Root zone soil moisture redistribution in maize (*Zea mays* L.) under different water application regimes

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ABSTRACT

Soil moisture availability to plant roots is very important for crop growth. When soil moisture is not available in the root zone, plants wilt and yield is reduced. Adequate knowledge of the distribution of soil moisture within crop's root zone and its linkage to the amount of water applied is very important as it assists in optimising the efficient use of water and reducing yield losses. The study aimed at evaluating the spatial redistribution of soil moisture within maize roots zone under different irrigation water application regimes. The study was conducted during two irrigatation seasons of 2012 at Nkango Irrigation Scheme, Malawi. The trials consisted of factorial arrangement in a Randomised Complete Block Design (RCBD). The factors were water and nitrogen and both were at four levels. The Triscan Sensor was used to measure volumetric soil moisture contents at different vertical and lateral points. The study inferred that the degree of soil moisture loss depends on the amount of water present in the soil. The rate of soil moisture loss in 100% of full water requirement regime (100% FWRR) treatment was higher than that in 40% FWRR treatment. This was particularly noticed when maize leaves were dry. In 100% FWRR treatment, the attraction between water and the surfaces of soil particles was not tight and as such "free" water was lost through evaporation and deep percolation, while in 40% FWRR, water was strongly attracted to and held on the soil particles surfaces and as such its potential of losing water was reduced.

Keywords: Soil Moisture Content; Full Crop Water Requirement Regime; Maize Root Zone

1. INTRODUCTION

Water use efficiency and water productivity are important agricultural performance indicators that are used in assessing the impact of water management practices that are used to produce more crops with less water [1]. It is vital to specify the water use components when deriving water use efficiency and productivity to avoid the confusion over the two, since these terms are related, but are not essentially the same [2].

In irrigation engineering terms water use efficiency is defined as the ratio between amount of water required to grow a crop (*i.e.* evapotranspiration, percolation and seepage, leaching for salinity control, and land preparation), and the total amount of water applied in irrigation sink or within a spatial domain of interest [2]. Water use efficiency (WUE) as an agronomic term means the ratio between marketable crop yield and amount of water stored in the root zone that is only up-taken and transpired by the crop [3]. Under agronomic definition of water use efficiency, amount of water stored within the crop root zone but lost through evaporation is not accounted for [4]. Irrigation engineering and agronomic water use efficiencies may be related to each other but under normal circumstances increase in irrigation engineering water use efficiency does not result in an increase in agronomic water use efficiency. For example, in Irrigation engineering water use efficiency is directly correlated with decrease in applied water. But this does not mean that reduced amount of water will result in an increase in crop yield. This is because less amount of applied water may not have the ability to flush out salts or may not be enough to meet the demand of the crops hence low yield may occur meaning that agronomic water use efficiency is low. The ambiguity in the definitions and interpretation of wa-

ter use efficiency has resulted in the introduction of water productivity replacing agronomic water use efficiency [5].

Water Productivity (WP) is defined as a ratio of unit of yield produced to unit volume of water used to produce the yield [6]. When water is in short supply, the WP is substantially increased through deficit irrigation. [7,8] reported that in several situations, the 50% depletion level of available soil moisture is the critical point of many soils beyond which yields were reduced. On the other hand, the 50% - 60% replacement of total crop water requirements was found as the critical range in which WP realises acceptable yields under deficit irrigation [9,10]. Agronomically the 50% - 60% depletion of readily available water corresponds to the threshold for leaf expansion [11]. Soil moisture availability to plant roots is very important for crop growth. When soil moisture is not available in the root zone, plants wilt and yield is reduced. [12] reported that status, availability and distribution of soil moisture within a root zone of crop affect the growth and yield of crops. When crop roots are using less energy to extract water from the soil, the saved energy is converted into yield and this increases water productivity [13]. When crop roots are having difficulties in extracting water from the soil, the plant is stressed and this is manifested through decrease in leaf area growth which limits the ability of leaves to absorb sunlight and transpire water resulting in less crop yield.

Adequate knowledge of the distribution of soil moisture within crop's root zone and its linkage to the amount of water applied is very important as it will optimise the efficient use of water and reduce yield losses. The aim of this study was to evaluate the spatial redistribution of soil moisture within maize roots zone under different irrigation water application regimes.

2. MATERIALS AND METHODS

2.1. Site Description

The research study was done at Nkango Irrigation Scheme in Kasungu district. Data were taken in two irrigation growing seasons from 1st June to 8th September, 2012 during the first season, and from 10th September to 5th December, 2012 during the second season. Nkango Irrigation Scheme is an informal scheme which is owned and managed by the local communities and is situated at Latitude 12˚35' South and Longitudes 33˚31' East and is at 1186 m above mean sea level. The study area has a unimodal type of rainfall with rains between December and April. The mean annual rainfall is about 800 mm. The site lies within maize production zone of Malawi and has dominant soil type of coarse sandy loam. Smallholder farmers in the area practise irrigation and are conversant with water application regimes.

The soil of the plots is sandy loam with a low soil organic matter and nutrient concentration as described in

Table 1. Characteristics of the top soil (0 - 20 cm) of at the research site in Nkango, Malawi.

Soil properties	Values
Clay (%)	13
Silt (%)	17
Sand (%)	70
Carbon (%)	0.599
C/N ratio	13.011
OM (%)	1.0773
Total nitrogen (%)	0.046
Total phosphorus (ppm)	33.206
Total potassium ($\mu eq \cdot K \cdot g^{-1}$)	1.2153
Exchangeable calcium ($\mu eq \cdot K \cdot g^{-1}$)	19.254
Exchangeable magnesium ($\mu eq \cdot K \cdot g^{-1}$)	28.964
Moisture content (%)	4.163
Field capacity (%)	20
Wilting capacity (%)	10
Bulk density (g/cm^3)	1.59
pH	5.2

Table 1. The Cation Exchange Capacity is low (50.00 - 80.00 $\mu eq \cdot g^{-1}$), and the pH decreased from acidic (5.2) to strongly acidic (4.7). The salinity of the soil was very low (1.7 mmhos/cm).

2.2. Experimental Design

The plot size was 5 m by 5 m and ridges were spaced at 75 cm. The plots were separated from one another by a 2-metre boundary to avoid "sharing" of responses, water and nitrogen (edge effects). Three maize seeds of hybrid maize (SC 407) were planted per hole at plantspacing of 25 cm and row spacing of 75 cm. They were later on thinned to one seed per station 7 days after germination.

The trials consisted of factorial arrangement in a Randomised Complete Block Design (RCBD). The factors were water and nitrogen, and both were at four levels. Water had four application regimes and these were as follows: farmers' practice regime (contol); full (100%) water requirement regime (FWRR) of maize plant; 60% of FWRR; and 40% of FWRR. A full maize water requirement was determined by using the procudure described in [14]. Nitrogen had four application regimes and these were as follows: The Typical Nitrogen Application Rate in the area (TNPRA) of 92 kg N/ha was used as a basis (control) to determine other dosage levels in the study [15]. The nitrogen dosage levels were as follows: TNPRA, 92 kg N/ha; 125% of TNPRA, 115 kg N/ha; 75% of TNPRA, 69 kg N/ha; and 50% of TNPRA, 46 kg N/ha.

2.3. Data Collection

The Triscan Sensor (EnviroScan, Sentek Pty Ltd.,

Stepney, Australia), which has ability to sensor volumetric soil moisture at the instant time of inserting the monitoring probe in the soil, was used to measure soil moisture content at different points (defined by lateral and vertical distances) within maize root zone depth. The lateral distances were at interval of 5 cm as shown in **Figure 1**. The measured points were: at point of fertilizer application (represented by 0 cm, which is 10 cm from the plant), at 5 cm away from the plant (represented by −5 cm), at 5 cm towards the plant, 10 cm towards the plant (this point was maize planting station), and 15 cm (this point was 5 cm after planting station) as shown in **Figure 1**. The lateral distances were taken based on spreading and elongation pattern of lateral roots of maize plants. The lateral readings of nitrogen were respectively taken at five soil depths of 20, 40, 60, 80, and 100 cm from the soil surface,and were selected based on maize roots growth habits, which extend down to 100 cm [16].

2.4. Data Analysis

The data presented in this paper were from treatment combinations of 100% of FWRR and 92 N Kg/Ha and 40% of FWRR and 92 N Kg/Ha. This is because statistically treatment combination of 100% of FWRR and 92 N Kg/Ha gave the highest nitrogen use efficiency and 40% of FWRR and 92 N Kg/Hagave the highest water
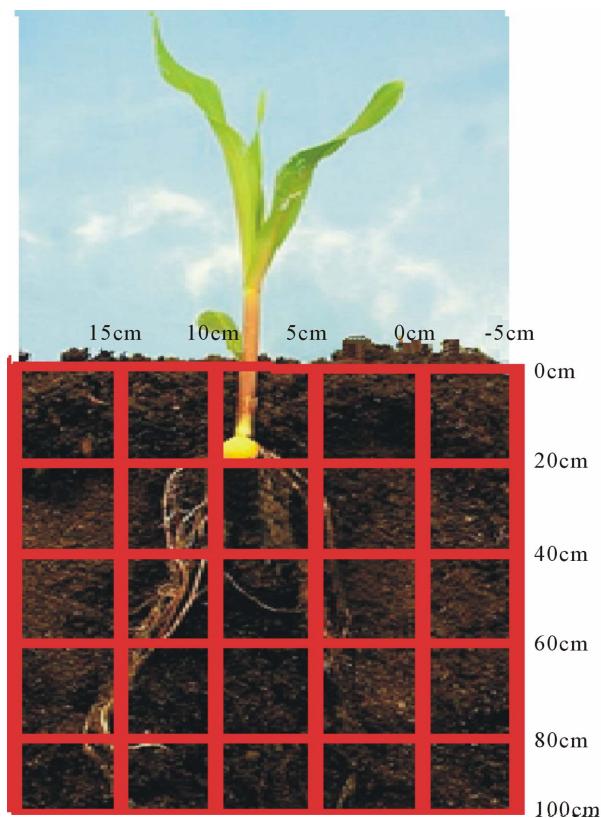

Figure 1. Showing measurement points.

productivities. The data are presented in graphical form to indicate comparative redistribution of soil moisture content in both treatment combinations.

3. RESULTS AND DISCUSSIONS

Figures 2 and **3** indicate the spatial distribution of soil moisture on 10th July in maize plots of 100% FWRR and 40% FWRR respectively. The figures indicate that at point where maize was planted, the soil moisture was high at 20 cm in 40% than in 100%, while at 40 cm deep
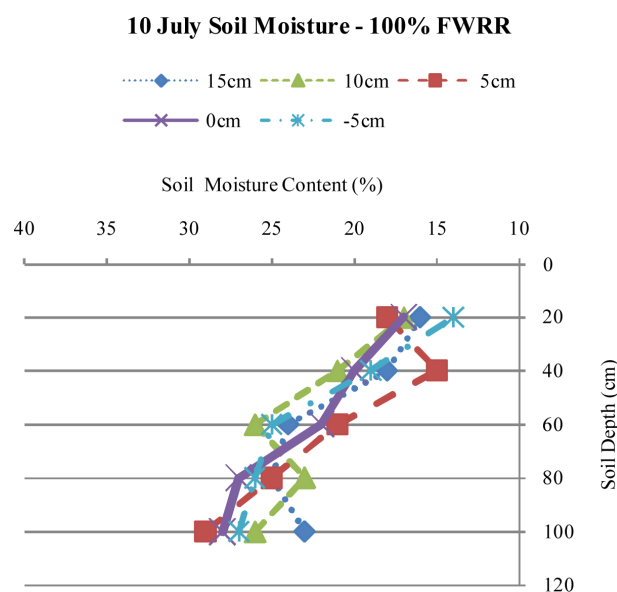

Figure 2. Soil moisture content distribution in 100% FWRR on 10 July.
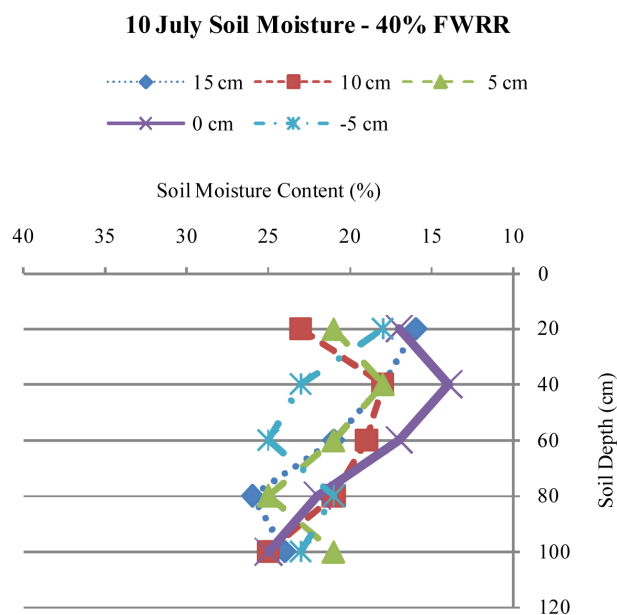

Figure 3. Soil moisture content distribution in 40% FWRR on 10 July.

soil moisture content was high in 100% FWRR than in 40% FWRR treatments. At 60 cm, the soil moisture was very high in 100% FWRR and was about 27% while in 40% FWRR, the soil moisture was about 18%. At 100 cm below, the soil moisture contents were relatively the same in both plots of 100% FWRR and 40% FWRR. The general observations indicate that at 20 cm below, there was negligible difference of soil moisture contents in both treatments.Higher soil moisture contents were observed from 40 cm, 60 cm to 80 cm. At 100 cm negligible differences were again observed in both treatments. The reason to this observation is that at shallow soil depths soil water loss through evaporation is proportional to the degree of soil wetness, *i.e.* moist surface loose high amount of water than less moist surfaces due latent heat which is absorbed by soil water and hence subjecting the surface to more water loss. Over the period, the surface will relatively have the same moisture contents. On 10th July, maize plants were almost 40 days after planting and the leaves were not fully developed to completely shade the land surface, as such during this period water loss through evaporation was high.

Between 20 and 80 cm deep the differences in soil moisture content may be due to uptake by maize roots. In 40% FWRR, the plants roots are stressed and have less ability to attract water from the surrounding areas. In 100% FWRR, the surrounding soil has high moisture contents due to applied water but also due to ability of plant roots to attract water from the surrounding areas. At the depth of 100 cm, the soil moisture contents may entirely be due to not being uptaken by maize roots. Several studies have shown that soil moisture increases with depth. It is unlikely that on 20th July, water through deep percolation may have greatly attributed to the changes of soil moisture at 100 cm in both treatments.

Figures 4 and 5 show that spatial distribution of soil moisture contents at 20 cm deep in both treatments had similar pattern and they all spread with 15% to 25% soil moisture contents. Big differences of spreading patterns were observed in at 40 cm below. At 60 cm below the distribution had similar pattern with the lowest figures at lateral distance of 10 cm and highest at 0 cm. At 100 cm below, soil moisture though similar distribution pattern in both treatments, but the figures in 100% FWRR treatment were much higher than those in 40% treatment. The high differences at 60 cm may be due to absorption of water by maize roots and this can be substantiated by a low figure at lateral distance of 10 cm which was at the point of maize seeds plantation. Many studies on maize roots behaviour suggests that maize roots tend to grow to 100 cm, but during flowering stages, maize roots are more active at depth between 50 to 70 cm below and this study suggest that rate of water absorption was very high within this soil depths. At 100 cm below soil moisture increase in 100% FWRR treatment may be due to deep

percolation of water from the applied water. On 20th July the maize plant had reached 50 days after planting. The plant leaves had fully developed with leaf area index at its highest, and during this period land surface is wholly covered by leaves resulting in less evaporation and high downward movement of water as there is less competing force.

Figures 6 and 7 indicate the spatial distribution of soil moisture on 30th July when the maize was 60 days after planting old. The behaviour of soil moisture contents at
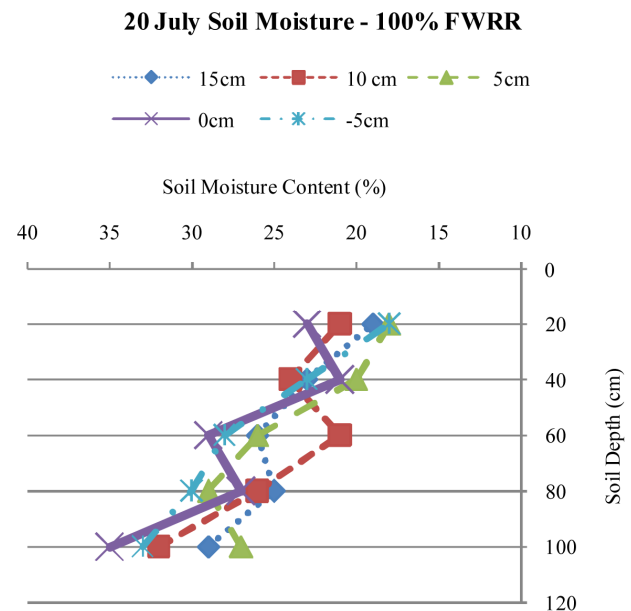

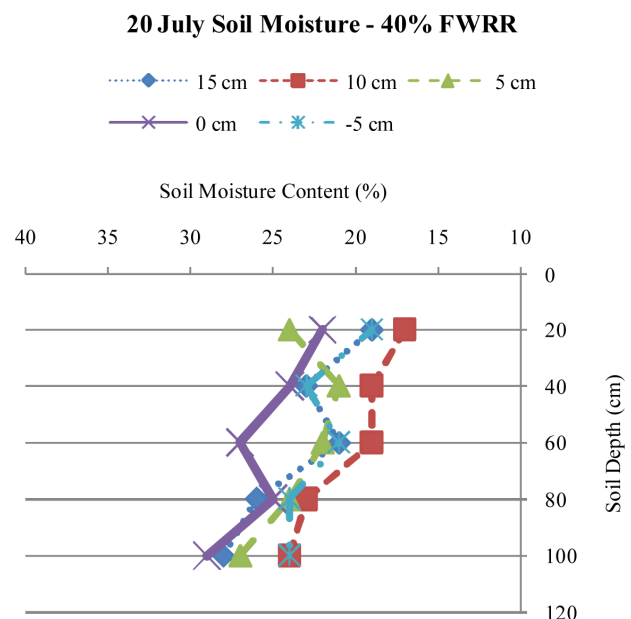**Figure 4.** Soil moisture content distribution in 100% FWRR on 20 July.

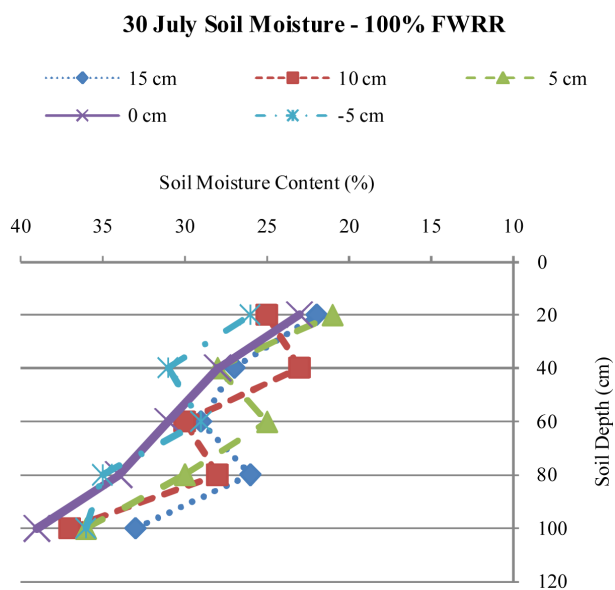**Figure 5.** Soil moisture content distribution in 40% FWRR on 20 July.

30 July Soil Moisture - 100% FWRR

Figure 6. Soil moisture content distribution in 100% FWRR on 30 July.
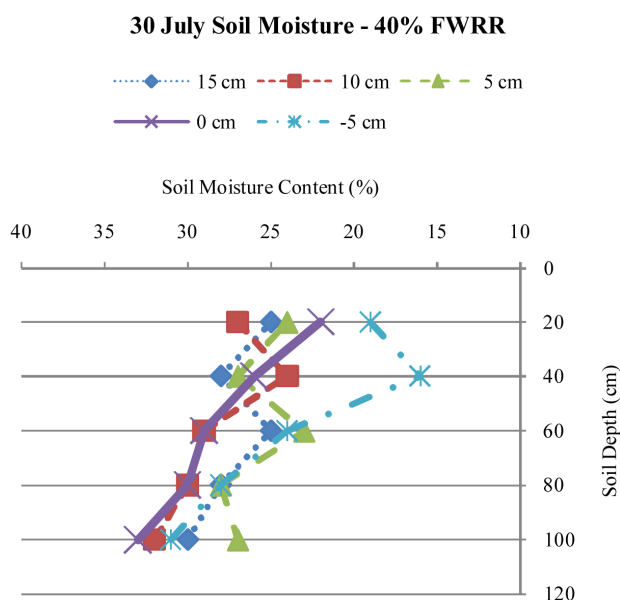
30 July Soil Moisture - 40% FWRR

Figure 7. Soil moisture content distribution in 40% FWRR on 30 July.

20 cm in both treatments suggests increase in all plants as compared to previous points *i.e.* the measured points at 20 cm have more soil moisture contents than those measured before. At 40 cm, huge differences are noted in 40% FWRR treatment where at lateral distance of −5 cm, the content of soil moisture was lowest followed by at 10 cm. This period due to development of leaves there are less evaporation losses but transpiration losses have increased meaning that the ability of maize roots to absorb soil water has increased, hence the negative gradient of water has been created around maize roots.

The stressed roots tend to grow towards the regions where there is water. This situation has made water to move from surrounding areas to the areas next to plant roots. The decrease in losses through evaporation has made the surface soil to have high moisture content than before.

On 9th August, when the maize plant was 70 days old, **Figures 8** and **9** indicate the high variations in the spatial distribution of soil moisture. At 20 cm below, the distribution of moisture is in both treatments spread out within 20 to 25%, at 40 cm below there is high variation
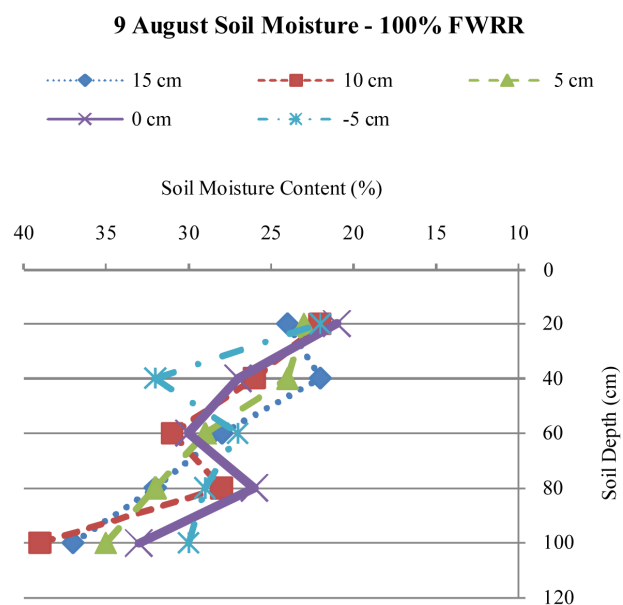
9 August Soil Moisture - 100% FWRR

Figure 8. Soil moisture content distribution in 100% FWRR on 9 August.
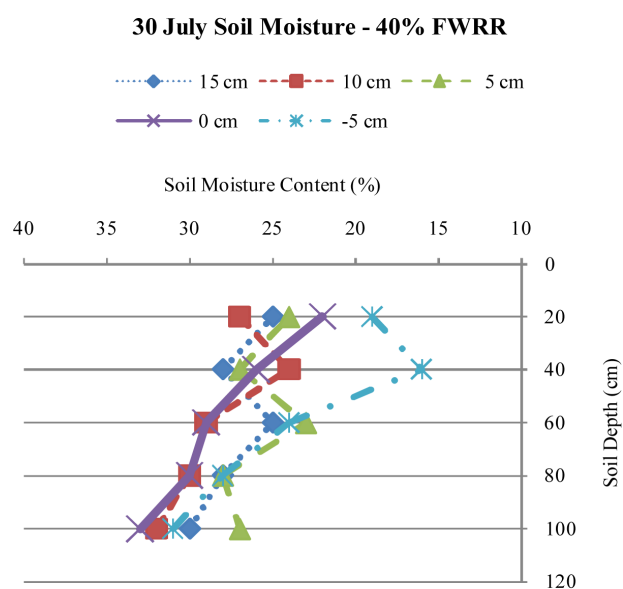
30 July Soil Moisture - 40% FWRR

Figure 9. Soil moisture content distribution in 40% FWRR on 9 August.

of moisture distribution *i.e.* spread out from 22 at 15 cm to 32% at −5 cm in 100% FWRR treatment while in 40% FWRR treatment the distribution is spread within 25 at −5 cm to 27% at 0 cm, the small difference at 40 cm in 40% FWRR shows that there was less water absorption activity which would have resulted in some points having less moisture content due to absorption than other points. In 100% FWRR treatment, the high variations of soil moisture contents indicates that some points were being absorbed than other points for example at the lateral distances of 15 cm, 5 cm, and 0 cm more water was being absorbed than at 5 cm away from the plants (−5 cm) which had high value of 32%. At 60 cm below, in 40% FWRR treatment we are now start to seeing an increase in variations of soil moisture distributions which ranged from 24% at 0 cm to 28% at 10 cm, and the increase in variations of soil moisture has continued to increase at 80 cm from 26% at 10 cm to 31% at 15 cm, and at 100 cm the variations has further increased from 24% at 10 cm to 31% at 0 cm. The general trend of spatial soil moisture distribution in 40% FWRR treatment is that is declining while in 100% treatment the trend of spatial moisture distribution is increasing but the variations of moisture distribution from 60 cm in decreasing. The differences may be attributed to the fact that maize roots in 40% FWRR treatment have grown longer and are able to tap soil water at lower depth of 60 cm to 100 cm while the maize roots in 100% FWRR have not developed progressively to actively tap water at lower depths. The roots develop in respond to degree of water availability, when soil water is scarce the plant roots develop surviving strategy of long roots so that it can tap water at lower depths but when soil moisture is available plant roots will convert the energy saved into yield and roots do not grow longer.

   Figures 10 and **11** show that the general trend of moisture contents at all points in both treatments is decreasing when compared with the trend of **Figures 8** and **9** on 9 August. Specific observations indicate that the variations of moisture contents in 40% FWRR treatment started at 60 cm than in 100% FWRR treatment. On 19 August, the maize plant was 80 days old and during this late stage most of the lower leaves of maize plants have dried exposing ground surface to evaporation which has increased due to high temperature. The evaporation made the soils to loss more water. However, the maize is still absorbing water because plant is still losing water through transpiration stream and this is creating demand of more water in the plants.

   Figures 12 and **13**, on 29th August, the maize plant was 90 days old and all the leaves in both treatments have dried and are no longer losing water through transpiration. The dying of leaves though has exposed the soil surface and water is being lost through evaporation.
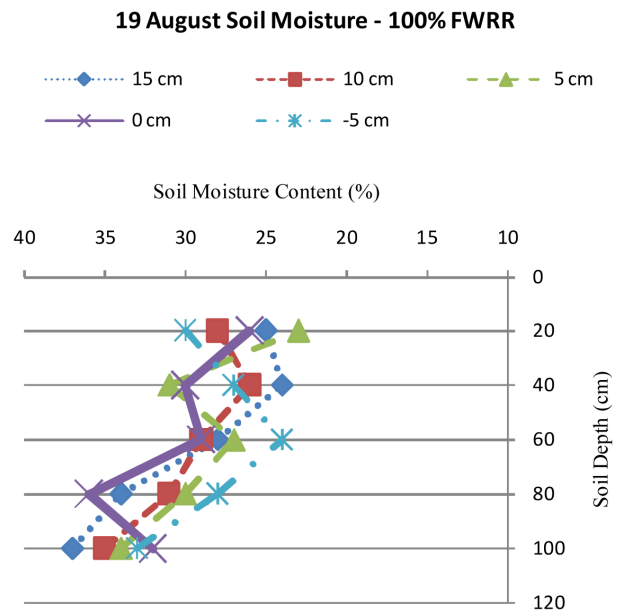

Figure 10. Soil moisture content distribution in 100% FWRR on 19 August.

However, of interest is the rate of soil water loss, if compared with figures of 10 and 11 it shows that **Figure 12** of 100% FWRR treatment has lost more water within the same period than that of 40% FWRR treatment. For example, at 100 cm below of **Figure 11** (100% FWRR), at point 15 cm has lost moisture from 37% on 19 August to 28% on 29 August, yet during the same period of 10 days and the same depth 100 cm in 40% FWRR treatment, the similar point (15 cm) has moisture from 24% on 19th August to 21%. This shows that the soil that has high moisture content loses more water than soil that has less moisture content. One of the reason is that there is loose water that is freely moving within soil pores and therefore less energy from the sun is required to evaporate them but in soil that have less water, water is held tightly together and more energy is required to evaporate them.

   On 8th September, the maize plant was 100 days old and the maize including the cobs have completely dried. The maize was harvested on this day. The spatial moisture content distribution in **Figures 14** and **15** indicated shows that there is huge decline of soil moisture content at the shallow depth of 20 cm in both treatments as compared to lower depths.

4. CONCLUSION

   In this study, we infer that the degree of soil moisture loss depends on the amount of water present in the soil. The rate of soil moisture loss in 100% FWRR treatment was higher than that in 40% FWRR treatment. This was particularly noticed when maize leaves were dry. In 100% FWRR treatment, the attraction between water
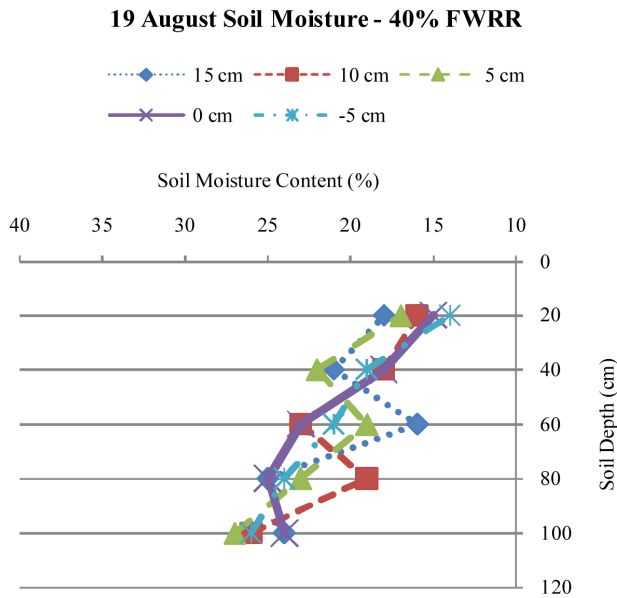
19 August Soil Moisture - 40% FWRR

Figure 11. Soil moisture content distribution in 40% FWRR on 19 August.

29 August Soil Moisture

Figure 12. Soil moisture content distribution in 100% FWRR on 29 August.

29 August Soil Moisture - 40% FWRR

Figure 13. Soil moisture content distribution in 40% FWRR on 29 August.

8 September Soil Moisture - 100% FWRR

Figure 14. Soil moisture content distribution in 100% FWRR on 8 September.

and the surfaces of soil particles was not tight and as such "free" water was lost through evaporation and deep percolation, while in 40% FWRR, water was strongly attracted to and held on the soil particles surfaces and as such its potential of losing water was reduced.

The soil moisture redistribution in the root zone is directly related to the amount of applied irrigation water and spatial distribution of soil moisture content was primarily influenced by roots water uptake and evaporation. Evaporation was critical especially before leaves were fully developed and after the leaves have dried.
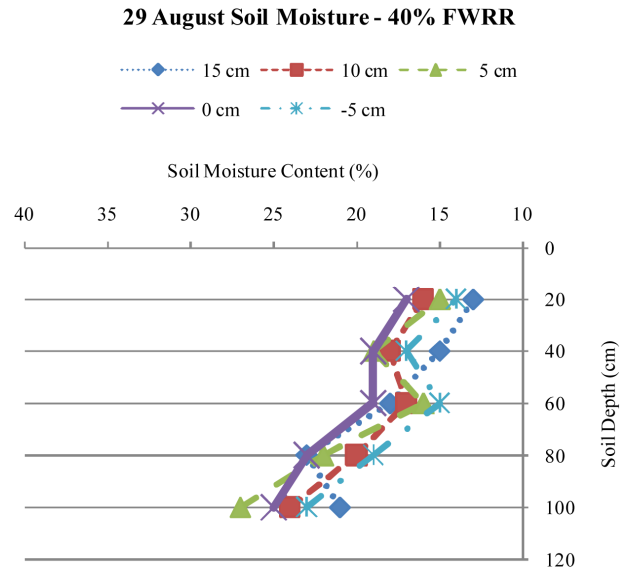
Soil loss through deep percolation was high in 100% FWRR. When the soil moisture content is optimal for plant growth, the water in the large- and intermediate-sized pores can easily move about in the soil which can result in a deep percolation.

The redistribution patterns of soil moisture in both treatments were similar. However in 100% FWRR, the measured points had higher soil moisture contents than that in 40% FWRR treatment and soil water has fluxed to deeper layers, while in 40% FWRR, soil moisture was only concentrated in the top layers of the soil and this restricted water uptake by plants roots in deeper layers.
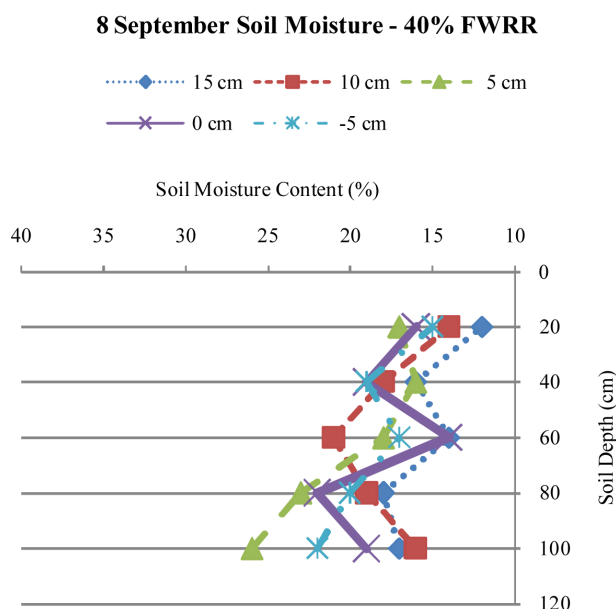
8 September Soil Moisture - 40% FWRR

Figure 15. Soil moisture content distribution in 40% FWRR on 8 September.

Less water uptake and high evaporation resulted in wilting of the some plants in some plots of the treatment.

5. ACKNOWLEDGEMENTS

REFERENCES

[1] Sanaee-Jahromi, S., Feyen, J., Wyseure, G. and Javan, M. (2001) Approach to the evaluation of undependable delivery of water in irrigation schemes. *Irrigation and Drainage*, **15**, 197-213. http://dx.doi.org/10.1023/A:1012674714229

[2] Shideed, K., Oweis, T. and Osman, M.E. (2003) Enhancing agricultural productivity through on-farm water-use efficiency: An empirical case study of wheat production in Iraq. Economic and Social Commission for Western Asia (ESCWA) and International Center for Agricultural Research in the Dry Areas (ICARDA), 12-67.

[3] Saleh, A.F.M. and Mondal, M.S. (2001) Performance evaluation of rubber dam projects of Bangladesh in irrigation development. *Irrigation and Drainage*, **50**, 237-248. http://dx.doi.org/10.1002/ird.18

[4] Pandey, R.K., Maranville, J.W. and Chetima, M.M. (2000) Deficit irrigation and nitrogen effects on maize in a Sahelian environment II. Shoot growth, nitrogen uptake and water extraction. *Agricultural Water Management*, **46**, 15-27. http://dx.doi.org/10.1016/S0378-3774(00)00074-3

[5] Barker, R., Dawe, D. and Inocencio, A. (2003) Economics of water productivity in managing water for agriculture. In: Kijne, W.J., *et al.*, Eds., *Water Productivity in Agriculture*: *Limits and Opportunities for Improvement*. CABI Publishing, Wallingford, 19-35. http://dx.doi.org/10.1079/9780851996691.0019

[6] Renault, D. and Wallendar, W.W. (2002) Nutritional water productivity and diet: From "crop per drop" towards "nutrition per drop". *Agricultural Water Management*, **45**, 275-296.

[7] English (1990) Deficit irrigation I: Analytical framework. *Irrigation and Drainage Engineering*, **116**, 399-410.

[8] Lamm, F.R., Rodgers, D.H. and Manges, H.L. (1994) Irrigation scheduling with planned soil water depletion. *Transactions of the ASAE*, **37**, 1491-1497.

[9] Sarwar, A. and Perry, C. (2002) Increasing water productivity through deficit irrigation: Evidence from the Indus Plains of Pakistan. *Irrigation and Drainage*, **51**, 87-92.

[10] Dichio, B., Xiloyannis, C., Nuzzo, V., Montanaro, G. and Palese, A.M. (2004) Regulated deficit irrigation inPeach tree in semi-arid climate. www.biomet.ucdavis.edu

[11] Steduto, P., Raes, D.T., Hsiao, C., Fereres, E., Heng, L., Izzi, G. and Hoogeveen, J. (2008) AquaCrop: A new model for crop prediction under water deficit conditions. Options Méditerranéennes, Series A, No. 80, Rome.

[12] Fasinmirin, J.T. and Oguntuase, A.M. (2008) Soil moisture distribution pattern in *Amaranthus cruentus* field under drip irrigation system. *African Journal of Agricultural Research*, **3**, 486-493. www.academicjournals.org

[13] Mloza-Banda, H.R. (1994) Principles and practices of crop management. A field study guide. Bunda College of Agriculture, Lilongwe.

[14] Allen, G.R., Pereira, S.L., Raes, D. and Smith, M. (1998) FAO Irrigation and Drainage Paper No. 56. Crop Evapotranspiration (guidelines for computing crop water requirements) (FAO) Food and Agriculture Organization of the United Nations, Rome.

[15] Ministry of Agriculture and Food Security (2011) Annual reports and notes. Lilongwe.

[16] FOASTAT (2000) Maize. http://www.fao.org/nr/water/cropinfo_maize.html