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Performance of bucket drip irrigation powered by treadle pump on tomato and maize/bean production in Malawi

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Abstract The performance of a bucket drip irrigation system (BDI) powered by treadle pump was evaluated on tomato and intercropped maize/bean crops, between 2005 and 2007 in Malawi. It was a split plot experiment with three replicates. The BDI system consisted of a 1,300-l tank mounted 1.5 m above ground and connected with a 32-mm mainline and 15-mm lateral lines spaced at 1 m by 0.6 m. A treadle pump was used to uplift water to the tank. Tomato and intercropped maize/bean were irrigated every 4 days. The system reduced labour and water by >25% and it showed high uniform application depth and wetted diameter. Yields were significantly different between tomato varieties ($P < 0.05$). Maize/bean yields were highly significantly different between monoculture, intercropping system and bean varieties ($P < 0.001$). Consequently, an economic analysis shows that there is a significant difference, in terms of net income, between the various crop enterprises. Tomato was more valuable with BDI, compared to maize and beans. It can be concluded that BDI, powered by a treadle pump, saves labour and time and it provides uniform irrigation for crop production. Therefore, tomato is recommended for use with this system, compared to maize and bean.

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Introduction

The 'carry-and-irrigate' method together with treadle pumps are commonly used by smallholder farmers, in order to irrigate dry season crops, such as tomatoes, maize and bean, along river banks, dambos and home gardens in Malawi (Barak 1986; Mangison 2006; Malawi Government 2006). These technologies are highly adopted and practiced, although they are labour intensive and not water saving (Maweru 2004; Mzembe 1994; Ministry of Agriculture and Irrigation 2003). The treadle pump was introduced into Malawi in 1994 (Mangison 2006; Maweru 2004), in order to reduce the cumbersome and limited productivity experienced with the carry-and-irrigate method.

The treadle pump supersedes the carry-and-irrigate method for water supply and size of production area. According to Kay and Brabben (2000), the treadle pump is a simple, human-powered device, which can be manufactured and maintained at low cost. The principle on which a treadle pump works is based on suction lift, which uses a cylinder and piston to draw water from a source below ground level (Kay and Brabben 2000). However, a treadle pump is laborious and tedious, since it requires three people: two pumping the water, whilst one directs it to crops in the field (Mangison 2006). In addition, it requires improvement, through the consolidation of other technologies that can enhance productivity, whilst (at the same time) saving labour, water and energy costs, such as the bucket drip irrigation method (BDI).

Drip irrigation was introduced into Malawi because it was reported to reduce energy costs and it applies water and nutrients efficiently (Chanson et al. 1994; Shock 2006; Zotarelli et al. 2009a, b), whilst improving crop production (Mzembe 1994), compared to surface irrigation methods (Fandika and Burgess 2008; Ministry of Agriculture and Irrigation 2003) and a treadle pump on its own. Drip irrigation applies water precisely and slowly, in the form of discrete drops, which is achieved through pressure-reducing paths and emitters (Keller and Karmeli 1974; Keller and Bleisner 1990; Van der Gulik 1999). These emitters are allocated at prescribed points, corresponding to the required crop spacing, in order to introduce water into plant roots at the correct time and rate (Goldberg et al. 1976; Nir 1982; Van der Gulik 1999). The majority of drip irrigation systems operate under high-pressure heads, with more than 1 bar (10 m water head), which is expensive for small-scale farmers. Experience from other countries, such as Kenya (Kabutha et al. 2000), has shown that the bucket drip suits a low head condition (approximately 1 m head), which makes it perfect for smallholder farming conditions in remote areas where electricity is not accessible. A local water head provides discharge without pumping, thus leaving the laborious component of filling the bucket unsolved. In this study, it was hypothesised that the incorporation of the treadle pump into the BDI system could help economise labour and water use of drippers and improve crop productivity, rather than the use of a surface irrigation system, such as a furrow, where electricity is limited. There is no information available, relating to this area, because there has been scarce research on water and labour saving micro-irrigation technologies in Malawi.

Irrigation research in Malawi has been focused on a traditional surface irrigation system for field crops (Kadyampakeni et al. 2004). However, due to the current water scarcity (Kaluwa et al. 1997) and high energy costs, interest in agricultural water-saving technologies (drip irrigation) and an intercropping farming system for home gardens is developing (Malawi Government 2006). Nevertheless, there is no local information available concerning low costs and labour and water-saving micro-irrigation performance (such as bucket drip irrigation), on yield and income, in addition to irrigation distribution uniformity. This information would be important for the scientific, economic and technical feasibility of a BDI system in Malawi. Therefore, an experiment was conducted, in order to evaluate the performance of a locally designed bucket drip irrigation powered by a treadle pump and its economic impact on tomato, monocropped and intercropped maize/bean crops, on yield and net income, water use efficiency and application uniformity. The purpose of the research programme was to promote ‘micro’-gardens and backyard gardens, which could supplement smallholders’ food supply, in both urban and rural areas, where water, labour and electricity are limited.

Materials and methods

Location and weather

The studies of tomato (*Lycopersicon esculentum*) and intercropped maize/bean (*Zea mays/Phaseolus vulgaris*) were conducted at Kasinthula Agricultural Research Station in Chikwawa, Malawi, from 2005 to 2007. The station is located at latitude 16°S, longitude, 34°5′E, at an altitude of 70 m above sea level. According to the long-term data, the annual average minimum and maximum temperature, annual precipitation, relative humidity, wind speed and evaporation are 18.6, 35.6°C, 520 mm, 70%, 4.7 km day^{-1} and 5.1–8.6 mm day^{-1}, respectively (Fandika and Burgess 2008). The soil texture of this site is sandy loam with a bulk density of 1.31 g cm^{-3} and a volumetric water content of 5.5–22.07.

Experimental design

Both experiments were split plots, laid out in a randomised complete block design (RCBD) with three replicates. The replicates were determined by distance from the water source, in order to measure yield variation or irrigation uniformity between lateral lines and furrows. The tomato trial consisted of two varieties (Rodade and Moneymaker) as sub-plots, whilst intercropped maize/bean had five treatments coded as: (1) Sole bean var. 1 = B1; (2) Sole bean var. 2 = B2; (3) Sole Maize = M1; (4) Maize/Bean var. 1 intercropping = M_1B_2 and (5) Maize/Bean var. 2 intercropping = M_1B_2. The maize variety was DK8031, bean var. 1 was Nasaka and bean var. 2 was Kalima. Irrigation methods (bucket drip and furrow irrigation) were used in the main plots with a furrow being the control. Both crops were spaced 1 m by 0.6 m, according to emitter and drip lines spacing. One drip emitter was designed to irrigate one plant station.

The BDI plot size for the tomato trial consisted of 216 plants on six drip lines of 21.6 m each, whilst the BDI plot size for the maize/bean trial consisted of 72 plants on two drip lines of 21.6 m each. In the furrow irrigation, both crops had net plot sizes of five rows spaced at 0.75 m by 20 m with plant spacing, as in the BDI. Fertiliser was dissolved in water and applied through the 1,300-l tank in five phases, through fertigation (Burt et al. 1995) in the intercropped maize/bean and tomato at 5.2 and 9.4 g l^{-1} per application, every 2 weeks after planting, in order to give a total application of 100 and 180 kg N ha^{-1}, respectively. Furrow-irrigated crops received the same fertiliser in two phases, at planting and 3 weeks after a basal dressing, using the dollop method. All husbandry practices, such as weeding and pest and disease management, were the same over the entire experiment.

Drip irrigation system design and field layout

The bucket drip irrigation system (BDI) consisted of a 1,300-l tank mounted 1.5 m above the ground and connected to a 32-mm PVC mainline, with 15-mm garden hose lateral lines. There were eighteen (18) drip lateral lines of 21.6 m each, in which thirty-six pressure-compensated drippers were spaced at 1 m by 0.6 m. These drip lines were laid out alongside each crop row, each with a dripper delivering 2 l h^{-1}. The irrigation water was uplifted to the tank by the use of a treadle pump that was incorporated into the drip system at a distance of 10 m. Each discharge manifold had removable end cups for flushing (Figs. 1, 2). The system was totally designed with a maximum net irrigation of 10.8 mm and gross irrigation of 12 mm per day, based on the climate and soil and plant properties, prior to the system being installed in the field (Figs. 1, 2).

Irrigation water application and evapotranspiration determination

Irrigation water was applied, based on cumulative Class-A Pan Evaporation within irrigation, at intervals of 4 days, using 1.0 coefficient of Class-A Pan Evaporation, as recommended by Cetin et al. (2002) under bucket drip irrigation. In the study, the amount of irrigation water was determined by using the following equation: $I = A*\text{Ep}*\text{Kpc}*P$, where I equals amount of irrigation water (l); A equals plot area (m^2); Ep equals cumulative evaporation amount considering irrigation intervals (mm); Kpc equals coefficients (including pan coefficient, Kp crop coefficient kc and application efficiency of 90%) and P equals percentage of the wetted area. The Kc pan

Fig. 1 *Front view* showing drip main line from the drip tank raised 1.5 m on concrete

Fig. 2 Treadle pump uplifting water into a bucket drip irrigation system

coefficient used was 0.65 for Class-A Pan and it was placed in a short green cropped and medium wind area (Allen et al. 1998). Crop coefficients (kc) for tomatoes were 0.64, 1.03, 1.48 and 0.73 (André and Churata-Masca 1992), whilst for maize, it was 0.4, 0.8, 1–1.2 and 0.6 (Allen et al. 1998) for vegetative, development, mid-stage and final stage, respectively. The wetted area was 30%, as a result of using tables for determining the values of the proportion of soil (%) wetted by various discharge rates and spacing for a single row of uniformly spaced distributors in a straight line. The drip system was placed on the plots immediately following transplanting and planting. The initial amount was applied, based on a maximum soil moisture deficit of 100 mm m^{-1}, in order to bring it to a 90 cm layer of soil to field capacity. Subsequently, wetted depth and diameter measurements were taken, after initial irrigation. Subsequent irrigation was applied, following consideration of irrigation intervals and coefficients of Kcp. Soil water balance, at 40% depletion for intercropped maize/bean (Fandika and Burgess 2008) and 20% depletion for tomato, was used, in order to schedule irrigation.

Under surface irrigation, water was applied in furrows using siphon feeders. Each siphon was set at a flow rate of 0.5 l s^{-1}. These siphons were laid at the beginning of the furrows and connected to a concrete line canal, in which water was maintained at a constant head above the centre of the siphon pipe inlet. Irrigation was based on irrigating to field capacity, as detailed under BDI above.

Wetted diameter and wetted depth measurements

Wetted diameter, in this study, is defined as the distance across a water application pattern, from dry soil in the front of the system to dry soil behind the system (Camp et al. 1987), whilst wetted depth is defined as the vertical infiltration of water as a function of the volume of water applied for the studied soil. These parameters were measured at the initial and last irrigation, by physically measuring the wetted diameter with a tape measure and by digging the soil profile, in order to measure the wetted depth. Measurements were made along one drip line in each replicate. Catch cans were also used to measure discharge per dripper, in order to support the above data. It was important to gather information on uniform infiltration and application of water, in order to check whether a low-pressure system could give plants equal access to water, regardless of distance from the mainline. Infiltration depth and crop yield were correlated, in order to assess whether they deteriorated (since drip line deviated from the main line) as a measure of irrigation uniformity.

Uniformity evaluation and economic analysis of BDI system

Uniformity in irrigation refers to how evenly water is delivered over the ground. This was evaluated by measuring the in-field application depth (mm) from each dripper fitted along the drip lines (Wilson and Zoldoske 1997). This was aimed at measuring the in-field water distribution from various drip lines as they deviated from the mainline and clogging for maintenance was determined (Hassan 1998). A number of small catch cans were laid along the drip lines, spaced at 1 m by 0.6 m between drippers. The extended wetted diameter and the application depth were also measured. A measuring tape was used to measure the distance between the cans and the wetted diameter. The drip irrigation system was left to operate at its normal speed for 2 h. At the completion of the experiment, the water depth in the catch cans was measured and recorded, using a measuring cylinder, together with the precise position of each can.

The collected data on application depth from the catch cans were simulated, at the required spacing. Consequently, the Christiansen coefficient of uniformity and distribution uniformity was calculated for the designed bucket drip irrigation, according to Wilson and Zoldoske (1997). In addition, the wetted depths and wetted diameters were ranked, in order to plot a histogram, which was then used to compare the average application depth for the designed system. The Christiansen coefficient of uniformity (CU) was calculated using the following formula: $CU = 100\%\ (1 - \sum x/mn)$, where $\sum x$ is the sum of absolute deviation from the mean (mm) of all observations; M was the mean application depth measured (mm) and n was the number of observations (catch cans). Distribution uniformity (DU) = Average low 1/4/average*100% (Camp et al. 1987).

Water use and water use efficiency (WUE)

Evapotranspiration was estimated on a cumulative Class-A Pan Evaporation installed at approximately 90 m from the experimental site. Water use was the total of the seasonal cumulative Class-A Pan evaporation, plus a few days trace of rainfall, plus/minus change in soil moisture monitored by gravimetric method (Fig. 5). Water use efficiency, in this study, is defined as the crop yield (kg) per unit of volume of water used (Sinclair et al. 1984, Howell 2001) (kg ha^{-1} m^{-3}, g mm^{-1}). Yield was measured from plant (per plant level) to whole field level (per hectare), in order to measure the effect of the drippers' position on each plant yield (g) and water use efficiency (g mm^{-1}).

Economic analysis of BDI system

Economic analysis was computed, based on investment, operation and production costs. This analysis included time and labour (gain or loss) on the treadle pumps uplifting water to fill the tank, in order to irrigate the field, compared to furrow irrigation. Time and labour saving was measured, based on time and labour in man hours which were used to irrigate, using BDI, compared to furrow irrigation, in addition to comparing it to other carry-and-irrigate methods, according to previous study findings (Kay and Brabben 2000). Water prices were recorded from the Southern Region Water Board charges in Malawi (Table 8). The net income for each treatment was computed by subtracting all the production costs from the gross incomes. All calculations were undertaken, based on a unit area of 1 ha, according to Koral and Altun (2000).

Results and discussion

Drip irrigation operation and uniformity evaluation

The average time for pumping water into the 1,300-l tank raised at 1.5 m, using the treadle pump placed 10 m away, was 14–16 min for two people and 19–22 min for one person. Irrigation, lasting 43 min, was needed to irrigate 0.02 ha. During these 43 min, the treadle pump operators were resting or doing other work. The number of times needed to fill the tank depended on the crop's water requirement and this varied with crop stage and weather in relation to all crops. The drip irrigation, powered by the treadle pump, reduced irrigation time and labour by 25%, compared to furrow irrigation that required labour throughout the 43 min. The results for BDI also show a high efficiency in relation to labour and water saving, when compared to a treadle pump alone and the carry-and-irrigate method using a watering can. Kay and Brabben (2000) reported that a treadle pump can take 4 h per day or 20 h per week irrigating such an area, whilst the carry-and-irrigate method only covers a reduced area, over the same time period achieved by a treadle pump (such as the one above).

Christiansen coefficient and distribution uniformity analysis

The Christiansen coefficient of uniformity (CU) and the distribution uniformity (DU), for the designed BDI system, was 96 and 80% for application depth and 99 and 84% for wetted diameter, respectively (Table 1). Neither the CU nor the DU was poor, in regards to uniform distribution, according to Keller and Bleisner (1990) recommendations and classification of CU and DU. In most cases, distribution uniformity varies according to crop responses and purposes. Keller and Bleisner (1990) recommended CU > 85% for delicate crops and CU 75–83% for deep rooted crops and values of DU < 60% and CU < 75% appear to be low for such crops. This suggests that the designed bucket drip irrigation (powered by treadle pump) was adequate and it could be recommended for delicate and high-value crops.

The average application depth and wetted diameter for the system were 1.93 and 2.92 cm (Table 1, Fig. 3), and from the 180 samples, seventy-four application depths and 93 wetted diameters were above average. Thirty irrigation depths and 23 wetted diameters were equal to the average depth. Only 76 application depths and 64 wetted diameters were below the average depth (Figs. 3, 4). This means that 67% of irrigated spots were being over-wetted, 29% were being irrigated within the average depth and only 4% of the drippers' positions were under irrigated. This supports the DU and CU findings that a BDI powered by a treadle pump design is adequate, since many more wet spots can be obtained, than dry spots in the field. The rate of uniformity also counteracts the problem of water use efficiency at household level. The results of DU and CU also show that BDI can efficiently ensure that crops receive adequate water and it reduces water and nutrient loss, due to deep percolation. Apparently, a correct irrigation system design and management is the key to uniformity within an irrigation system (Hassan 1998) and farmers can, therefore, optimise such a performance from their irrigation system, through proper maintenance and management. A lack of optimising these variables may reduce system efficiency and uniformity, in due course (Wilson and Zoldoske 1997).

Relationship of wetted diameter and wetted depth to drip positions and crop yields

The correlation analysis results between wetted diameter, wetted depth and crop yield per dripper position deviating from the mainline show that application depth did not correlate with the drippers 'positions, whether they were close to the mainline or placed at the far end, as explained by the linear regression equations: wetted diameter $= -0.2188x + 26.921$, $R^2 = 0.15$, wetted depth $= -0.004x + 23.282$ ($R^2 = 0.0001$). In addition, there was no correlation between crop yields per dripper, since they deviated from the mainline with wetted diameter or wetted depth (Fig. 4), as expressed by the equations: for wetted depth $Y = 3.2072x + 717.93$ ($R^2 = 0.001$) and for wetted diameter $Y = 9.0126x + 570.38$ ($R^2 = 0.008$). These results support the results of high distribution uniformity above. They show that uneven crop yields and application depths, which may arise, are not necessarily due to a system design problem but possibly due to the clogging of individual emitters, in latter days (Figs. 3, 4).

These insignificant correlations also show that the design did not cause pressure variation, but it resulted in uniform water distribution and uniform yield. The actual wetted depth was greater than the designed net irrigation depth of 10.8 mm day^{-1} and that of the gross irrigation depth of 12 mm day^{-1}, which shows that the water head of 1.5 m was sufficient to irrigate more than 0.02 ha (Figs. 1, 2) with a tank of 1,300 l. High uniformity contributed to healthy plants and efficient water use within the system. This indicates that the design and management of the system was very adequate and fundamental to application efficiency and irrigation uniformity. Our results agree with findings of researchers in other regions, who used a trickle irrigation system (Alva et al. 1999; Fares and Alva 2000; Zotarelli et al. 2009a, b) and somewhat higher than those obtained by Martin et al. (1999).

Tomato yield response to BDI system

Tomato yields and water use efficiency (WUE), which were assessed through the use of two irrigation systems

Table 1 Christiansen coefficient of uniformity (CU) and distribution uniformity (DU) for designed bucket drip irrigation

Observations	Application depth (cm)		Wetted diameter (cm)	
	CU	DU	CU	DU
Number of observations (n)	180	45	180	45
Mean application (M) depth/diameter (mm)	1.93	1.52	2.92	2.46
Uniformity (%)	96	83	99	84

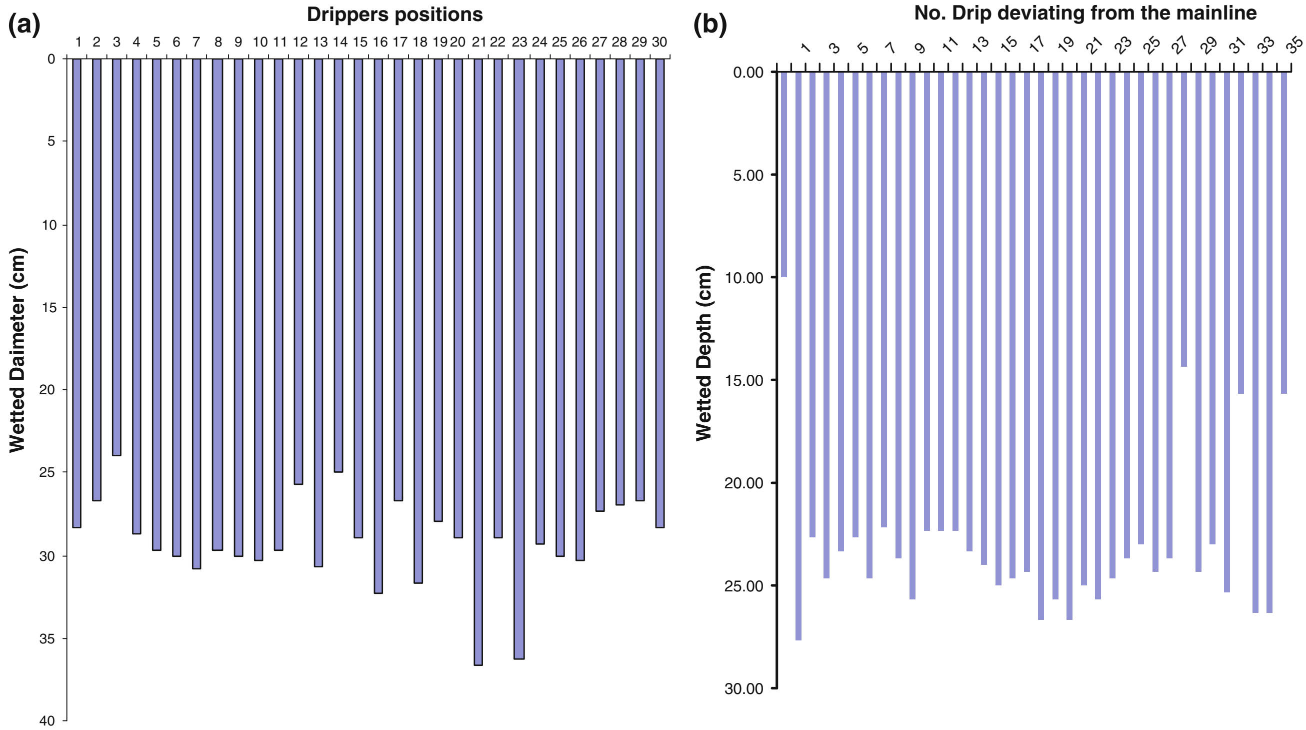

Fig. 3 **a** Wetted diameter for drippers as they deviate from the mainline. **b** Wetted depth for drippers deviating from the mainline

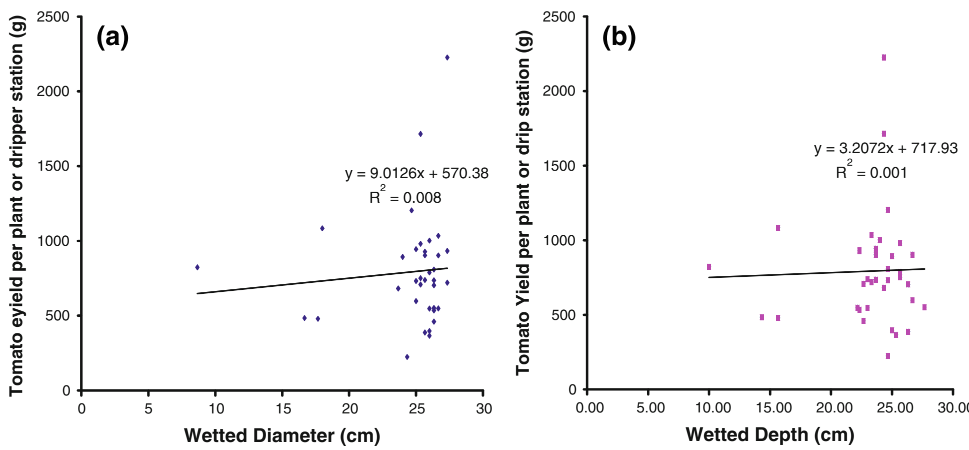

Fig. 4 **a** Correlation between plant yield per dripper and wetted diameter. **b** Correlation between plant yield per dripper and wetted depth

Table 2 Tomato yield t ha^{-1} and water use efficiency (kg ha^{-1} m^{-3}) under drip irrigation in 2005

Variety	Rep	First harvest (t ha^{-1})	Second harvest (t ha^{-1})	Third harvest (t ha^{-1})	Fourth harvest (t ha^{-1})	Total yield (t ha^{-1})	Water use (m^{-3})	WUE (kg ha^{-1} m^{-3})
Money maker	1	17.1	13.6	12.5	17.7	60.9	3,020	20.2
Money maker	2	14.4	13.6	13.9	15.7	57.6	3,020	19.1
Money maker	3	14.3	19.1	16.2	13.4	63.0	3,020	20.9
Mean		15.3	15.4	13.2	15.6	60.3	3,020	20.1
Rodade	1	20.4	29.8	28.0	24.9	103.1	3,020	34.1
Rodade	2	14.6	16.0	9.7	23.6	63.9	3,020	21.2
Rodade	3	14.6	25.6	17.7	11.8	69.7	3,020	23.1
Mean		16.5	23.8	18.4	20.1	78.9	3,020	26.1

Rep replicate, *WUE* Water use efficiency

Table 3 Tomato WUE ($g\ mm^{-1}$) at plant level for drip-irrigated Moneymaker

Plant no.	Tomato yield per plant (g)	Seasonal irrigation (mm)	Water use (mm)	Water use efficiency ($g\ mm^{-1}$)
1	823.49	335.5	302	2.73
2	551.70	335.5	302	1.83
3	708.10	335.5	302	2.34
4	808.41	335.5	302	2.68
5	1,033.78	335.5	302	3.42
6	460.10	335.5	302	1.52
7	224.36	335.5	302	0.74
8	548.50	335.5	302	1.82
9	944.87	335.5	302	3.13
10	788.38	335.5	302	2.61
11	928.21	335.5	302	3.07
12	933.02	335.5	302	3.09
13	535.38	335.5	302	1.77
14	720.55	335.5	302	2.39
15	1,002.00	335.5	302	3.32
16	397.10	335.5	302	1.31
17	1,204.39	335.5	302	3.99
18	682.30	335.5	302	2.26
Mean				2.45

Table 4 Tomato water use and WUE ($g\ mm^{-1}$) at plant level for drip-irrigated Rodade

Plant no.	Tomato yield per plant (g)	Seasonal irrigation (mm)	Water Use (mm)	Water use efficiency ($g\ mm^{-1}$)
1	953.45	335.5	302	3.16
2	606.00	335.5	302	2.01
3	905.40	335.5	302	3.00
4	938.60	335.5	302	3.11
5	1,443.76	335.5	302	4.78
6	671.00	335.5	302	2.22
7	804.20	335.5	302	2.66
8	520.94	335.5	302	1.72
9	1,143.80	335.5	302	3.79
10	1,181.80	335.5	302	3.91
11	864.46	335.5	302	2.86
12	1,074.10	335.5	302	3.56
13	1,348.10	335.5	302	4.46
14	947.15	335.5	302	3.14
15	835.36	335.5	302	2.77
16	1,238.50	335.5	302	4.10
17	1,592.35	335.5	302	5.27
18	1,242.10	335.5	302	4.11
Mean				3.37

(Tables 2, 3, 4; Fig. 5), show that there were differences in yields between tomato varieties and irrigation systems. The average marketable yield for Moneymaker was 60.3 $t\ ha^{-1}$ and for Rodade was 78.9 $t\ ha^{-1}$. This shows that production under BDI can vary with varieties and high yields can be realised by selection of a high yielding variety, in order to earn higher profits. These findings are consistent with marketable fruit yields reported by Cetin et al. (2002) Surface irrigation reported average yields of 32.0 and 48.1 $t\ ha^{-1}$, with an average WUE of 10.7 $kg\ ha^{-1}\ m^{-3}$

for Moneymaker and Rodade, respectively (Tables 3, 4, 5). Yield and WUE for BDI tomato were higher than those with surface irrigation. The yields and WUE realised in this study were lower than those reported by Çevik (1977, 1978) and also those reported by Cetin and Uygan (2008), being 63.8–136.2 t ha^{-1} and WUE of 14.3–25.8 kg ha^{-1} m^{3} under drip irrigation.

The yield for this study was lower, compared to other findings (Cevik 1978; Cetin and Uygan 2008), which would be either due to climatic factors, management practices (fertiliser levels) and/or differences in the crop variety planted. However, the experimental WUEs found in the study were higher than those obtained in other studies by Kauta and Kadwa (1994), who reported their highest yields being 84 and 39 t ha^{-1} in 1993 and 1994, respectively, at 120% ET water level at the same site. The results for Kauta and Kadwa (1994) suggest that increased yield, under a surface irrigation system, could be achieved by water increments, unlike the findings under BDI. Kauta and Kadwa (1994), who reported that a reduced water application under surface irrigation (to 20% ET) resulted in the lowest tomato yields of 59 and 19 t ha^{-1} in 1993 and 1994, respectively.

In a world study, tomato yields under drip irrigation registered above 48 t ha^{-1} and above 32 t ha^{-1} obtained under surface irrigation (Jadhaw et al. 1990). In general, BDI increased tomato yields and WUE, compared to surface irrigation, which is in line with world findings on the conventional drip irrigation system (Cetin et al. 2002; Keller and Karmeli 1974). However, the irrigation schedule (every 4 days using a coefficient of 1.00 as recommended by Cetin et al. (2002) worked well for the Shire valley region in Malawi. Further research on irrigation scheduling will be required on tomato (for this region).

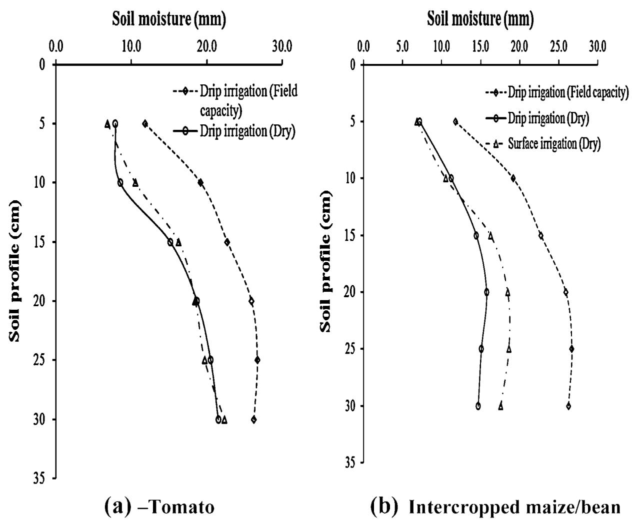

Fig. 5 Change in stored soil water before next irrigation in tomato and intercropped maize/bean system under drip and surface irrigation **a** Tomato **b** Intercropped maize/bean

Table 6 WUE (kg ha^{-1} m^{3}) of maize/bean intercrop under drip and surface irrigation

Treatment Code	Treatments	Drip irrigation Maize	Drip irrigation Beans	Surface irrigation Maize	Surface irrigation Beans
B1	NASAKA		0.55		0.20
B2	KALIMA		0.83		0.22
M1	DK8031	4.88		1.54	
M1b1	NASAKA + DK8031	3.92	0.55	1.34	0.18
M1B2	KALIMA + DK8031	4.22	0.53	1.40	0.20

Table 5 Yield response of intercropped maize–bean crops to BDI fed by Treadle pump at Kasinthula Research Station, 2006–2007

Code	Treatments	Bucket drip irrigation				Surface irrigation	
		2006		2007		2007	
		Maize yield t ha^{-1}	Bean yield t ha^{-1}	Maize yield t ha^{-1}	Bean yield t ha^{-1}	Maize yield t ha^{-1}	Bean yield t ha^{-1}
B_1	Nasaka		0.74 b		1.43		0.72
B_2	Kalima		0.95 a		1.22		0.81
M_1	DK8031	6.89 a		5.78		5.48	
M_1B_1	Nasaka + DK8031	5.30 b	0.72 b	4.91	0.72	4.80	0.64
M_1B_2	Kalima + DK8031	5.66 ab	0.77 b	5.32	0.61	4.98	0.71
CV	Cv. (%)	22.32	13.5	17.5	17.5		
Sig.	Sign.	***	***	NS	NS		
Mean	$LSD_{0.05}$	1.50	0.16	0.70	0.17		

Bean price = MK250 kg^{-1}

Maize = MK40 kg^{-1}, 2007–2008

*** refers to $P < 0.0001$

Table 7 Effect of dripper positions and maize/bean intercropping on drip-irrigated maize grain yields and WUE

Plant no.	Grain yield per dripper (g)			I (mm)	WU (mm)	Crop water productivity (g mm^{-1})			Irrigation use efficiency (g mm^{-1})		
	S	S + N	S + K			S	S + N	S + K	S	S + N	S + K
1	59.2	20.1	26.7	390.1	260	0.15	0.05	0.07	0.23	0.08	0.10
2	47.5	16.5	22.0	390.1	260	0.12	0.04	0.06	0.18	0.06	0.08
3	54.2	19.1	25.4	390.1	260	0.14	0.05	0.07	0.21	0.07	0.10
4	35.6	13.2	17.6	390.1	260	0.09	0.03	0.05	0.14	0.05	0.07
5	80.9	28.6	38.2	390.1	260	0.21	0.07	0.10	0.31	0.11	0.15
6	43.1	16.4	21.8	390.1	260	0.11	0.04	0.06	0.17	0.06	0.08
7	68.6	25.2	33.6	390.1	260	0.18	0.06	0.09	0.26	0.10	0.13
8	52.5	20.2	26.9	390.1	260	0.13	0.05	0.07	0.20	0.08	0.10
9	64.2	24.4	32.5	390.1	260	0.16	0.06	0.08	0.25	0.09	0.13
10	59.3	23.1	30.8	390.1	260	0.15	0.06	0.08	0.23	0.09	0.12
11	12.7	7.9	10.6	390.1	260	0.03	0.02	0.03	0.05	0.03	0.04
12	54.4	22.1	29.5	390.1	260	0.14	0.06	0.08	0.21	0.09	0.11
13	69.7	27.6	36.8	390.1	260	0.18	0.07	0.09	0.27	0.11	0.14
14	58.0	24.0	32.0	390.1	260	0.15	0.06	0.08	0.22	0.09	0.12
15	83.9	33.0	44.0	390.1	260	0.22	0.08	0.11	0.32	0.13	0.17
16	55.6	23.9	31.8	390.1	260	0.14	0.06	0.08	0.21	0.09	0.12
17	65.4	27.5	36.6	390.1	260	0.17	0.07	0.09	0.25	0.11	0.14
18	60.7	26.2	35.0	390.1	260	0.16	0.07	0.09	0.23	0.10	0.13
19	101.0	40.0	53.3	390.1	260	0.26	0.10	0.14	0.39	0.15	0.21
20	74.7	31.6	42.1	390.1	260	0.19	0.08	0.11	0.29	0.12	0.16
21	81.3	34.1	45.5	390.1	260	0.21	0.09	0.12	0.31	0.13	0.17
22	40.8	20.9	27.9	390.1	260	0.10	0.05	0.07	0.16	0.08	0.11
23	53.8	25.6	34.1	390.1	260	0.14	0.07	0.09	0.21	0.10	0.13
24	54.2	26.1	34.8	390.1	260	0.14	0.07	0.09	0.21	0.10	0.13
25	60.0	28.3	37.8	390.1	260	0.15	0.07	0.10	0.23	0.11	0.15
26	72.3	32.8	43.7	390.1	260	0.19	0.08	0.11	0.28	0.13	0.17
27	77.8	34.9	46.6	390.1	260	0.20	0.09	0.12	0.30	0.13	0.18
28	62.0	30.0	40.0	390.1	260	0.16	0.08	0.10	0.24	0.12	0.15
29	55.0	28.0	37.4	390.1	260	0.14	0.07	0.10	0.21	0.11	0.14
30	81.8	37.3	49.7	390.1	260	0.21	0.10	0.13	0.31	0.14	0.19
Mean	61.3	25.6	34.2	390.1	260	0.16	0.07	0.09	0.24	0.10	0.13

I irrigation (mm); *WU* water use (mm), *S* = SC403 maize variety; *K* = Kalima bean variety; *N* = Nasaka bean variety

Intercropped maize/bean response to BDI system

Maize/bean yields were highly and significantly different ($P < 0.001$), both in monoculture and mixed cropping treatments. Monocropped maize (6.9, 5.78 t ha^{-1}) and monocropped beans (0.95, 1.43 t ha^{-1}) outweighed intercropped maize/bean yields (Tables 5, 6, 7). The yields for the Kalima bean variety significantly ($P < 0.001$) outyielded the Nasaka variety (in 2006 and vice versa in 2007) under both cropping systems. The results show the existence of interspecific competition in the mixed cropping system, as reported by Barak (1986), under surface irrigation at the same site. Barak (1986) reported competition amongst maize/bean yields mixed cropping, under surface irrigation. In 2006, bean yield levels were very low in both mixed and monocropping systems, which might have been affected by high vapour pressure or high leaf evapotranspiration in hot weather, compared to 2007. Despite interspecific competition under the intercropped maize/bean system, their combined yields were significantly higher than monocropped beans and maize, which implied a high gross margin and profits.

The results of the intercropped maize/bean system show that it is recommended to intercrop maize/bean, in order to gain high profits under drip irrigation, rather than monocropping (Table 5). Proper use of BDI can help improve maize yields and WUE to levels reported in Turkey (Yazzar et al. 2002), which ranged from 7.2 to 11.3 t ha^{-1} with WUE of 1.94–2.27 m^3 under drip irrigation. Despite this being lower, compared to other parts of the world,

Table 8 Economic analysis and results for the treatments

Treatments	Amount of irrigation water (mm) (1[a])	Irrigation water (m^3 ha^{-1}) (2[a])	Irrigation duration for the irrigation season (h) (3[a])	Labour cost for irrigation (MK h^{-1}) (4[a])	Total cost for irrigation labour (MK) (5 (3 × 4)[a])	Water price (MK m^{-3}) (6[a])	Water cost (MK ha^{-1}) (7 (2 × 6)[a])	Crop production costs (MK ha^{-1}) (8[a])
Rodade	302	3,020	88	29.33	2,582.04	7.42	22,408	234,000
Money Maker	302	3,020	88	29.33	2,582.04	7.42	22,408	234,000
Nasaka	390	3,900	114	29.33	3,343.62	7.42	28,938	113,500
Kalima	390	3,900	114	29.33	3,343.62	7.42	28,938	113,500
DK8031	390	3,900	114	29.33	3,343.62	7.42	28,938	76,825
Nasaka + DK8031	390	3,900	114	29.33	3,343.62	7.42	28,938	113,825
Kalima + DK8031	390	3,900	114	29.33	3,343.62	7.42	28,938	113,825

Treatments	Irrigation system cost for 1 ha (MK ha^{-1}) (9[a])	Yearly cost of irrigation system (MK ha^{-1}) (10 (9/7 years)[a])	Total cost for one year (MK ha^{-1}) (11 (5 + 7 + 8 + 10)[a])	Yield (t ha^{-1}) (12[a])	Tomato/maize/bean sale price (MK kg^{-1}) (13[a])	Gross income per ha (MK ha^{-1} $year^{-1}$) (14 (12 × 13)[a])	Net income (MK ha^{-1} $year^{-1}$) (15 (14 − 11)[a])
Rodade	700,000	100,000	358,990.44	60.3	25	1,507,500	1,148,509.56
Money maker	700,000	100,000	358,990.44	78.9	25	1,972,500	1,613,509.56
Nasaka	700,000	100,000	245,781.62	1.083	250	270,750	24,968.38
Kalima	700,000	100,000	245,781.62	1.085	250	271,250	25,468.38
DK8031	700,000	100,000	209,106.62	6.34	40	253,600	44,493.38
Nasaka + DK8031	700,000	100,000	246,106.62	0.72 + 5.11	40/250	290,800	44,693.38
Kalima + DK8031	700,000	100,000	246,106.62	0.6975 + 5.49	40/250	303,240	57,133.38

[a] Column numbers

The irrigation water pricing was MK7.42 m^{-3} for a household (1 US Dollar = 140.930 Malawi Kwacha, MK) these yields were found to be higher (15–23%), compared to surface irrigation, carry-and-irrigate and treadle pump systems. Our current average intercropped maize/bean yields are 4.8 t ha^{-1} and 641 kg ha^{-1} under surface irrigation (Malawi government 2006), which are comparatively lower than the yields realised under BDI experiments/both in 2006 and 2007. The research results also reveal that BDI can be used for maize/bean production under the prevailing climatic conditions in Malawi.

The bucket drip irrigation system improved yields and water use efficiency in maize and beans without consideration of investment costs. In addition, the results obtained by other researchers, in relation to drip-irrigated corn (Payero et al. 2008), show that the relationship obtained between crop performance indicators and seasonal basis can be valuable for the making of tactical in-season irrigation management decisions and also for strategic irrigation planning and management.

Economic analysis for BDI powered by treadle pump

The production costs were computed by considering all production inputs (i.e. cost of seeds, plowing of land, transplanting, hoeing, pesticides, fertilisers, harvesting, etc.) for tomato, maize and bean growth, within the study area. Thus, the seasonal production costs varied with the enterprise, except for the labour costs, water charges and the investment cost of the drip irrigation system, which was estimated at US$5,000 per ha, with a life period of 7 years (Enciso et al. 2005). The cost of the drip irrigation system, per ha computed, was relatively high, due to the use of compensating emitters. These costs were calculated for high-quality systems and include treadle pumps, filters, mainlines, manifolds and emitters, which are not readily available in the region.

According to the calculation and evaluation, the maximum net income obtained was US$11,525 ha^{-1} (Table 8) for the Moneymaker tomato variety. It can be noted that there was a significant difference in terms of net income between the crop enterprises. On the one hand, both tomato varieties resulted in significant net income, compared to maize and beans and an intercropped maize/bean cropping system, which had a low positive net income (Table 8). On the other hand, the cost per ha expenditure was expensive for the bucket drip irrigation system. However, initial investment costs can be amortised over the expected lifespan of a drip system fed by treadle pump. In fact, the financial net returns were both positive and relatively high for tomatoes. This finding supports the FAO (1966) report that gross margins for vegetables in Malawi are comparatively more profitable than that for maize and bean. For that reason, the use of a bucket drip irrigation system for highly valued crops, such as tomatoes, is strongly recommended, due to the significant increase in yield being reported in this study.

Conclusion and recommendations

This study evaluated the effect of a bucket drip irrigation powered by treadle pump, for tomato and intercropped maize/bean, on yields and income, water use efficiency and application uniformity, during the dry seasons of 2005, 2006 and 2007, in comparison with furrow irrigation. The BDI systems reduced irrigation time and labour by 25%, in all these years, compared to furrow irrigation and treadle pump alone, or carry-and-irrigate systems. The Christiansen coefficient of uniformity (CU) and the distribution uniformity (DU) for application depth and wetted diameter show that the locally designed BDI was adequate and it is, therefore, recommended for high-value crops that require high DU of 85% and CU of 75–83% and deep rooted crops that require DU $< 60\%$ and CU $< 75\%$.

The average marketable yields and WUE for the tomato and intercropped maize/bean crops show that they were higher, through using BDI, rather than the furrow irrigation system. Tomato produced more net income, compared to maize and bean and the intercropped maize/bean crop. It can be concluded that a BDI (designed with a water head of 1.5 m) can save water and labour, whilst at the same time, increasing crop water productivity and also that tomato (as a high-value crop) is more suitable for the BDI system, rather than maize and bean crops, in Malawi.

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References

Allen RA, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements (FAO irrigation and drainage paper 56). FAO, Rome

Alva AK, Prakash A, Hornsby A, Fares A (1999) Distribution of rainfall and soil moisture content in soil profile under citrus tree canopy and dripline. Irrig Sci 18:109–115

André RGB, Churata-Masca MGC (1992) Water requirement and crop coefficient for processing tomatoes. Acta Hortic (ISHS) 301:165–170 http://www.actahort.org/books/301/301_18.htm

Barak E (1986) In-service training irrigation research project. December 1981 to November. Final activity available: ministry of agriculture. Department of Agriculture Research, Malawi

Burt CM, O'Connor K, Ruehr T (1995) Fertigation, California polytechnic state university. Order from: the irrigation training and research center, California polytechnic state university (Cal Poly). San Luis Obispo, California

Camp CR, Sadler EJ, Busscher WJ (1987) A comparison of uniformity measures for drip irrigation systems. Trans ASAE 40(4):1013–1020

Cetin O, Uygan D (2008) The effect of drip line spacing, irrigation regimes and planting geometries of tomato on yield, irrigation water use efficiency and net return. Agric Water Manage 95(8):949–958

Cetin O, Yildirim O, Uygan D, Boyaci H (2002) Irrigation scheduling of drip irrigated tomato using class A pan evaporation. Turk J Agric For 26:171–178 TUB/TAK

Cevik B (1978) The effect of trickle irrigation method applied to different textured soils in greenhouse on the yield, quality and earliness of tomatoes under Çukurova conditions. Yearbook of Çukurova University of Agriculture Faculty, Adana, Turkey. No 9(8), 204–218

Çevik B (1977) A research on selection of most suitable irrigation methods for tomato growth under greenhouse conditions in Çukurova. Department of Irrigation and Drainage, Agricultural Faculty, Çukurova University, Adana, 124 p

Chanson B, Schwankl L, Grattan S, Prichard T (1994) Drip irrigation for row crops. University of California, Davis. Order from Cooperative Extension office, Department of LAWR, 113 Veihmeyer Hall, University of California, Davis

Enciso JM, Coloaizzi PD, Multer WL (2005) Economic analysis of subsurface drip irrigation lateral spacing and installation depth for cotton. Trans ASAE 48(1):197–204

Fandika IR, Burgess P (2008) Comparative response of irrigated maize to organic and inorganic fertilizer at Kasinthula Research Station in Malawi. In: Nhira C, Mapiki A, Rankhumise P (eds) In land and water management for the Southern Africa: towards sustainable agriculture. Chapter 17. RSA, Pretoria, pp 216–236

FAO (1966) Water development for food security, irrigation technology transfer to East and Southern Africa. Irrigation economist,- Tanzania, Malawi, Zambia, Zimbabwe, by K. Palanisami, Water development management services, land and water development division, Rome July, 1996

Fares A, Alva AK (2000) Evaluation of capacitance probes for optimal irrigation of citrus through soil moisture monitoring in an Entisol profile. Irrig Sci 19:57–64

Goldberg D, Gornat B, Rimon D (1976) Drip irrigation. Drip Irrigation Scientific Publications, Kfar Shmaryahu, 296 p

Hassan FA (1998) Microirrigation management and maintenance, agro industrial management. Fresno, California, p 233

Howell T (2001) Enhancing water use efficiency in irrigated agriculture. Agron J 19:281–289

Jadhaw SS, Gutal GB, Chougule AA (1990) Cost economies of the drip irrigation system for tomatoes crop. Department of agricultural engineering, college of agriculture, Pune

Kabutha C, Blank H, van Koppen B (2000) Drip irrigation kits for small-holder farmers in Kenya: experience and way forward. In: 6th international microirrigation congress, South Africa. 22–27 Oct 2000

Kadyampakeni D, Mangisoni JH, Singa DD, Mloza-Banda HR, Ferguson A, Snapp S, Mwendo-Phiri E (2004) Impact of irrigated and water management practices on bean production in Chingale area development programme, Zomba, Malawi. East African Journal of Rural Development, Msc Thesis

Kaluwa PWR, Mtambo FM, Fatch R (1997) The country situation report on water resources in Malawi. UNDP/SADC Water Initiative

Kauta GJC, Kadwa FE (1994) Yield response to water. A paper presented at the soils and agricultural engineering group project meeting, August, 1994, Chitedze Agricultural Research station, Lilongwe, Malawi

Kay M, Brabben T (2000) Treadle pumps for irrigation in Africa. International programme for technology and research in irrigation and drainage. Knowledge synthesis report No 1, Oct 2001, ISSN 1607-6613

Keller J, Bleisner RD (1990) Sprinkler and trickle irrigation. Chapman and Hall. Republished by Blackburn Press, Nov 2000, ISBN 1-930665-19-9

Keller J, Karmeli D (1974) Trickle irrigation design for optimal soil wetting. Proceedings of II International Drip Irrigation Congress 7–14 July 1974, San Diego, California, USA

Koral AI, Altun A (2000) The production inputs guidelines of agricultural products in Turkiye. The General Directorate of Rural Services Publications, No: 104, Ankara, pp 360

Malawi Government (2006) Guide to agriculture production manual. Ministry of Agriculture, Lilongwe

Mangison JH (2006) Impact of treadle pump irrigation technology on smallholder poverty and food security in Malawi. A case study of Blantyre and Mchinji District report to IWMI Southern Africa Sub-Region Office. Pretoria, RSA. http://treadle-pump.com/download/Malawi%20Treadle%20Pump.pdf

Martin EC, Obermyer KC, Pegelow FJ, Sheedy M, Ditmar S (1999) Effects of high frequency irrigation on irrigation uniformity. In: COTTON. A College of Agriculture Report. The University of Arizona. Series P-116, Pub. AZ1123

Maweru SCY (2004) Current initiatives on micro-irrigation and smallholder markets in Malawi. In: Mangisoni JH (ed) Proceedings of stakeholders experience and lesson sharing workshop on small scale irrigation and market development. Malawi Institute of Management, Lilongwe, pp 19–24

Ministry of Agriculture and irrigation (2003) Simple priority Irrigation programs, Lilongwe, Malawi

Mzembe CP (1994) Overview of irrigation development in Malawi. Ministry of Agriculture and Irrigation, Lilongwe

Nir D (1982) Drip irrigation. In: Finkel HJ (ed) Handbook of irrigation technology, vol 1. CRC Press, Boca Raton, pp 247–298

Payero JO, Tarkalson DD, Irmak S, Davison D, Petersen JL (2008) Effects of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in semiarid climate. Agric Water Manage 95:895–908

Shock CC (2006) Drip irrigation: an introduction. EM8782. In: sustainable agricultural technique. Oregon State University, USA

Sinclair TR, Tanner CB, Bennet JM (1984) Water use efficiency in crop production. Bioscience 34:34–40

Van der Gulik BC (1999) BC trickle irrigation manual. Ministry of agriculture and food resource management branch. Order from irrigation association of British Columbia, Abbotsford

Wilson TP, Zoldoske DF (1997) Evaluation of sprinkler irrigation uniformity. Department of Water Resources, California CATI Publication #970703

Yazzar A, Sezen SM, Gencel B (2002) Drip irrigation of corn in Southeast Anatalia Project (GAP) area in Turkey. Irrig Drain 51:293–300

Zotarelli L, Scholberg JM, Dukes MD, Muñoz-Carpena R, Icerman I (2009a) Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil as affected by nitrogen rate and irrigation scheduling. Agric Water Manage 96:23–34

Zotarelli L, Dukes MD, Scholberg JM, Muñoz-Carpena R, Icerman I (2009b) Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, affected by nitrogen rate and irrigation scheduling. Agric Water Manage 96:1247–1258