Irrigation regimes affect early root development, shoot growth and yields of maize (*Zea mays* L.) in tropical minor seasons

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ABSTRACT

Moisture stress is an important factor affecting field-grown maize in the tropics, especially in the minor dry seasons, and irrigation is required for successful crop growth and yields. Field experiments evaluated the impact of four irrigation regimes ranging from 3 to 21-day intervals on growth of maize (*Zea mays* L.) roots and shoots at critical stages and on seed yields when compared to those of irrigated maize plants in two minor seasons at Sri Lanka. While surface wetting at planting induced germination in all treatments, growth of seminal and first-order lateral roots was enhanced by increasing irrigation intervals. Relative water contents were similar at irrigation intervals of 3, 7 and 14 days and declined thereafter. At anthesis, root length and weight densities indicated the greater penetration into soil layers with increasing intervals of water supply. The highest yields were at 7 and 14-day irrigation intervals thus illustrating that regular water supply in minor dry seasons may be detrimental for maize growth and yields.

Keywords: maize; minor seasons; tropics, irrigation, root initiation, development, yields

Maize (*Zea mays* L.) is the most extensively cultivated highland cereal grain crop cultivated in South Asia both for food and feed (Devendra and Thomas 2002, FAO 2008). It is generally cultivated under smallholder subsistence farming systems, both under rainfed and irrigated conditions in the major and minor seasons that correspond to the two monsoons. However, crop growth and seed yields are generally lower in the drier minor seasons due to moisture stress and higher ambient temperatures as moisture stress is the second most important cause for yield loss in maize after low soil fertility (Edmeades et al. 1992). Thus whenever possible, farmers irrigate their crops to enhance yields, although irrigation water is fast becoming a scarce resource and is an important limiting factor for tropical crop production due to erratic rainfall, haphazard irrigation schedules coupled with rising temperatures, which have a significant impact on tropical maize production (Zaidi et al. 2008, Messmer et al. 2009). Optimal water management strategies thus become an important factor due to limitations in the supply of irrigation water in minor seasons, especially as rice, the most important and staple food crop, receives priority in these dry seasons in most nations of South Asia. Furthermore, water management becomes important in maize as both limited and excess supplies could affect maize growth in the tropics (Zaidi et al. 2007).

Soil environments have a significant impact on plant growth and development, and moisture is a crucial factor for successful establishment of annual food crops such as maize (e.g. Konopka et al. 2008, 2009). The lack of sufficient soil moisture affects the growth and development of roots, which are the organs responsible for water uptake from the rhizosphere and for establishing a soil – plant atmosphere continuum (Kuchenbuch et al. 2006). Furthermore, these studies also clearly highlight the adaptability of maize seedlings roots to different soil moisture regimes under conditions of rhizotrons. Thus, root development in soils, especially during the early growth stages, can be considered vital for successful crop establishment, since roots can determine the content of water extracted for crop growth and for final seed yields.

In general, studies on root growth in relation to soil moisture have clearly illustrated the impact of different moisture regimes which were held constant during the entire experiment (e.g. Seiffert et al. 1995, Sangakkara et al. 1996), and most of these were under controlled pot culture conditions. Field studies do not clearly indicate the impact of different soil moisture regimes, and especially different irrigation regimes, on growth of roots during the seedling stage in maize or even other cereal crops, and its subsequent impact on root growth at anthesis and on final yields. Thus experiments were carried out in the field in two minor seasons at Sri Lanka, which corresponds to the South west monsoonal periods, when soil moisture loss exceeds rainfall, thus subjecting the crop to moisture stress. The objectives were to determine the impact of different irrigation regimes on root development and shoot water contents in the early growth phase, root development and root:shoot ratios at anthesis and the subsequent impact of the adopted treatments on seed yields and harvest indices.

MATERIALS AND METHODS

Location and climate. The experiment was carried out at the Experimental unit of the University of Peradeniya, Sri Lanka (8°N, 81°E, 418 m a.s.l.) in the mid country intermediate zone of Sri Lanka, in the latter part of the minor season in 2004 and 2005 (late June–September), that corresponds to the south west monsoon. The soil of the site is an Ultisol (Rhododhult) with pH (1:25 H_2O) 6.85 ± 0.09, total N content of 61 mg/g soil, CEC of 40.81 ± 3.55 meq.100/g soil and organic C content of 0.74% ± 0.07 in the top 25 cm soil layer, which is considered to be the effective rooting zone.

The rainfall over the experimental periods in 2004 and 2005 were 265 mm and 227 mm with mean air and soil temperatures of 32.1°C and 32.7°C, respectively, over the two years without much interseasonal variation, with a mean pan evaporation of 3.61 mm/day and 3.43 mm/day in the two years. The mean relative humidity was 66.4 ± 2.08 over the seasons. Hence the crops grown in this season were subjected to moisture deficits. The soil moisture content at field capacity was 0.24 g/g.

Treatments and experimental procedure. The treatments were to irrigate predetermined plots at the intervals of 3, 7, 14, or 21 days up to 90 days, when seeds began to ripen. However, one plot was maintained under rainfed conditions without an additional supply of water. The experiment carried out on separate but adjacent plots to avoid carrying over the effects contained five irrigation treatments within a randomized block design with four replicates.

In late June of both seasons when most of the monsoonal rains were received, plots of dimensions 5 × 4 m were prepared manually with border areas between plots being 100 cm wide to avoid horizontal movement of irrigated water. The irrigation regimes were initiated before planting and each plot received two of the identified regimes before planting. Thus, the plots receiving water at 21-day intervals received the first irrigation 33 days and the second 12 days before planting. Similarly, the plots receiving water at 3-day intervals received the first and second watering at 5 and 2 days before planting.

At the predetermined intervals irrigation water was provided manually to the respective plots at a rate of 160 l per plot to bring the soil to field capacity. Care was taken to avoid lateral movement of water between the different plots. The total volumes of water added in the treatments were 4800, 2080, 1120 and 900 l per plot in the irrigation regimes of 3, 7, 14 and 21 day intervals. Water was not applied to the non-irrigated plots, which received only rainfall.

Maize seeds (open pollinated variety Bhadra – germination 87%) were planted between the second and the third irrigation of the predetermined treatments, at the recommended spacing of 60 × 30 cm to obtain a population of 55 000 plants/ha. Hence the seeds of the 3, 7, 14 and 21 day intervals were planted at 2, 4, 7 and 12 days, respectively after the second irrigation. The pre-planting irrigation schedules were planned so, as to complete planting within two days. The non-irrigated plots were planted at the same time. However, just prior to planting all plots were supplied with 10 l of water to uniformly wet the surface and facilitate planting.

The fertilizer applied was equivalent to 25 kg of N, 45 kg of P and 30 kg of K per ha at planting, followed by 45 kg of N at 45 days after planting. Manual weeding was adopted at two-week intervals to remove all weeds to overcome errors in root mass due to the presence of these plants.

Measurements. The measurements taken from all plots in both seasons were as follows:

Up to 75% germination of planted seeds was determined by daily examination of plots from two days after planting. From 7 days after plating, four seeds were carefully removed from the soil and examined at × 10 magnification for the presence of seminal roots to determine days of seminal root appearance.

At Leaf Development Stage 1 (LDS 1), five randomly selected plants per plot were carefully uprooted and the seminal roots per plant were counted. Thereafter, they were removed from the seedlings and length was measured using a ruler.

At Leaf Development Stage 2 (LDS 2), other four plants were carefully removed using a root balling system to avoid possible damage to the roots. The First-Order Laterals (FOL) were carefully counted, removed, their lengths determined using the Line intersection method (Tennent 1975), the branching index measured by counting the number of root branches arising per cm of FOL, using a random subsample and dry weights were measured after drying at 80°C for 48 h. The leaf area of the shoots was determined using a Leaf area (Li Cor 4000, Li Cor, USA) meter, fresh weights of shoots were determined using a Mettler balance and dried at 80°C for 48 h prior to determining the dry weights. These were used to determine the Relative Water Content (RWC %) of shoots at this stage.

The soil of each plot was randomly sampled at four places at 75% anthesis of plants, using a soil sampler (5 × 20 cm diameter × length) at depths of 0–20, 20–40, 40–60 and 60–80 cm, as described by Bohm (1979). The soil cores were individually washed onto a 0.5 mm mesh and roots collected. The total root lengths of all samples were determined using the grid technique (Tennant 1975). From each plot, three plants were uprooted and shoots and roots were separated. The shoots and roots of the entire plants and the roots from the core samples were dried at 80°C before weighing. The root length density (RLD) and root weight density (RWD) were calculated as follows:

RLD (cm/cm^3) – Total length in a soil core/volume of core

RWD (mg/cm^3) – Total dry weight of roots in core/volume of core

Root: shoot ratios were calculated using the dry weights.

At crop maturity, stover and seed yield were determined from 10 undisturbed plants. The seeds and stover were dried at 80°C for 48 h prior to determining dry weights as described earlier. The weights were used for calculating the seed yields per ha and Harvest Indices (HI)) as follows:

Harvest Index (HI) = Seed yield/Stover yield

In all plots, four soil samples were obtained up to a depth of 80 cm using an auger to determine soil moisture content prior to each irrigation. In the rainfed plots, similar soil samples were obtained at 21-day intervals. These were used to calculate the mean soil moisture content prior to each irrigation in the irrigated plots and the mean soil moisture content in the rainfed plots over the growing season.

Data analysis. Due to the similarity of the data in both seasons, the data was pooled before subjecting to appropriate statistical analysis using a GLM procedure of the SAS program for Windows version 6 (SAS Institute Inc, NC, USA) Treatment differences were determined by probability (P = 0.05) or Fisher's protected LSD, and when required, the data was transformed using logarithmic values to ensure normal distribution (Gomez and Gomez 1984). Correlations were calculated wherever necessary to determine relationships between the measured parameters using the same program. The presented data are thus means of two seasons.

RESULTS AND DISCUSSION

The adopted irrigation regimes had a significant impact on soil moisture contents. While the soil moisture content at field capacity was 0.24 g/g (±0.04 ± indicates S.E.), they were 0.22, 0.15, 0.11 and 0.05 g/g ($S.E._{mean}$ 0.02, n = 20) at irrigation regimes of 3, 7, 14 and 21 day intervals. In the non-irrigated plots, the mean soil moisture content of 0.05 g/g was similar to that of the 21 day irrigation interval. Thus application of water at 21 day intervals, which was similar to rainfed conditions, would subject the maize plants to moisture stress in this minor season. The soil moisture at 3 day irrigation interval was similar to that of field capacity, while that of irrigation intervals of 7 and 14 days were by 37% and 54% lower than the value of field capacity, respectively, and hence would not have subjected the crop to excessive soil moisture stress.

Germination of maize seeds was not affected by the irrigation regimes (Table 1) as 75% germination was observed in all treatments within 8 (± 0.4) days due to planting of seeds soon after moistening the surface of the soil. However irrigation intervals of 14 or 21 days initiated an earlier growth of seminal roots in the seedlings than when irrigated more frequently (Table 1). This implied that moisture stress induces root initiation earlier even under

Table 1. Germination and development of seminal roots in maize as affected by irrigation regimes (mean of two seasons)

Irrigation regime (day interval)	Days to 75%	Seminal Roots		
	germination	days to appearance	At LDS 1*	
			number	length (cm)
3	7.5	9.6	5.8	32
7	8.4	9.1	6.5	48
14	8.1	8.8	7.6	54
21	8.2	8.4	8.9	67
None	8.1	8.4	8.7	68
LSD (*P* = 0.059)	0.14	0.06	0.47	5.41
CV (%)	5.86	2.34	10.56	14.04

*LDS – leaf development stage. Based on the full development of the first leaf in 75% of the population of plants

field conditions, as suggested by Konopka et al. (2008) under controlled conditions. The delay in root emergence with frequent irrigations could be due to the diffusion of water into the seed for its physiological processes of early growth. Similarly, the numbers of seminal roots at Leaf Development Stage (LDS 1) and their lengths were significantly affected by the irrigation regimes (Table 1). The mean increase in numbers and lengths of seminal roots when irrigated at 21 day intervals or under no irrigation were 51% and 112%, respectively, when compared to those of plots irrigated at 3 day intervals. This implies that when maize seedlings subjected to low moisture regimes develop a greater number of roots and facilitate their growth to capture the available moisture. Irrigation intervals of 7 or 14 days also increased numbers and lengths of seminal roots when compared to that of seedlings irrigated every 3 days and the mean increments were 20% and 59%, respectively. The greater numbers and lengths of the first roots of maize seedlings under moisture deficits may be beneficial for the plants to overcome stress at early growth stages.

The growth of First-Order Lateral (FOL) roots at Leaf development Stage (LDS 2) follow the same trend as seminal roots (Table 2). The lowest root growth in terms of numbers, lengths, dry

Table 2. Growth of first order lateral roots, leaf area and relative water content of shoots in maize as affected by irrigation intervals at LDS 2* (mean of two seasons)

Irrigation regime RWC# (%)	Number length (cm)		Dry weight (mg)	Branching index (No./cm)	LA (cm^2)
3 day interval	10	415	0.58	2.9	1458
128 ± 2.1					
7 day interval	17	527	0.78	4.1	1922
129 ± 3.6					
14 day interval	24	611	0.83	5.3	2185
131 ± 1.4					
21 day interval	27	655	0.94	6.4	1259
109 ± 2.7					
No irrigation	28	664	0.90	6.6	1197
P = 0.059	0.014	0.035	0.024	0.037	159.4

*LDS – leaf development stage; # relative water content indicates the water content of irrigated plants in relation to that of non irrigated plants (± S.E.)

weights and branching patterns were observed when the plants were irrigated at 3 day intervals. This could be attributed to the presence of adequate soil moisture for plant uptake or even to possible restriction of root development due to excessive moisture (Zaidi et al. 2008). In contrast, the absence of irrigation or supply of water at 21 day intervals induced a greater FOL root development. The mean increments in numbers, lengths, dry weights and branching of FOL were 180%, 59%, 58% and 121%, respectively when compared to that of plants grown with 3 day irrigation schedules. These values indicated an interesting phenomenon where the lack of moisture developed more FOLs and induced greater branching than increasing lengths or building up the dry weights. This was in contrast to development of seminal roots, which had greater root lengths under moisture deficit conditions. The supply of irrigation at 14 day intervals also increased FOL numbers, lengths, dry weights and branching indices by 140%, 47%, 45% and 85%, respectively, when compared to that of plants under the 3 day irrigation regime. Increments of the same parameters in plants grown with a 7 day irrigation schedule over that of a 3 day schedule were 70%, 26%, 34% and 41%, respectively. This clearly indicated that the response of the measured parameters of the FOLs to moisture deficits was similar although the magnitudes were lower under regular irrigation regimes. The phenomenon of root stimulation by the alternative wetting and drying could be due to the possibility of the roots sensing moisture reductions by producing root signals that regulate shoot development to promote root growth and to capture moisture (Kang et al. 2002). Research has also shown that this root signal is due to the development of Abscisic acid (ABA) concentrations in the xylem (Jia et al. 1996). The data however clearly presented the greater stimulation of FOL root numbers and their branching in response to soil moisture changes than lengths and dry weights under field conditions akin to farmer situations at LDS 2, a phenomenon that warrants further elucidation, as Hund et al. (2009) reported greater extensions of roots in drought-tolerant maize subjected to moisture deficits in pouch studies under controlled conditions.

At LDS 2, leaf area was the highest when irrigation interval was 7 or 14 days (Table 2), with no significant difference between the two treatments. Application of water at 3 day intervals reduced the leaf area by 27% when compared to the mean value observed in plants growth with 7 or 14 day watering schedules, which again could be due to excessive moisture restricting plant growth at this early stage. Irrigation at 21 day intervals or the non-supply of additional water produced the lowest leaf area in maize seedlings due to moisture stress, although they had the highest numbers of FOL roots.

Table 3. Root distribution in soil as affected by irrigation regimes at anthesis of maize in minor seasons (mean of two seasons)

Irrigation schedule (day interval)	Soil depth (cm)	RLD (cm/cm^3)	RWD (mg/cm^3)
3	0–20	6.82	0.56
	20–40	4.22	0.42
	40–60	3.25	0.32
	60–80	1.58	0.18
Mean		3.96	0.37
7	0–20	6.10	0.49
	20–40	5.42	0.44
	40–60	4.62	0.38
	60–80	3.04	0.28
Mean		4.79	0.39
14	0–20	5.62	0.45
	20–40	5.98	0.49
	40–60	4.77	0.42
	60–80	3.45	0.34
Mean		4.95	0.42
21	0–20	4.98	0.48
	20–40	4.22	0.54
	40–60	3.25	0.44
	60–80	3.28	0.36
Mean		3.93	0.45
No irrigation	0–20	4.22	0.45
	20–40	4.08	0.50
	40–60	3.66	0.47
	60–80	3.42	0.44
Mean		3.84	0.46
$P = 0.05$			
Irrigation regime		0.018	0.029
Depth		0.007	0.031
Interaction		*	*

*indicates significance at 0.05 probability

The Relative Water Contents (RWC) of plants irrigated at 3, 7 or 14 days intervals were not significantly different, suggesting similar patterns of water retention in the shoot systems. In contrast, supply of water at 21-day intervals or growing plants under rainfed conditions induced the lowest RWC values. Correlations (r = 0.52*) between the leaf area and RWC indicated the impact of moisture contents in the seedlings on leaf development and the lower leaf area in the infrequently irrigated or non-irrigated conditions could be attributed at least partially to the RWC at this growth stage.

Root Length Densities (RLD) and Root Weight Densities (RWD) at anthesis changed significantly with the adopted irrigation regimes (Table 3). The supply of water at three-day intervals produced the highest RLD and RWD in the top 20 cm layer and the decline of both parameters with depth was the most evident in this irrigation regime. This implies that the maize plants grown with high moisture supply produce a large root volume with the highest biomass in the top layers of soil. Thus the root:shoot ratio was the lowest in plants of this treatment implying the greater growth of shoots at the expense of roots. The presence of high soil moisture could also restrict root development as shown by the lower mean RLD and RWD values in these plants, thus reducing the root:shoot ratio.

Increasing the irrigation interval to 7 or 14 days increased the RLD with soil depth and produced the highest mean values. However the supply of irrigation water at 21 day intervals or under rainfed conditions reduced RLD with depth and also the mean values. This suggested that overall root extension is stimulated by infrequent irrigation up to a frequency of once in 14 days. Thereafter, the low soil moisture content is seen to restrict root extension in the soil. In contrast, while the RWD decreased in the 0–20 cm layer with increasing irrigation intervals, the values increased with depth, especially in the 20–40 cm and 40–60 cm soil layers (Table 3). The highest mean RWD values were observed at an irrigation frequency of 21 days or under rainfed conditions, with no supplementary irrigation. Thus the data indicated that maize plants tend to produce a lower number of heavier roots under increasing soil moisture deficits, as shown by the RLD and RWD values of plants grown with a 21 day irrigation schedule or under rainfed conditions.

The Root:Shoot ratios of plants grown under 7, 14 or 21 day irrigation schedules or under rainfed conditions confirm the observations of RLD and RWD. While plants grown with a 3 day irrigation schedule had the lowest ratios (0.19), values of plants grown with 7 or 14 day schedules were also significantly lower (0.25 and 0.26, respectively) than those of plants grown under 21 day irrigation or rainfed conditions (0.31 and 0.28, respectively). This implies a greater portioning of biomass to roots under reduced soil moisture conditions, confirming earlier reports on maize, soybean and cotton (Spollen et al. 1993). The lack of significant differences between irrigation frequencies of 7 and 14 days and also between 21 days and rainfed conditions implied similarities in the partitioning of dry matter in these irrigation regimes.

Farmers cultivate maize in South Asia principally for seeds and not for fodder or silage; optimizing seed yields is thus priority. In these two seasons, the highest mean seed yields were obtained with an irrigation schedule of 7 day interval, followed by a 14 day interval. (Table 4). The yields of plants in these two treatments were followed by those of plants grown with a 3 day frequency. The harvest indices of plants in these three irrigation schedules were also similar. This indicates that regular watering of maize in this dry season may not provide the highest yields and the intermittent short dry periods developed in 7 or 14 day irrigation intervals tend to stimulate plant growth, especially of roots and thus provide higher yields, with no effect on harvest indices. The possible inhibitory effect of excessive soil moisture could also be a factor affecting optimal yields at frequent irrigations in this dry season where temperatures are also generally higher, and the causal factors need further study.

As expected, and in accordance with vegetative growth, the lowest seed yields were obtained at 21 day irrigation schedule or under rainfed conditions, which also produced the lowest harvest indices. This confirmed the requirements of irrigation

Table 4. Impact of irrigation frequency on yields and harvest indices of maize grown in minor seasons (mean of two seasons)

Irrigation regime (day interval)	Seed yields (kg/ha)	Harvest index
3	2310	0.43
7	2614	0.44
14	2491	0.41
21	1855	0.37
No irrigation	1307	0.34
LSD (P = 0.05)	344.9	0.02
CV (%)	11.90	5.21

at 7 or 14 day intervals for obtaining high yields of maize by stimulating root growth. The general farmer practice of providing excessive moisture at frequent intervals may in fact be detrimental rather than beneficial to maize grown in the minor seasons of South Asia.

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