilizers were applied as basal application plus top dressing through a drip irrigation system during the maize growth period. Fertilizers were applied according to a target yield level of 12 Mg ha^{-1}. In all the treatment, the total amount of nitrogen (N) fertilizer was 240 kg N ha^{-1}. For phosphorus (P), fertilizer was applied in the form of phosphorus pentoxide (P_2O_5) at 110, 110, 120 and 100 kg ha^{-1} in each year of the experiment, respectively. Similarly, potassium (K) fertilizer was applied in the form of potassium oxide at 112, 112, 120, and 110 kg (K_2O) ha^{-1}. For the CK and DI treatments, all N, P, and K fertilizers were supplied basally using a compound fertilizer (N-P_2O_5-K_2O: 28-12-12), potassium chloride, and super calcium phosphate. For the DF treatment, a compound fertilizer of 15-15-15 was applied as a basal fertilizer, which comprised 30, 77 and 64% of the total N, P, and K input. The remaining N, P, and K was supplied via a fertigation system using urea (46% N) and a soluble compound fertilizer (N-P_2O_5-K_2O:30-6-12) from the company Gaipo. For the irrigated treatments (DI and DF), water supply was calculated according to the water requirement of the plant's developmental stage, minus precipitation. Rainfall was recorded regularly during the experiment.

The plot size was 25×6 m, with 10 rows in each plot. Maize was planted in a wide-narrow pattern (Fig. 3), that is, the distance between rows was 40 and 80 cm, alternately. The main pipes were

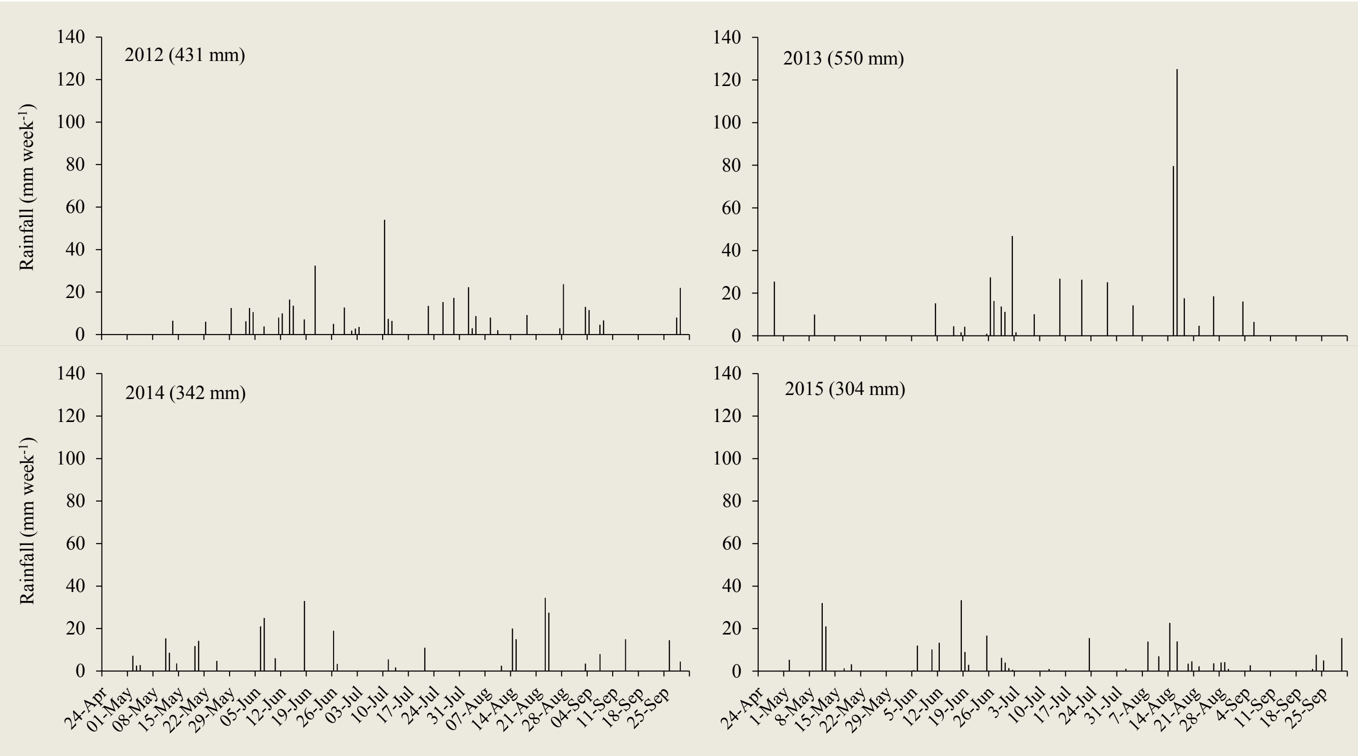

Fig. 1. Rainfall events (quantity and timing) during the 4-year experiment.

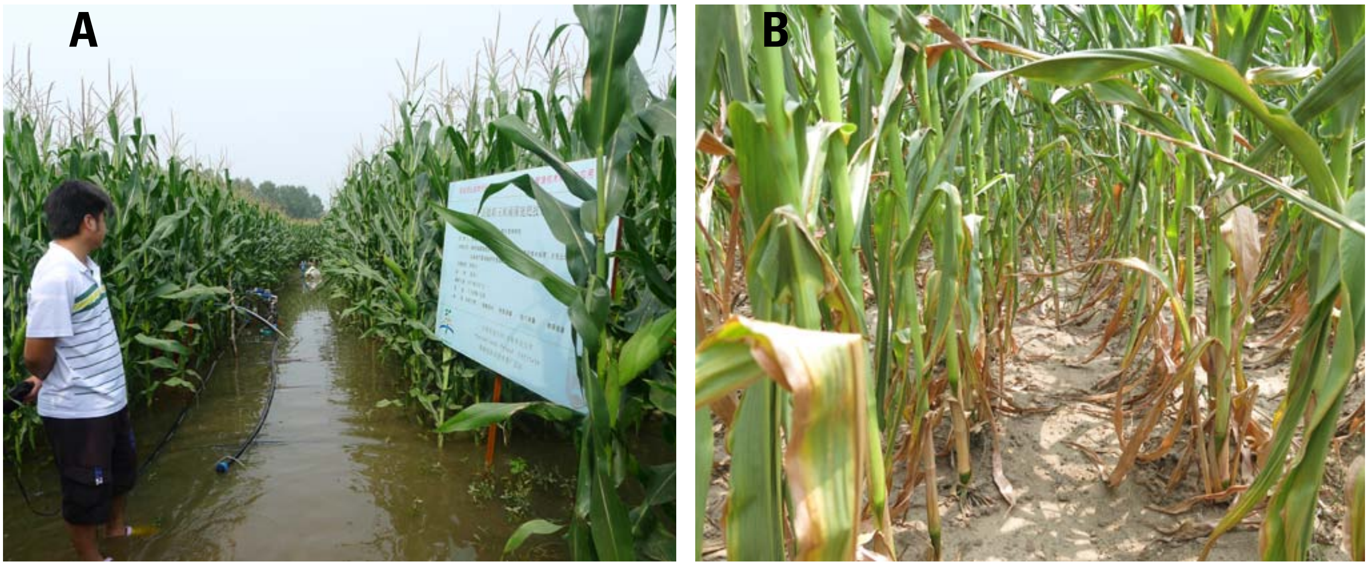

Fig. 2A, B. Flood event during mid-August 2013 at the grain-filling stage (Fig. 2A, left); drought stress impacts on maize during the 2014 season (Fig. 2B, right). Photos by authors.

positioned perpendicular to row direction, in the middle of the plots. The irrigation pipes were placed along the narrow inter-row gaps only. Each plot was equipped with a separate pump.

The maize hybrid cv. Liangyu 11 was planted each year on 1 May at a density of 70,000 plants ha^{-1}, and harvested on 1 October. Weeds, diseases and pests were well controlled by chemicals.

Measurements

Leaf area was measured during the grain filling period. Above-ground plant biomass was measured by harvesting three mature plants per plot. The above-ground plants were separated into leaves, stems (comprising the leaf sheath, tassels, and ear shoots), and grains. The samples were weighed and dried in an oven at

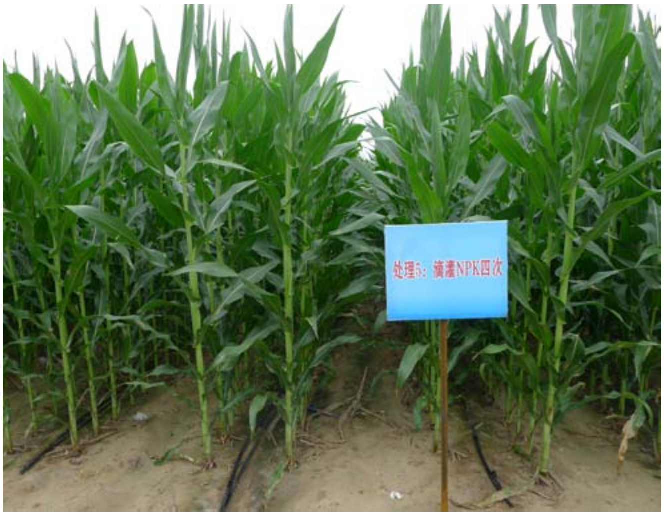

Fig. 3. The wide-narrow (80 and 40 cm gap between rows) pattern of planting. Irrigation pipes were positioned along narrow paths only. Photo by authors.

70°C. Grain yield was determined by harvesting an area of 20 m^2. Grain yield was adjusted to the standard water content of 14%.

Two random soil samples were taken from each plot using an auger at 0-80 cm from the soil surface at VT (tasseling stage, the onset of the reproductive phase). Each sample was divided into four layers at 20 cm intervals. Soil water content was determined by the gravimetric method (oven dry basis).

Water content at 0-2 m soil depth was measured before sowing and at harvest. The total water consumption, i.e. evapo-transpiration (ET), was calculated as ET = precipitation + irrigation + Δs, where Δs is the difference in water content between sowing and at harvest (Lamn *et al.*, 1995). Water productivity (WP) in kg m^{-3} was calculated as WP = (GY/ET) x 100, where GY is grain yield (kg ha^{-1}) for each treatment.

Statistical analyses

Data were analyzed using a SAS software variance analysis. Treatment means were compared using Duncan's multiple test. Probability levels lower than 0.05 or 0.01 were held to be significant.

Results

Grain yield

No significant difference was found in yield under the CK and DI treatments in 2012 and 2013. However, in 2014 and 2015, the DI yield was significantly higher than that of CK, by 38 and 20%, respectively (Fig. 4A; Fig. 5). The DF grain yield was significantly higher than CK in 2012, 2014 and 2015, by 19, 53 and 31%, respectively. However, no significant difference was observed for the DF and CK yields in 2013. There was no significant difference in yield between DF and DI in 2013 and 2014, while in 2012 and 2015, the DF yield was 15 and 9% higher than that of DI, respectively. When pooling the years together, the DI and DF treatments yielded an additional 1,482 and 2,483 kg grains ha^{-1} compared to the CK treatment - 16 and 27% higher, respectively. Nevertheless, the difference between the DI and DF yields remained insignificant (Fig. 4B).

Leaf area

The effects of DI and DF on plant growth varied between years, affected by seasonal precipitation. No difference in leaf area per plant during the grain filling stage was found among the three

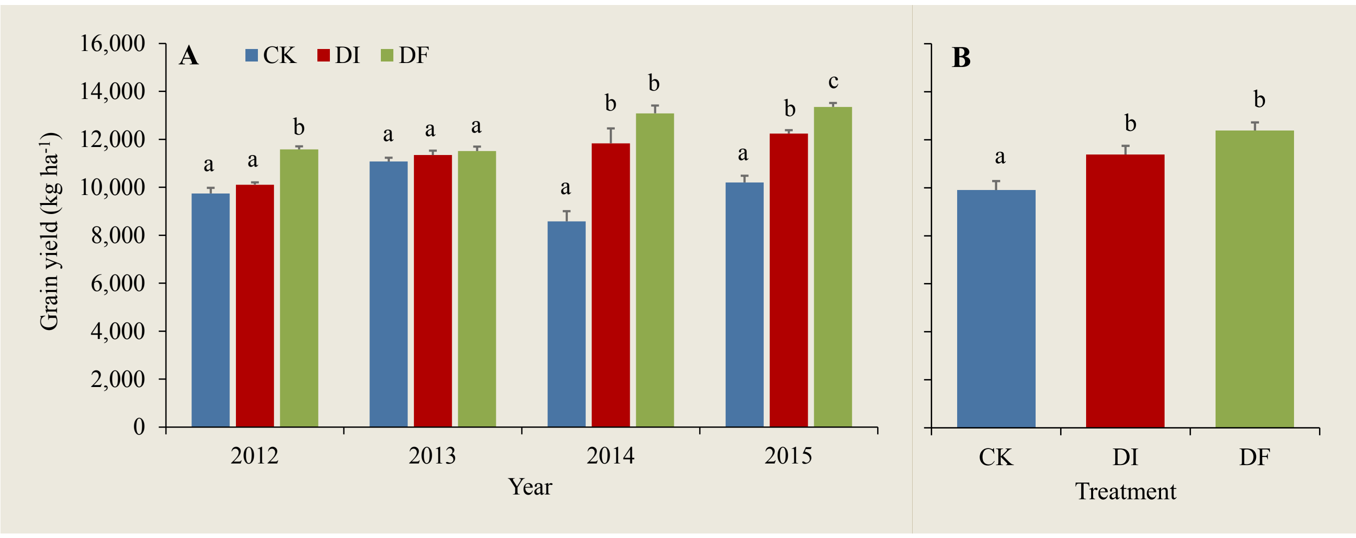

Fig. 4A, B. A: mean yield comparison under the DI, DF and CK treatments during the 4-year experiment; B: multi-annual comparison between treatments. Data in figure A with the same letter within the same year, do not differ at the 0.05 level of significance.

treatments in 2012 and 2013 (Fig. 6). In 2014, however, the leaf area of DI was 79% higher than that of CK (Fig. 5; Fig. 6), and the leaf area of DF was 25 and 124% higher than that of DI and CK, respectively. In 2015, the leaf area of DI and DF were 20 and 23% higher than that of CK, respectively.

Dry matter accumulation and harvest index

In 2012, 2014 and 2015, the dry matter accumulation of DI was 10, 26, and 17% greater than that of CK, respectively (Table 1). DF dry matter accumulation was 9, 38 and 23% higher than that of CK, respectively, while in 2013 no significant difference in dry matter accumulation was observed between the treatments.

In 2012, the harvest index of DI was lower than that of CK, while those of DF and CK did not differ significantly. In 2014, DI and DF had significantly higher harvest indices than CK, whereas in 2013 and 2015, no significant difference in harvest index occurred between the treatments (Table 1).

Soil moisture

Soil moisture was measured at the silking stage (Fig. 7). Excluding 2015, moisture was lowest at the upper soil layer (0-20 cm) and increased at deeper soil layers. In 2012, DF soil moisture at 20-40 cm deep was slightly though significantly higher than that of CK, but no other significant differences occurred between treatments. In the 2013 rainy season (Fig. 1), no treatment seemed to have any effect on soil moisture. On the contrary, during the two relatively dry summers of 2014 and 2015, significantly higher soil moisture contents at most depths were displayed under the DI and DF treatments when compared to CK (Fig. 7).

Water consumption and water productivity

Plant water consumption under the CK treatment varied greatly among years (Table 2) due to large differences in the levels of precipitation (Fig. 1). In contrast, the water consumption rate under the DI and DF treatments was much more stable between years, and significantly higher than that of CK (excluding DI in 2012). Plant water consumption under the DI and DF treatments did not differ.

Fig. 5. Effects of the DI and CK treatments on maize plant vitality (top) and on grain formation at the filling stage (bottom), in 2014.

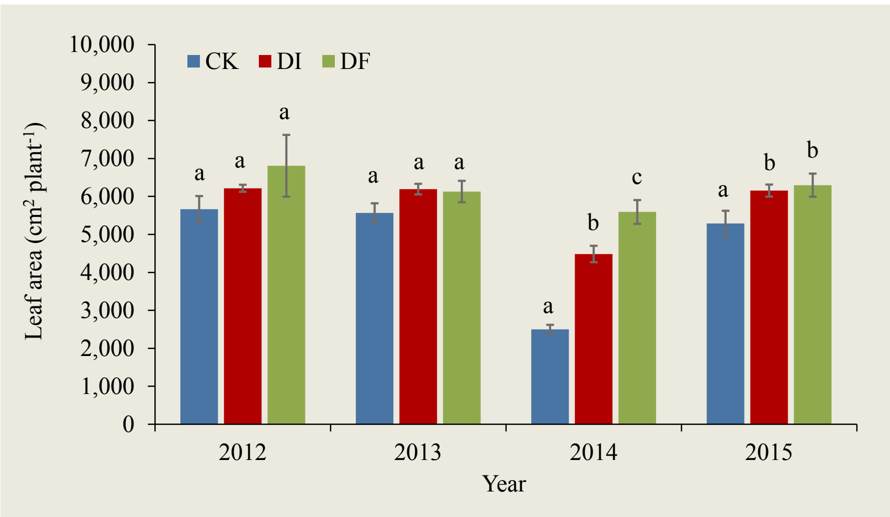

Fig. 6. Effect of DI and DF on leaf area at the grain filling stage. Data within the same year with the same letter do not differ at the 0.05 level of significance.

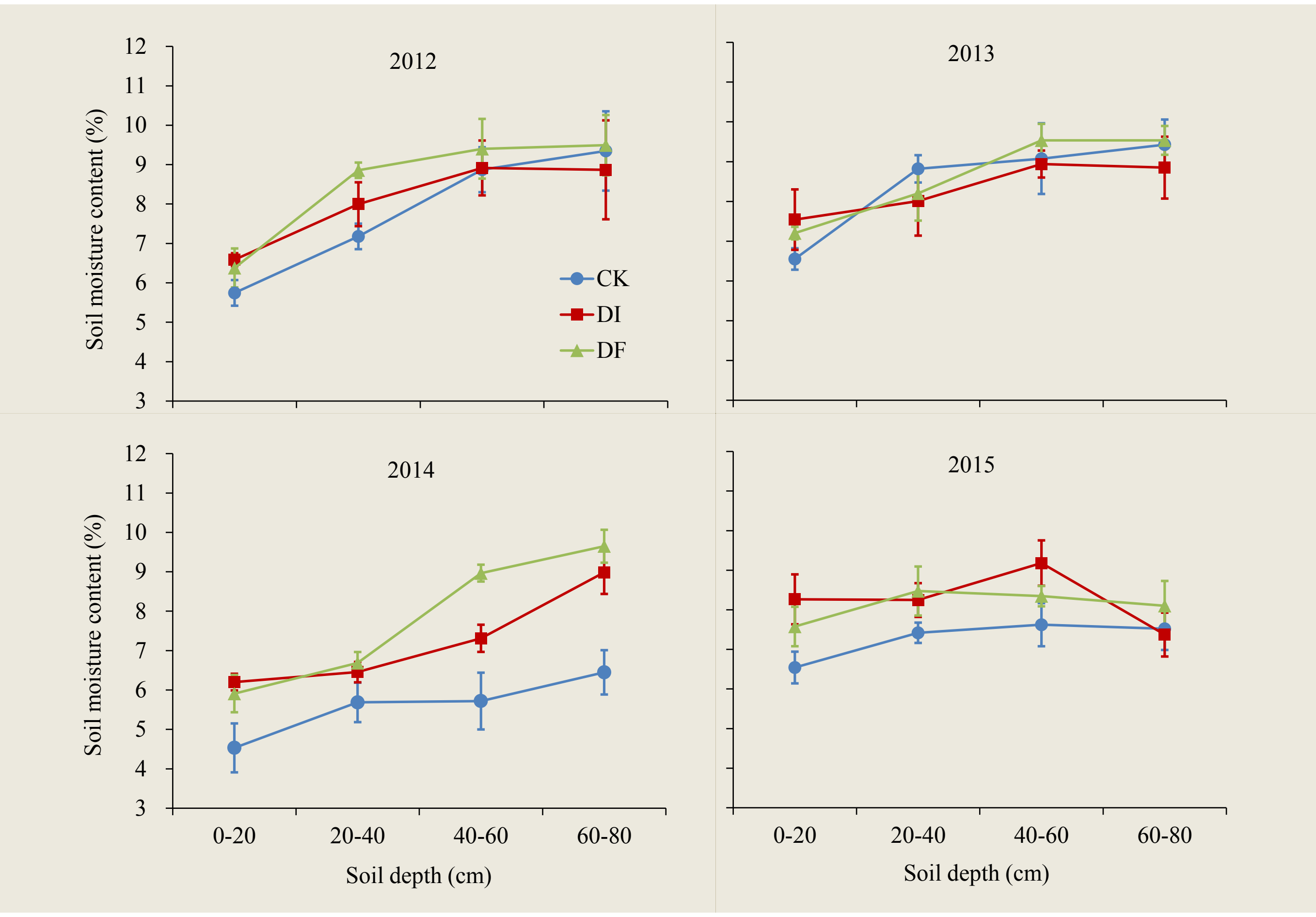

Fig. 7. Soil moisture content at the silking stage. Bars indicate SE.

Table 1. Dry matter accumulation and harvest index at harvest.

Treatment	Dry matter accumulation				Harvest index			
	2012	2013	2014	2015	2012	2013	2014	2015
	------------------*g plant*$^{-1}$------------------				--------------------%--------------------			
CK	255 b	267 a	222 b	260 b	53 a	54 a	41 b	53 a
DI	280 a	274 a	279 a	303 a	50 b	54 a	53 a	52 a
DF	279 a	262 a	305 a	319 a	51 ab	55 a	54 a	53 a

Note: Data within the same year with the same letter do not differ at the 0.05 level of significance.

Table 2. Plant water consumption and water productivity.

Treatment	Water consumption				Water productivity			
	2012	2013	2014	2015	2012	2013	2014	2015
	---------------------*mm*---------------------				---------------*kg ha*$^{-1}$ *mm*$^{-1}$---------------			
CK	405 b	416 b	344 b	352 b	24 b	27 a	25 b	29 b
DI	429 ab	446 a	457 a	432 a	24 b	25 a	26 b	28 b
DF	441 a	447 a	418 a	425 a	26 a	26 a	31 a	32 a

Note: Data within the same year with the same letter do not differ at the 0.05 level of significance.

Water productivity was similar under the DI and CK treatments (Table 2). In 2012, 2014 and 2015, DF water productivity was 11, 21 and 11% higher than that of DI, and 9, 26 and 8% higher than that of CK, respectively. In 2013, no differences in water productivity occurred between treatments.

Discussion

Grain yield in corn is comprised of the following components: ears per unit area, kernel number per ear (consisting kernel rows and kernels per row), and kernel weight. Each of these yield components is determined at different stages in the lifecycle of the plant. Sufficient water and nutrient availability is essential for adequate canopy size and high yield.

The number of early reproductive structures is often greater than what the plant is later capable of supporting. The size of yield components is then influenced by the environmental and management stresses of the growing season (Sacks and Kucharik, 2011; Harrison *et al*., 2014). During the 4-year experiment from 2012 to 2015, rainfall amount and distribution varied considerably (Fig. 1), having significant effects on CK maize yields. These yields fluctuated significantly, from pretty high levels in the rainy year of 2013 to low levels in the relatively dry year of 2014 (Fig. 2).

Rain distribution throughout the growing season, and particularly the timing of sufficient rain events, is sometimes even more important than rain quantity. The tasseling, silking and pollination stages of corn development are extremely critical because after these, the ear and kernel numbers can no longer be increased by the plant, and the potential size of the kernel is determined. Thus, kernel number is at its greatest potential slightly before R1, the earliest reproductive stage; the actual number of kernels formed is determined by pollination of the kernel ovule. Kernel weight, the last yield component, is determined during the first 7-10 days after pollination, at the cell division phase of the endosperm, which determines the potential number of starch accumulating cells. Thus, short drought periods that occur at critical developmental stages may cause significant yield reduction, even if the seasonal precipitation level is sufficient (Lu *et al*., 2014; Messina *et al*., 2014). On the other hand, a well-distributed precipitation pattern may sometimes compensate for a relatively dry season, and may explain the differences in CK yields between the dry seasons of 2014 and 2015 (Fig. 2).

Stable, accurate, and sufficient water supply is the major advantage expected from drip irrigation (Bar-Yosef, 1999). Indeed, DI increased soil moisture content (Fig. 7), leaf area (Fig. 6), and dry matter accumulation (Table 1) in 2014 and 2015, with corresponding increases in grain yield by 38 and 20%, respectively, and without any effect on the harvest index. In 2012 and 2013, however, DI did not have the same influence on yield due to adequate precipitation that satisfied plant water demands. In 2012, DI increased dry matter accumulation but the grain yield did not differ from that of CK. The reduced DI harvest index in that year may suggest that in spite of the improved vegetative growth, there were some occasional problems following the reproductive process. Interestingly, DI had no influence on water productivity (Table 2); any increase in dry matter or grain yield was accompanied by a corresponding increase in water consumption. Therefore, drip irrigation alone is a matter of improved water availability rather than of a physiological water use efficiency by the plant. Nevertheless, in order to fully extract the potential of this technology, the implementation of drip irrigation must be carefully attuned to the local soil and environmental conditions, and crop species.

On sandy soils, the profile shape of moist soil under each emitter tends to be deep and narrow, due to the low hydraulic conductivity of sand. The maize root system is usually shallow, as indicated by the pattern of soil moisture in the present study (Fig. 7). In addition, the water retention of sandy soils is very low, 2-8%, v/v. These restrictions dictate small gaps between emitters are required, along with a high-frequency irrigation regime, in order to maintain the steady adequately moist rhizosphere required to realize maize productivity (Djaman *et al*., 2013).

A major advantage of drip irrigation lies in its ability to deliver soluble nutrients directly to the plant roots at the required amount and timing. This enables accurate nutrition management according to the crop's varying requirements across development stages (Pettigrew, 2008). This advantage is demonstrated by the DF results of the present study. Further to the yield increase observed under DI, the DF treatment displayed an added benefit - significantly higher grain yield in 2012 and 2015, and an obvious same tendency in 2014 (Fig. 4A). On average, DF increased grain yield by 27 and 9% compared to CK and DI, respectively (Fig. 4B). Excluding 2014 - when the maize under DF displayed a significantly higher leaf area - the advantage of DF over DI in the other years seemed to evolve from aggregated insignificant rises in several parameters (leaf area, dry matter accumulation, and harvest index). Consequent to the higher grain yield accompanied by insignificant changes in water consumption (Table 2), the DF water productivity was significantly higher than that of DI in 2012, 2014, and 2015. In contrast, the results in 2013 demonstrate that the advantages of DI or DF may disappear following heavy rain events that coincide with critical stages of development.

In conclusion, DI is remarkably advantageous in dry years, providing sufficient water supply throughout the growing season and enabling the avoidance of water stress during critical stages at the reproductive phase. Thus, DI supports vigorous and productive maize crop growth under environmental uncertainties, but it does not affect water productivity. The direct and continuous nutrient supply to the root system, as under DF, enhances crop performance; plants are more vigorous, build more dry matter and increase water productivity, altogether leading to grain yields higher than those of DI in years of regular rainfall and dry years. Nevertheless, the advantages of DF and DI are expected to decline under a well-distributed and sufficient precipitation regime or diminish under flood events.

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