INCREASING THE WATER USE EFFICIENCY AND CROP YIELD UNDER SALINE CONDITIONS USING LOW-PRESSURE DRIP IRRIGATION AND METEOROLOGICAL DATA

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FINAL REPORT

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A) EXECUTIVE SUMMARY

Over-irrigation, increasing soil salinity and recurrent droughts has led to a significant decline in crop productivity in the Accra Plains of Ghana, threatening farmers' livelihoods and food security. This project aimed to investigate a potential tool for reversing this trend – low-pressure drip (LPD) irrigation – testing its effects on the water and salt regime in the soil, and to improve irrigation scheduling and water use efficiency. Experiments on pepper as a test crop were carried out over three seasons at two sites in the Accra Plains and in Israel. Scientific results showed that crop water use can be accurately predicted using meteorological data. Soil water content measurements, modeling and observed plant growth led to the conclusion that LPD and high frequency drip (HFD) are indeed alternatives producing similar wetting and growth patterns that are superior to one water application per day. HFD improved the uptake efficiency of Phosphorous and Manganese. The effects of salinity on mineral uptake and yield are quantified and discussed. Fresh yield and water use efficiency were significantly higher than other reported data and a simple model is presented that predicts yield and water use in the saline treatments using data from the fresh water treatments and direct measurements of stomatal conductance.

The cooperation between both research groups has been very fruitful, involving meetings in Ghana and Israel, exchanging technical notes and sharing experimental data. A collaborator scientist and an irrigation technician were trained in Israel for few weeks. A Ghanaian PhD student was trained at ARO for 12 months. Knowledge gained in this project was disseminated through demonstration plots, workshops (in Ghana) and the publication of articles in peer-reviewed journals. The acquired equipment and know-how make the Ghanaian research group a leader in the field of LPD and enables them to independently conduct future irrigation experiments, such as the new wind-pump, low pressure-drip irrigation experiment at the village of Anloga, Ghana.

B) Research Objectives

Rationale and problem identification

Crop production in the costal savannah of Ghana (2°E-0°W; 5-6°W; 50-150 m AMSL) is mainly rain-fed. However, over the last 2 decades decreasing rainfall amounts and increasing rainfall variability (Adiku and Stone, 1995) constituted and a major challenge to agricultural production in this region, to the effect that successful and sustainable rain-fed production are no longer guaranteed. In the late 1960's, the Ghana Irrigation Development Authority GIDA embarked on irrigation projects at various sites, however progress in the conversion of rain-fed to irrigated agricultural land has been rather slow, only 0.2% of all cultivated land was irrigated some 20 years later (Ministry of Agriculture, 1991).

Today, the existing surface irrigation schemes in Ghana – such as the 130 ha Ashaiman project in the Accra Plains – are characterized by a number of drawbacks: Firstly, water management is generally poor, from the main canal down to the tertiary canal level, aggravated by poor in-farm water management caused by the lack of farmers' knowledge and understanding. The overall project efficiency is thus rated at 45%. It follows that, secondly, the irrigated area is less than half of its full potential given the limited amount of water available. And thirdly, in the past few years, crop productivity has severely declined, mainly as a consequence of over-irrigation with the inefficient flooding technique and the use of saline water, leading to an increase in root zone salinity causing reduced crop growth.

The only alternative irrigation method that has been tested at Ashaiman so far was in 1993 by Dr. Agodzo and comprised the buried pot micro-irrigation or pitcher system (Agodzo et al., 1991), but this system might be more suitable to greenhouse production. In order to address today's challenges with regard to irrigation development, an irrigation system is required, that provides the benefits of efficient drip irrigation but at the same time has low capital and energy requirements and is oriented towards small-scale farmer management, is easy to operate and gives growers the flexibility to alter their production according to market demand. The system should also be sustainable and ensure minimum deterioration of the soil quality.

Aim and objectives

The overall scientific aim of this project is to evaluate low pressure/high frequency drip irrigation (LPD/HFD) and improved methods of crop water requirement estimation and to incorporate them into irrigation development programs in Ghana with a view to increasing (i) the water use efficiency and crop yield, (ii) the efficiency of salt leaching and (iii) the income of poor farmers and their quality of life.

The scientific objectives of the project are to:

1. Investigate the effects of LPD/HFD irrigation on water and salt regime, water use efficiency, and salt leaching.
2. Improve the evaluation of crop water requirements under saline conditions using meteorological data.
3. Determine the feasibility of increasing crop yield using LPD irrigation and meteorological data in irrigated sites in the semi-arid regions of Ghana.

Innovative aspects and organizational support

In Ghana, low-pressure drip irrigation is new and its effect on the water and salt regime in the root zone has not yet been studied scientifically. Some observations have been carried out recently in greenhouses. However, no comprehensive investigation of the system in vegetable crops under field conditions is yet available. Combining this relatively efficient low-cost technology and a better evaluation method for crop water requirements should enhance crop productivity on a sustainable basis. Using a crop modeling approach, the results can be extrapolated to other places in the world with similar climate and soil conditions.

In Israel, the innovative aspects of this project comprise a comparison between the water and salt regime under low-pressure and high-frequency drip irrigation in order to establish whether they are alternatives leading to similar results. Additional emphasis was on establishing the effects of irrigation frequency, salinity and water amounts on mineral uptake and crop production. The Israeli part of this project is thus expanding more recent findings by Son and Oh (2003) and Katsoulas et al. (2006) on the effects of irrigation frequency to the commercially important sweet pepper crop grown under protective shading screens in an arid climate.

The main cooperating organization of this project was the University of Ghana (UG) through the co-principal investigators: Prof. SGK Adiku (UG). The Ghana Irrigation Development Authority GIDA through Mr. Akagbor (GIDA), was also involved. The support of the GIDA was important with regard to reaching out and disseminating the gained knowledge to the farming community in the project area.

C) Methods and Results

Materials and methods - Israel

In Israel, field experiments were conducted during three years (2003-2005) at the Volcani Center, Bet Dagan (31°59'N, 34°49'E, 40 m a.m.s.l.) and the Besor Experimental Station (31°16'N, 34°24'E, 75 m a.m.s.l.). Sweet pepper (*Capsicum annuum L.*) was grown in a screenhouse (black shading screen) using different growing media and various irrigation and salinity regimes (Table 1).

Table 1. Summary of experimental details for the entire CDR project period and additional measurements not mentioned in the text.

Year, location	**Growing media**	**Treatments**	**Additional sensors/measurements**
2003, Bet Dagan	Coarse sand	- different drip emitter flow rates: 0.5; 2.0; 4.0 and 8.0 l h^{-1}	- leaf water potential (LWP)
2004, Bet Dagan	Coarse sand, synthetic perlite	- different growing media - different drip emitter flow rates: 0.5 and 2.0 l h^{-1}	- soil water content with TDR probes - drainage - evapotranspiration with lysimeters - root density distribution
2004, Besor	Loamy sand	- different irrigation frequencies: once daily and 10 times per day - different irrigation water salinities: 1.7 and 4.2 dS m^{-1} - different water amounts: 100 and 125% of ET_o	- soil chemistry at 20, 40, 60 and 80 cm depth prior to and after experiment - soil water content at 20, 40 and 60 cm depth tensiometers - mineral concentration in fruits and leaves
2005, Besor	Loamy sand	- different irrigation frequencies: once daily and 10-25 times per day - different irrigation water salinities: 1.5 and 6.0 dS m^{-1} - different water amounts: 100 and 130% of ET_o	- soil chemistry at 20, 40, 60 and 80 cm depth at harvest - soil water content at 20, 40 and 60 cm depth tensiometers - mineral concentration in fruits and leaves

Plant physiology (plant height, plant dry weight, leaf area index, stomatal conductance, total and export yield) was measured repeatedly throughout the growing seasons. Meteorological data (global radiation, wind speed, temperature and relative humidity) measured with standard sensors was recorded at 30 minute intervals in a set of data loggers. Calculated reference evapotransiration ET_o (see Allen et al., 1998) was used to determine water requirements of the sweet pepper plants free of water and salinity stress. Actual plant water uptake was measured as sap flow *SF* by means of a heat-pulse system (Cohen, 1994). All experiments were laid out in a fully randomized block design, with four to eight replicates. Results were analyzed using standard statistic procedures (e.g. analysis of variance, Duncan-Multiple Rage Test, DMRT) and software (JMP, 2002).

The temporal evolution of the soil water content was simulated using the HYDRUS-2D model (Simunek et al., 1996) for the daily and high-frequency fresh-water treatments. The size of the modeled flow domain was 0.2 m in width and 1.0 m in depth, a vertical symmetry plane perpendicular to the drip line, from the emitter to halfway the distance between the drip lines, assuming the line source wetting condition. It is assumed that the model domain has uniform soil physical properties. Vertical boundaries were assumed to be no-flow boundaries, and the lower boundary, to be a free-drainage boundary. The water application for the pulsed/high-frequency treatment was simulated assuming a continuous low wetting rate equal to the time-averaged rate of the pulsed application over an irrigation interval of 10 h. The simulation procedure thus assumes that temporal evolution of soil water content under pulsed irrigation is similar to that under LPD microdrip irrigation. Therefore, this simulation addressed two issues: (i) comparing between the soil water content dynamics during the two water application methods; (ii) checking the assumption that pulsed and LPD irrigations are alternatives.

Materials and methods - Ghana

In Ghana, three field trials were conducted. The first was in 2004 with limited success, partly due to the fact that the infrastructure was then being established. The second trial conducted from October 2004 to May 2005 was successful and the findings are reported here. The third trial conducted from late 2005 to early 2006 had to be truncated due to a severe water shortage.

Two sites were selected for the study, sites A and B. Site A which lies in the bottom slope position has heavy textured clay with drainage problems and high salinity. The non-saline site B is light textured sand lying in the middle slope position. The field size at each site was 50 × 60 m and each site had 36 plots, each measuring 10 × 4 m. Even though the study was also intended to include the traditional furrow irrigation treatment, there were design problems that would achieve true statistical randomization. So this report will not include information on these furrow trials.

Pepper plants (*Capsicum annum* cv Legon 18) were transplanted in November 2004 after the plant beds were treated with nematicides. The number of drip lines per bed was five and there were 4 replications. After establishment, fertilizer NPK was applied at 5.0 g plant^{-1}.

Water was supplied to plants under two main delivery rates: 0.8 L h^{-1} and 0.5 L h^{-1} designated as High and Low Pressures respectively. Under each pressure treatment there were three sub-treatments: 0.8, 1.0 and 1.2 ET_o. Amounts of water given also varied with plant growth stage, ranging from 0.35 ET_o, 0.7 ET_o and 1.0 ET_o for pepper growth stages 1, 2 and 3 respectively. The coefficients 0.35, 0.7 and 1.0 were stage dependent crop coefficients taken from FAO Manuals. The ET_o was estimated from CROPWAT and a seasonal value of 4 mm day^{-1} was used throughout the study.

There were 16 plants per bed (or drip line) so that each plot contained 80 plants. Six plants per plot were tagged soon after establishment and all non-destructive data were taken on these tagged plants. Crop parameters measured include plants height, stem dry weight, leaf dry weight, fruit dry weight, total dry weight and plants survival rate. For growth analysis, dry matter harvests for the saline and the non-saline sites were carried out at weeks 12 and 16 respectively. Four plants harvested from each plot were separated in the laboratory into leaves, stems and fruits for growth analysis.

For simplicity, the following acronyms were used to represent plant parameters:

H8WAT :	Plant height at 8 weeks after transplanting.
Psv14WAT:	Plant survival rate at week 14 after transplanting.
SDW:	Stem dry weight. LDW: Leaf dry weight
TDMY:	Total dry matter yield, FDW: Fruit dry weight.

Results – Israel

Figure 1 shows calculated daily crop water requirements ET_c and actual crop water use (WU) determined using lysimeter data. The results therefore test the accuracy of the ET_o model and the K_c curve for sweet pepper during the development stage (see Allen et al., 1998). It can be seen that the FAO-56 model for estimating crop water requirements satisfactorily reflects the actual conditions, i.e. the steadily increasing water demand during the plant development stage, although measured crop water use was on average 5% lower than the model forecast, particularly for values of $ET_c > 1.9$ mm day^{-1}. Modified plant development inside the screenhouse being slightly slower than in the open field and/or the growing medium, perlite, with its physical and chemical properties that are different from natural soils, are believed to be the causes of this small discrepancy between predicted and observed crop evapotranspiration.

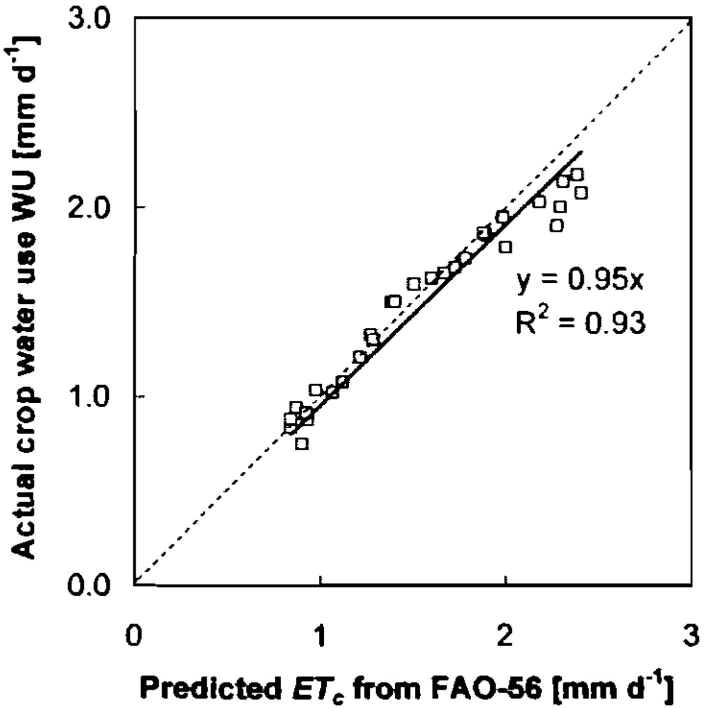

Fig. 1. Crop water use of young sweet pepper plants grown in perlite filled pots, predicted from FAO-56 (Allen et al., 1998) and measured with the lysimeter. The dotted line is the 1:1 line.

Figure 2 shows the volumetric soil water content θ measured with the tensiometer at 0.2 m depth in the daily (DI) and high frequency (HFI) treatments with freshwater at Besor in 2004. Soil water content in the active root zone of both treatments (upper 0.3 m) was high and continuously exceeded field capacity FC. Under daily irrigation DI, peak soil water content at 0.2 m depth occurred approximately 50 min after the start of irrigation. In contrast, under high frequency irrigation HFI, the local maximum of θ at 0.2 m depth was lower than in DI, but had the shape of a plateau lasting approximately 4 h, which coincided with the period of maximum plant water demand. Fig. 2 also depicts the simulated θ(t) curves for both irrigation frequencies (solid lines). The simulated θ(t) are in good agreement with those measured with the tensiometers, although some underestimation of θ occurred at night. This is due to redistribution process occurring into the root zone after plants have ceased their water uptake. This process is not accounted for in the simulation since the root system is not represented deterministically, and the uptake function varies with depth but is applied equally over the entire depth. Consequently, the soil continues to dry in the simulation while data indicate some rewetting due to redistribution before drying took place again. It can be assumed that, at the 0.2 m depth, LPD and HFI produce similar water content regimes, and can be considered as alternatives.

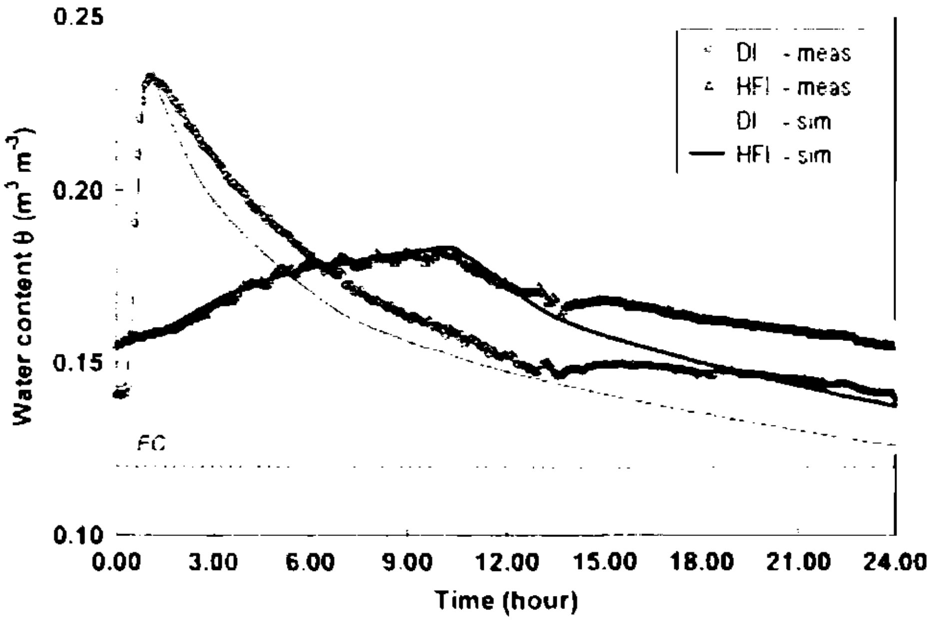

Fig. 2. Soil water content under daily *DI* and high-frequency *HFI* irrigation treatments, calculated from tensiometer measurements at the 20-cm depth using the soil water release curve after Assouline (1998), and the corresponding simulated θ(t) curves (solid lines). Irrigation commenced at $t = 0$. The dotted horizontal line is estimated field capacity, *FC*.

This is also supported by Fig. 3, which shows the total dry matter production in coarse sand 47 days after transplanting. Statistical analysis with the General Linear Models procedure (GLM)(SAS Inst., 1982) showed that the effect of the irrigation treatment on total dry matter production was highly significant ($p < 0.01$). Low discharge (0.5 l h^{-1}) and high frequency (pulse) treatments had produced very similar total dry matter of 37.5 g and 39.4 g, respectively, which was significantly higher than the control (19.1 % and 23.1 %, respectively). These figures correspond closely to the relative increases that were observed for evapotranspiration (Tab. 3), which were 18.4 % and 20.6 % higher in the low-flow and high-frequency treatments, respectively. Irrigation water use efficiencies *IWUE* (kg dry matter per m^3 water) of the low-flow and high-frequency treatments were significantly higher than in the control (Tab. 3), + 19.1 % and + 23.1 %, respectively, and reflect the increased dry matter production. It is emphasized that these increases in *IWUE* occurred even though all treatments were watered daily with drainage occurring throughout the experiment.

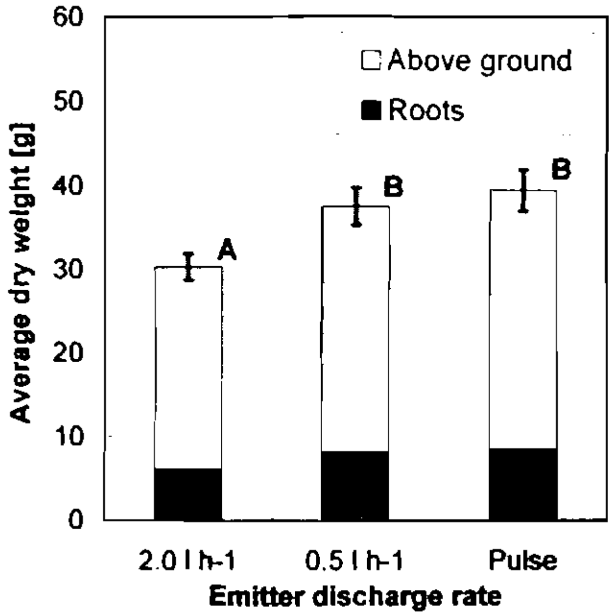

Fig. 3. Root, above ground and total dry weight under three irrigation treatments, 47 days after transplanting. Values with identical subscripts are not significantly different (Duncan's multiple range test). Bars represent two standard errors of the treatment mean.

Tab. 3. Cumulative irrigation (*I*), drainage (*D*), evapotranspiration (*ET*) and irrigation water use efficiency (*IWUE*) 47 days after transplanting. Values in brackets indicate the deviation of the low-flow and high-frequency treatments from the control. Means with the same superscript are not significantly different (results of Duncan's multiple range test). Levels of significance from the General Linear Models Procedure Type III SS (SAS Inst., 1982).

	Irrigation treatment			
	control 2.0 l h^{-1}	*low-discharge* 0.5 l h^{-1}	*high-frequency* Pulse	Significance P
I [l plant^{-1}]	33.38	33.38	33.38	n.a.
D [l plant^{-1}]	21.72	19.58 (- 9.9 %)	19.32 (- 11.1 %)	n.a.
ET [l plant^{-1}]	11.66	13.81 (+ 18.4 %)	14.06 (+ 20.6 %)	n.a.
IWUE [kg m^{-3}]	0.91^{A}	1.12^{B}	1.18^{B}	< 0.01

Table 4 shows the element concentration in young and old leaves, fruits, and in the top soil (0–40 cm). Highly significant impacts of the treatments existed on the concentration of P, Cl, Ca, and Mg in young leaves and N, P, Cl, Ca, Mg, and Mn in old leaves. The chloride level shows the effect of the salinity treatments as was also reported for field grown pepper irrigated with saline water (De Pascale et al., 2003). Leaf-Cl concentration under the HFI treatment PF100 was approximately 50% higher than under DF100. There was a strong correlation between EC_e in the upper 20 cm of the soil and the leaf-Cl concentration (R= 0.97 and 0.92 for young and old leaves, respectively, both significant at p< 0.01). High irrigation frequency (HFI treatments, designated P) increased the

Tab. 4. Concentration of selected elements in young and old leaves, in fruit dry matter, and in the 1:1 soil extract, measured on 13 October 2004. Numbers with identical superscript are not significantly different (DMRT, α= 5%). D= Daily; P= Pulses=HFI; S= Saline; F= Non-saline.

Treatment	N	P	K	Na	Cl	Ca	Mg	Fe	Zn	Mn	B
	g kg^{-1}							mg kg^{-1}			
					Young leaves						
DS_{100}	38.2	2.7^{B}	50.3	8.2	15.2^{A}	32.0^{A}	5.3^{BC}	[illegible]	44.5	[illegible]	0.18
PS_{100}	38.8	3.0^{AB}	50.3	8.1	14.4^{A}	29.4^{C}	5.0^{C}	[illegible]	65.5	127	0.19
DS_{125}	38.8	3.0^{AB}	47.4	8.1	14.5^{A}	30.8^{ABC}	5.2^{BC}	[illegible]	41.0	118	0.14
PS_{125}	37.6	3.4^{A}	53.3	8.6	15.0^{A}	30.9^{ABC}	5.1^{C}	[illegible]	37.6	134	0.16
DF_{100}	37.8	2.6^{B}	49.1	8.0	6.0^{C}	31.6^{AB}	6.0^{A}	271	65.5	103	0.16
PF_{100}	38.2	3.0^{B}	48.5	8.0	10.0^{B}	29.8^{BC}	5.8^{B}	[illegible]	[illegible]	111	0.15
$p<F$	n.s.	<0.01	n.s.	n.s.	<0.001	0.01	0.01	n.s.	n.s.	n.s.	n.s.
Significance											
EC_{iw}† (S vs. F)	n.s.	n.s.	n.s.	n.s.	<0.001	n.s.	0.001	n.s.	n.s.	n.s.	n.s.
WA (100 vs. 125)	n.s.	<0.05	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	<0.05
IF (D vs. P)	n.s.	<0.05	n.s.	n.s.	<0.05	n.s.	n.s.	n.s.	<0.05	<0.05	n.s.
					Old leaves						
DS_{100}	33.6^{C}	1.8^{C}	53.3	7.95	21.6^{A}	47.6^{B}	11.2^{A}	455	37.0	148^{BC}	0.18
PS_{100}	33.8^{C}	1.9^{BC}	51.0	8.15	22.3^{A}	47.9^{AB}	9.2^{BC}	525	56.0	167^{BC}	0.17
DS_{125}	33.0^{C}	1.8^{C}	50.3	8.24	18.8^{A}	51.1^{A}	10.7^{AB}	[illegible]	33.5	146^{BC}	0.19
PS_{125}	37.0^{A}	2.5^{A}	55.8	8.73	19.2^{A}	45.2^{BC}	8.0^{C}	[illegible]	35.6	224^{A}	0.21
DF_{100}	34.2^{BC}	1.8^{C}	55.8	9.25	9.8^{B}	45.8^{BC}	11.0^{A}	[illegible]	34.5	127^{C}	0.18
PF_{100}	36.0^{AB}	2.1^{B}	57.7	8.84	14.1^{C}	41.2^{C}	9.7^{AB}	[illegible]	32.0	192^{AB}	0.18
$p<F$	<0.01	0.001	n.s.	n.s.	0.001	0.01	<0.01	n.s.	n.s.	<0.01	n.s.
Significance											
EC_{iw}† (S vs. F)	n.s.	n.s.	n.s.	<0.05	<0.001	<0.05	n.s.	n.s.	n.s.	n.s.	n.s.
WA (100 vs. 125)	n.s.	<0.001	n.s.	n.s.	<0.05	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
IF (D vs. P)	<0.01	<0.001	n.s.	n.s.	n.s.	<0.01	0.01	n.s.	n.s.	<0.001	n.s.
					Fruit dry matter						
DS_{100}	25.6	3.54	34.6	6.8		1.2^{A}	2.0	94	36.9	19.6	
PS_{100}	28.4	4.38	36.6	6.6		1.5^{AB}	2.2	105	41.2	21.8	
DS_{125}	27.8	4.10	34.6	6.8		1.7^{B}	2.2	88	36.8	22.6	
PS_{125}	27.6	4.32	35.0	7.0		1.4^{AB}	2.0	91	36.4	25.4	
DF_{100}	27.6	3.52	40.4	7.0		1.3^{A}	2.0	93	36.2	26.4	
PF_{100}	28.8	4.16	42.6	7.4		1.7^{B}	2.1	94	34.2	25.4	
$p<F$	n.s.	n.s.	n.s.	n.s.		<0.05	n.s.	n.s.	n.s.	n.s.	
Significance											
EC_{iw}† (S vs. F)	n.s.	n.s.	<0.05	n.s.		n.s.	n.s.	n.s.	n.s.	n.s.	
WA (100 vs. 125)	n.s.	n.s.	n.s.	n.s.		n.s.	n.s.	n.s.	n.s.	n.s.	
IF (D vs. P)	n.s.	n.s.	n.s.	n.s.		n.s.	n.s.	n.s.	n.s.	<0.05	
					1:1 Soil extract						
DS_{100}		0.03	0.51^{A}	6.0^{A}	3.6^{AB}	1.8	0.6	417^{A}		55^{AB}	129
PS_{100}		0.03	0.33^{AB}	6.9^{A}	5.0^{B}	1.4	0.5	462^{A}		54^{AB}	117
DS_{125}		0.03	0.51^{A}	5.6^{A}	3.0^{AB}	1.4	0.5	357^{A}		55^{AB}	[illegible]
PS_{125}		0.02	0.30^{AB}	6.9^{A}	4.3^{B}	1.5	0.5	1749^{B}		70^{A}	115
DF_{100}		0.04	0.50^{A}	2.6^{B}	2.8^{A}	1.5	0.7	393^{A}		39^{B}	49
PF_{100}		0.03	0.21^{B}	1.5^{B}	2.8^{A}	1.7	0.9	275^{A}		41^{B}	47
$p<F$		n.s.	<0.05	<0.001	<0.01	n.s.	n.s.	<0.01		<0.05	n.s.
Significance											
EC_{iw}† (S vs. F)		n.s.	n.s.	<0.001	<0.001	n.s.	0.05	0.05		<0.05	<0.05
WA (100 vs. 125)		n.s.	n.s.	n.s.	0.05	n.s.	n.s.	0.05		<0.05	n.s.
IF (D vs. P)		n.s.	0.01	<0.05	n.s.	n.s.	n.s.	n.s.		n.s.	n.s.

† EC_{iw}, electrical conductivity of irrigation water; WA, water amount; IF, irrigation frequency.

uptake efficiency of P and Mn when compared with the once daily application (designated D treatments). These findings are in line with observations made by Xu et al. (2004) and Silber et al. (2005), who showed that P concentration in lettuce and bell pepper was directly correlated with irrigation frequency. High irrigation frequency improved the concentration of Mn in the fruits (p< 0.05). Irrigation water salinity did not have a significant impact on fruit mineral concentration, except for K, which was reduced under the saline water treatments S (p< 0.05), indicating a major interaction between soil Na and K uptake similar to the tomato crop, as reported by Adams (1991) and Adams and Ho (1995). Saline irrigation water caused significantly higher concentrations of Na, Cl, B, Fe, and Mn in the upper 40-cm soil layer, while the Mn concentration was lower in the saline treatments S. Soil K concentration was consistently lower under high frequency irrigation ($p < 0.01$) but this has apparently not affected K concentrations in leaves and fruits. Both Na and Cl concentrations in the top soil were higher ($p < 0.05$ for Na and n.s. for Cl) in the HFI treatment than under once daily irrigation.

A summary of the yield and water use efficiency *WUE* data (kg fresh yield per m^3 applied water) of the final experimental cycle (2005) is presented in Table 5. The treatments had a significant effect ($p < 0.001$) on both yield (total and export quality) and *WUE*. Salinity had a negative effect on yield and *WUE*, and differences between saline (labeled S) and non-saline treatments (labeled F) were more marked for yield of export quality than for total yield. HFI significantly improved ($p < 0.05$) total yield and *WUE*, however no such effects were observed for export yield. The increased water amount (130 *vs*. 100 % of ET_o) led to higher yield of export quality, however they also caused a lower WUE when total yield was considered. This indicates that applying more water then the scheduled amount is not advisable, since this extra amount could be used more efficiently for other agricultural activities.

Tab. 5. Summary of total yield (export and total), irrigation amounts and water use efficiency for the 8 treatments in Besor 2005. Numbers with identical superscript are not significantly different (Duncan Multiple Range Test; DMRT, $\alpha = 5\%$). A total of 11 mm of rain occurred 10 days prior to final harvest and is included in the calculation of WUE.

Treatment	Total Yield [kg m^{-2}]	St-Error [kg m^{-2}]	Irrigation [mm]	WUE [kg m^{-3}]	Export Yield [kg m^{-2}]	St-Error [kg m^{-2}]	Irrigation [mm]	WUE [kg m^{-3}]
DS_{100}	7.0^{A}	0.4	673	10.2^{AB}	5.1^{AB}	0.5	673	7.5^{ABC}
PS_{100}	6.7^{A}	0.1	673	9.8^{A}	4.1^{A}	0.6	673	6.0^{A}
DS_{130}	7.8^{AB}	0.3	854	9.1^{A}	6.0^{BC}	0.5	854	7.0^{AB}
PS_{130}	8.5^{BC}	0.1	854	9.8^{A}	7.3^{CD}	0.3	854	8.5^{BC}
DF_{100}	9.3^{CD}	0.4	673	13.5^{C}	8.1^{DE}	0.6	673	11.9^{DE}
PF_{100}	10.5^{E}	0.6	673	15.3^{D}	9.3^{E}	1.2	673	13.6^{E}
DF_{130}	9.0^{BCD}	0.6	854	10.4^{AB}	8.4^{DE}	0.6	854	9.7^{CD}
PF_{130}	10.1^{DE}	0.2	854	11.7^{B}	9.5^{E}	0.2	854	11.0^{D}
p>F	<0.001			<0.001	<0.001			<0.001
Significance								
EC_{iw} * (S vs. F)	<0.001			<0.001	<0.001			<0.001
WA (100 vs. 130)	n.a.			<0.001	<0.01			n.s.
IF (D vs. P)	<0.05			<0.05	n.s.			n.s.
Interactions								
EC_{iw} x WA	<0.01			<0.001	<0.05			<0.01
EC_{iw} x IF	n.s.			n.s.	n.s.			n.s.
WA x IF	n.s.			n.s.	n.s.			n.s.

D - Daily; P - Pulsed or HFI; S - Saline; F - Fresh water; IF - irrigation frequency

EC_{iw} - electrical conductivity of the irrigation water; WA - water amount

It is noted that yield and WUE obtained in this field experiment were higher than those values reported for the open field, such as Doorenbos and Kassam (1979) who reported yields of 2.0-2.5 kg m^{-2} and *WUE's* of 1.5-3.0 kg m^{-3} or Rilsky and Adamati (1989) who reported yields of 2.5-4.5 kg m^{-2} and *WUE's* of 3.6-4.5 kg m^{-3}. It is difficult however, to separate the contributions of the irrigation and fertilization schedule, the screenhouse and crop husbandry to the observed increase in yield and *WUE*.

The negative effect of soil salinity, measured as the electrical conductivity of the saturated soil extract EC_e is illustrated in Figure 4. Yield of export quality was between 8.0 and 9.5 kg m^{-2} at an EC_e of around 1.0 dS m^{-1} but decreased sharply to 4-5 kg m^{-2} when EC_e reached 2.0 dS m^{-1}.

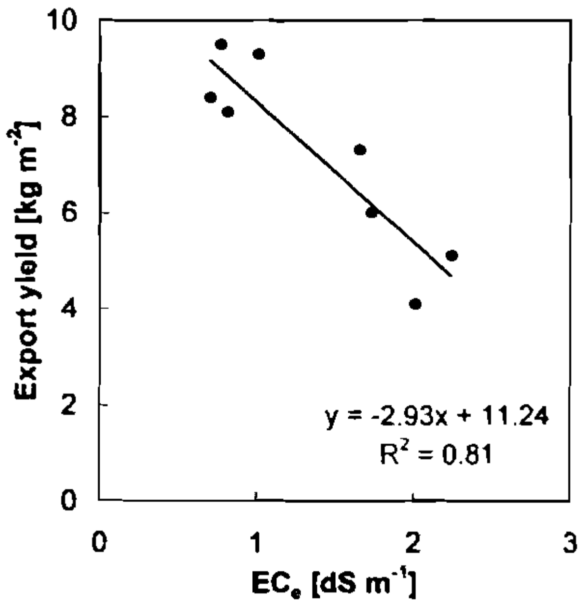

Fig. 4. Export yield (2005) *versus* electrical conductivity of the saturated soil extract EC_e in the active root zone (0–40 cm).

There was a strong correlation between stomatal conductance g_c measured in the early afternoon and cumulative yield of export quality (Fig. 5a). The R^2 value was somewhat lower (R^2= 0.79) when daily average g_c (from 8:30 until 16:00) was considered. Normalized with measured maximum stomatal conductance $g_{c,max}$ and maximum export yield Y_{max} (Fig. 5b), data points of Y and g_c fall on a 1:1 line, with an R^2 of 0.92. This finding enables us to express actual crop water use $ET_{c,a}$ in the salt- stressed treatments as a function of $ET_{c,max}$ - for the fresh-water reference - and stomatal conductance. FAO-33 (Doorenbos and Kassam, 1979) introduced a model relating the yield and evapotranspiration ratio of stressed treatments (subscript a) as:

$$\left(1-\frac{Y_a}{Y_{max}}\right)=k_y\left(1-\frac{ET_{c,a}}{ET_{c,max}}\right) \qquad (1)$$

where k_y is the yield response factor, equal to 1.1 for sweet pepper and the subscript $_{max}$ refers to yield and crop water use of an unstressed crop.

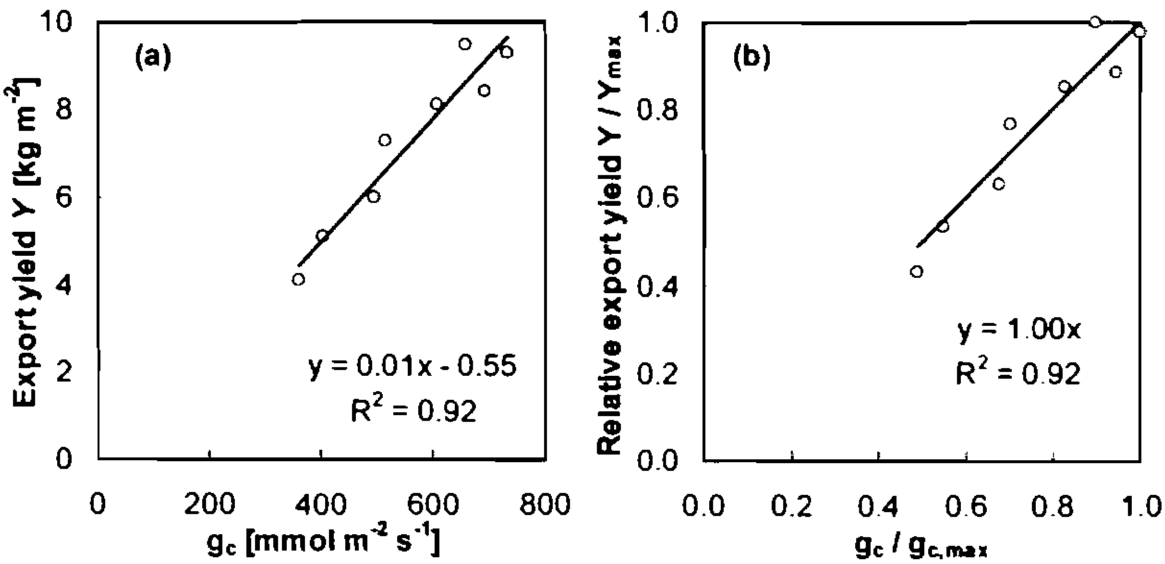

Fig. 5. Relationship between (a) stomatal conductance g_c at 14:30 on 14 August 2005 and cumulative export yield Y at final harvest and (b) between relative stomatal conductance and relative export yield.

Replacing the relative yield by relative stomatal conductance (see Fig. 5b) and re-arranging Eq. 1 for $ET_{c,a}$ of the salt stressed treatment, we obtain:

$$ET_{c,a} = ET_{c,max}\left(1 - \frac{1 - \frac{g_{c,a}}{g_{c,max}}}{k_y}\right) \qquad (2)$$

This simple model was verified using sap flow data measured in August 2005. According to Eq. 2 and measured g_c, the ratio of actual evapotranspiration in treatment *DS100* to that in treatment *DF100* is 0.73. The ratio of actual plant water uptake measured as sap flow was 0.71, which is in very close agreement with the model. A similarly good agreement was obtained when treatments *PS100* and *PF100* were compared: the ratio of $ET_{c,a} / ET_{c,max}$ measured as sap flow was 0.55, while the model forecast is 0.54. This indicates that if crop water use and yield of the unstressed treatments are known (either by direct measurements or by modeling, such as FAO-56) the corresponding values of yield and crop water use for salinity stressed treatments can be determined from simple leaf conductance measurements.

Results - Ghana

General effect of water application rates on plants in the saline soil

In order to understand how the interaction of water delivery rate and ET_o affected the pepper growth, the growth performance was analyzed under the two situations: (i) growth under separate water delivery and amount (0.8 L h^{-1} = High pressure & 0.5 L h^{-1}= Low pressure) and (ii) growth under equal water irrigation amounts but different delivery rates. It is worth noting that at each growth stage, there are pairs of the same amount of water delivered at either high or low rates. For example during growth stage 1 the high pressure treatment 0.8 ET_o (0.8 L h^{-1}) delivered the required water amount of 56 L d^{-1} (1.4 mm d^{-1}) in only 28 minutes while the low pressure treatment delivered the same amount in 45 minutes. Our discussion therefore attempts to bring these differences out.

Effect of ET_o treatments on plants performance

Figure 6 shows the mean survival rates of the plants under the various treatments. Survival rates were generally above 60% with the water application of 0.8 ET_o delivered at a slow rate of 0.5 L h^{-1} giving the highest rate of about 65% and the treatment 1.0 ET_o delivered slowly gave about 60%. Generally, the differences were not significant.

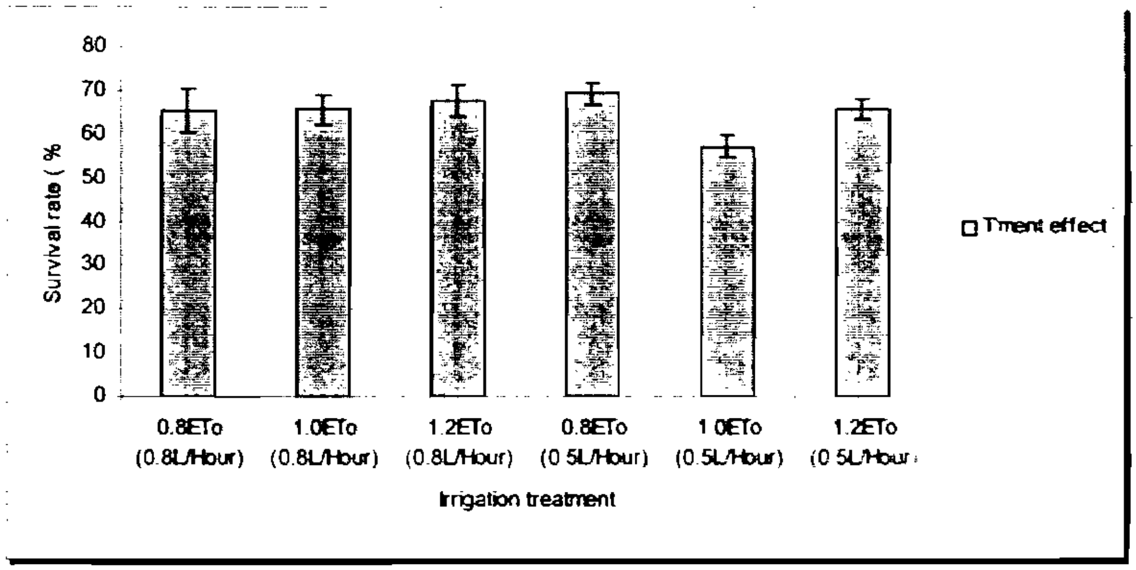

Fig. 6. Irrigation treatment effect on survival rates of plants at the saline site. Error bars indicate standard errors of the means at p= 0.05.

Unlike plant survival rate, plant height differed significantly among treatments (Fig. 7). Treatment 1.0 ET_o delivered at fast rate produced the tallest plant of height 37 cm at 8 weeks after establishment. The high water application (1.2 ET_o) delivered slowly produced the shortest plant of about 34 cm. Even though it may be expected that high water application at

high delivery will create local ponding conditions and therefore retard plant growth, it appears as though the ponding would result in diluting the salinity and reducing the osmotic pressure, so that plant water uptake would be
enhanced.

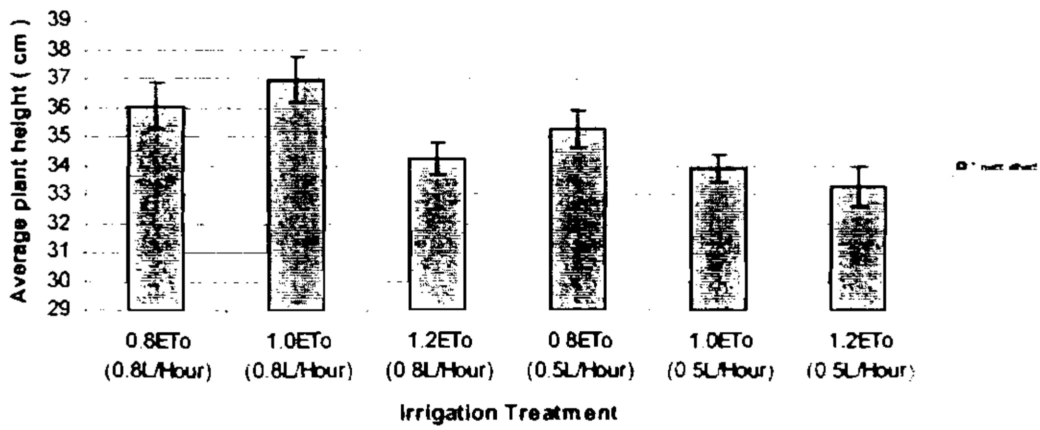

Fig. 7. Relative mean plant heights at week 8 after transplanting at the saline site. Vertical bars represent standard errors of the means at $p = 0.05$.

The effect of poor soil structure and high salinity complicates the interpretation of the data. As shown in Fig. 8, growth was generally better under high water delivery rates. The highest dry matter of about 55 g plant^{-1} was attained for water application of 1.2 ET_o with fast delivery and the least was for 0.8 ET_o with slow delivery.

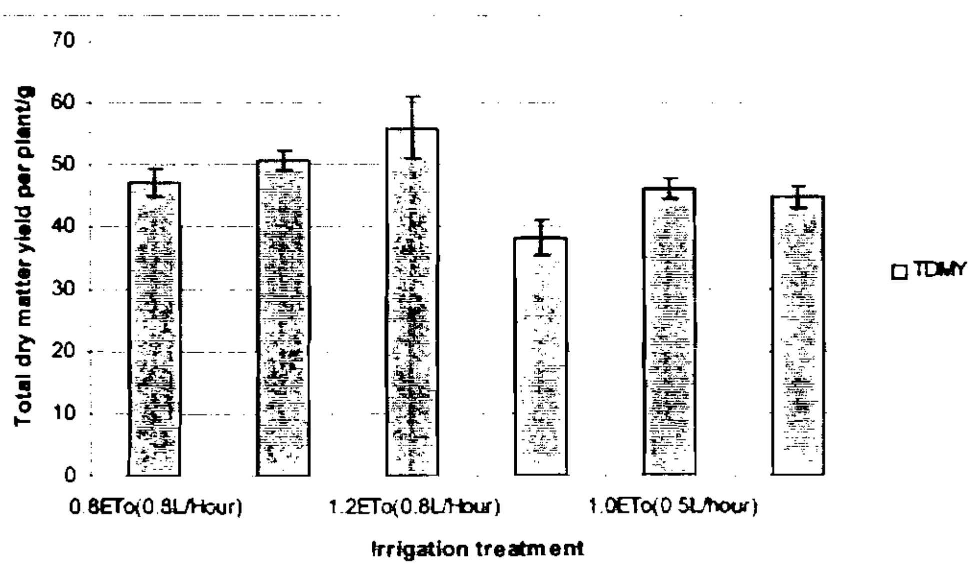

Fig. 8. Mean total plant dry matter yields (TDMY) from for saline site. Error represent standard errors of the means at $p = 0.05$.

Figure 9 shows the partitioning of dry matter between the parts of pepper under the various treatments. Stem growth dominated in all cases followed by leaf weight. Fruit weight was generally low. The treatment 1.2 ET_o at high delivery rate produced the highest dry matter and fruit weight (13 g plant^{-1}) while the least fruit weight was for the same water application treatment but slow delivery (5 g plant^{-1}).

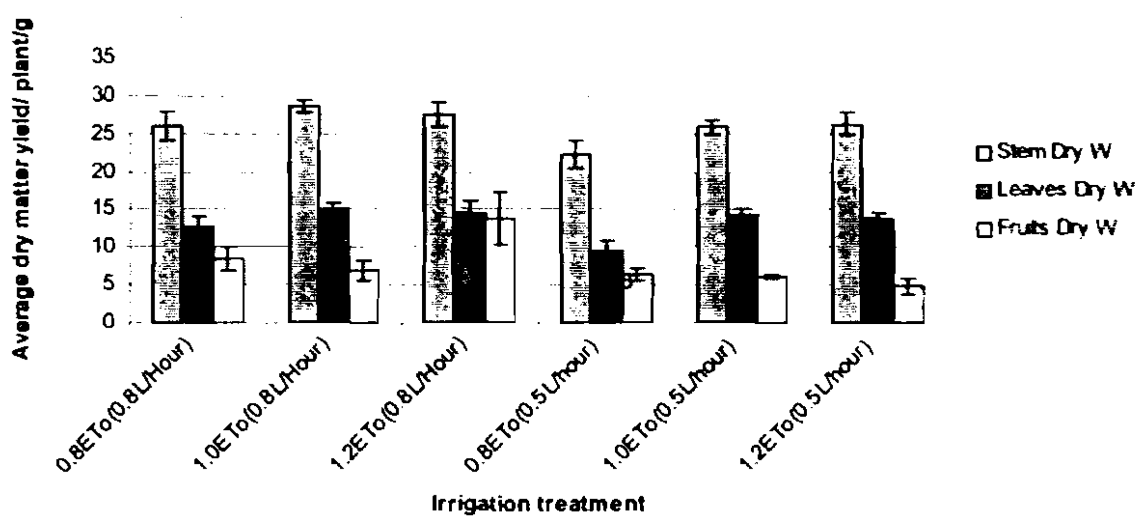

Fig. 9. Plant dry matter yields from non-saline site. Error bars represent standard errors of the means at p= 0.05

General effect of water application rates on plant growth on the non-saline soil

Survival rates of pepper plants on the non-saline and more sandy soil were comparable to those from the saline site. Survival rates were higher than 60% and the differences between treatments were very low. The highest rate was for the 0.8 ET_o at low delivery rate and the lowest was for the 1.0 ET_o at low delivery rate.

As for survival rate, treatment effect on plant height was also not significant; even though the water application of 1.2 ET_o delivered at high rate (0.8L h^{-1}) gave the highest value of about 45 cm at 8 weeks after transplanting. The least height was for the high water application of 0.8 ET_o delivered at high low rate (0.5 L hr^{-1}).

Figure 10 shows the general growth patterns of pepper and their partitioning of dry matter among stem leaf and fruit. Generally, growth improved with water application. The treatment with ET_o at high delivery rate produced close to 150 g plant^{-1} while the least yield was produced by the same water treatment at low delivery rate (80 g plant^{-1}). Thus, the difference was highly significant. It is not immediately clear why the high water application at slow delivery produced the least dry matter.

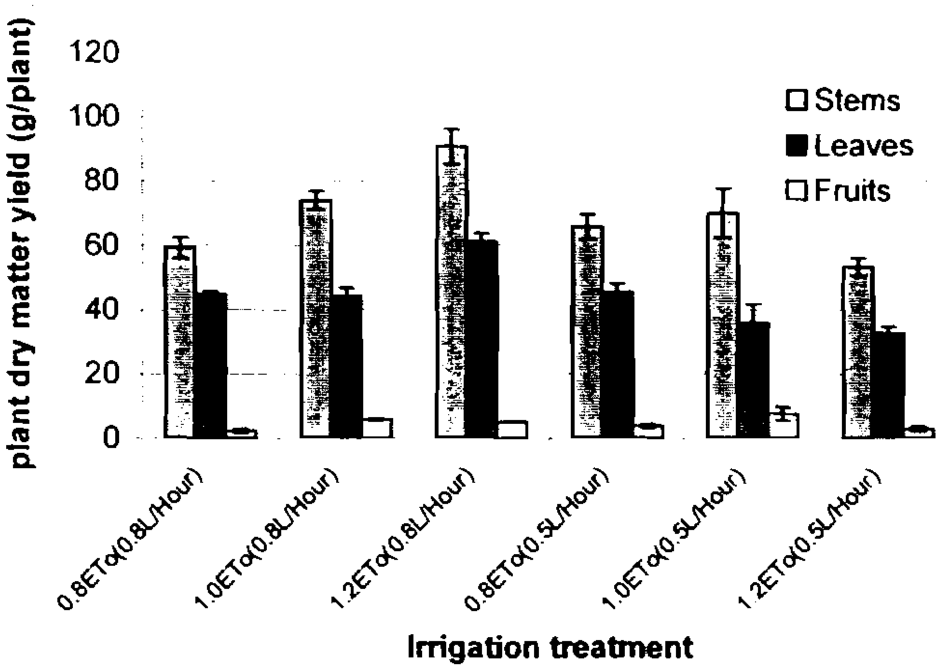

Fig. 10. Mean dry matter yields from different irrigation treatment plants on saline soil. Error bars indicate standard errors of the means.

As for the saline site, stem dry weight dominated followed by leaf dry weight. Fruit weight was relatively low but the differences among treatment were non-significant.

Comparing pepper growth on saline and non-saline fields

Considerable differences were observed between the growth of pepper under saline and non-saline sites. Even though survival rates appeared to be similar, growth and dry matter portioning differed. For example, the highest dry matter accumulated for the saline site was only 55 g $plant^{-1}$ compared to about 160 g $plant^{-1}$ in the non-saline situation. Also, relatively more dry matter was portioned to stems and leaves in the saline plots than in the non-saline plots. Despite the more vigorous growth observed for the non-saline soil, fruit yield was not significantly different from that of the saline site.

Thus even though the special characteristics of the saline soil site is that not only is it clayey and poorly drained but also saline and therefore only specially adapted salt-tolerant plant species thrive on it under normal conditions the drip irrigation could offer an avenue to bring such soils into production, as water delivery rates are slow to prevent ponding. However, the question of the salt leaching efficiency of the drip irrigation system on such poorly draining soils continues to be a major challenge for research.

D) Impact, Relevance and Technology Transfer

Usefulness of findings for the developing country

Our findings demonstrate that good crop husbandry and novel irrigation practices can offset some of the negative impacts caused by salinity. They are therefore very useful in the increasingly drought and salt affected agricultural areas of Ghana. Throughout the study, it also emerged that using high-frequency/low pressure drip irrigation, in combination with crop cultivation under protective shading screens enables very good yields at relatively low irrigation water requirements, leading to excellent water use efficiencies *WUE*. Increasing *WUE's* in developing countries is an urgent task, given the deterioration of both quantity and quality of water resources and the rising demand for food caused by population growth, which currently stands at 2.1% annually in Ghana (CIA, 2006).

Furthermore, farmers interested in investing in and installing the technology covered in this project might find our findings a useful reference, as will donor organizations and banks when considering financing irrigation development projects in Ghana.

Project's impact on individuals, departments, and institutions

The project had significant impact in the target country, both on individuals and on the Soil Science Department at the University of Ghana. During the course of the project, the equipment listed in table 6 was purchased.

Table 6. Equipment purchased by the Ghanaian group and condition as of 30 June 2006.

Item	**Quantity**	**Condition**
Drip irrigation equipment (lines, valves, etc)	N/A	Heavily used, some defective
Hobo Weather Station	1	Good
Water pumps	2	1 Good, 1 bad
Knapsack sprayer	1	Fair
Tensiometers (Mercury type)	15	Good
Field soil test kit	1	Good
Overhead water tanks	16	Heavily used, some defective
Air conditioners	3	Good
Fax machine	1	Good
Laptop computer	1	Good

In consultation with the Management of the Ghana Irrigation Development Authority at Ashaiman, (which was also a collaborator in this project), the experimental fields of the

Ghanaian research group will be handed over to local farmers who will now use the installed facilities (water reservoirs, overhead tanks, water pump and drip lines) to carry out their dry season commercial vegetable production. Prof. Adiku's group will offer technical advice to these farmers. There is thus a direct positive benefit of this new technology and the acquired knowledge on a small number of farmers in the drought affected areas of the Accra Plains.

Are large scale trials warranted?

We strongly recommend conducting large scale trials with the LPD technology, especially at other sites in Ghana such as Anloga. In light of the recent water shortages and low overall irrigation efficiencies of less than 50%, it is crucial to make most efficient use of the limited amount of available water resources. If properly installed, managed and maintained, LPD systems can be a very powerful tool to that end, at a relatively low cost. Preliminary results with low-pressure gravity-fed drip systems reported from Ethiopia and Niger are very promising and show excellent water use efficiency and financial return (Loans, 2005). The Ghana Irrigation Development Authority has become acquainted with LPD technology throughout the course of this project and could thus play a leading role in its introduction on a larger scale, with scientific support coming from Prof. Adiku's group. For simplicity, irrigation water requirements in large scale trials could alternatively be determined by reference evaporation from a Class A pan (Stanhill, 2002).

Improvements of scientific capabilities of the Ghanaian scientists

The scientific capabilities of the Ghanaian scientists were excellent prior to the commencement of this project. It is noted that Prof. Adiku and Dr. Assuming-Brempong obtained their MSc and PhD degrees from Universities in the USA and in Europe. Beyond that, this CDR project improved their scientific capabilities insofar as it equipped their laboratory with up-to-date sensors as a prerequisite for running state-of-the art experiments on the soil-plant-atmosphere continuum. Furthermore, the Israeli research group introduced the Penman-Monteith irrigation scheduling approach (Allen et al., 1998) to the Ghanaian counterpart. This know-how will help Prof. Adiku's group to plan and conduct other successful irrigation experiments in the future.

E) Project Activities/Outputs

1) Meetings held over the course of the entire project period

The meetings held over the entire project period are listed in table 7. These meetings proved very fruitful, both in terms of streamlining overall project planning and experimental layout of both research groups as well as in getting to know each other.

Table 7. Time, location, attendance and topics of all relevant meetings held during the June 2002-June 2006 period.

Time	Location	Attendance	Topics
Dec 2003	Bet Dagan, Israel	S. Assuming-Prempong (GHA), S. Assouline, S. Cohen, M. Ben-Hur (all ISR)	Experimental layout and treatments, equipment purchase, finances
June 2005	Bet Dagan, Israel	S. Assouline, S. Cohen, M. Mōller (all ISR), Mr. Anipa (GHA)	Experimental layout, design, planning and installation of drip irrigation systems; maintenance and repair of drip irrigation system components
September 2005	Accra, Ghana	S. Adiku, S. Assuming-Brempong (both GHA), C. Grewe (USA)	Project review
9 Nov 2005	Bet Dagan, Israel	S. Cohen, M. Mōller (both ISR), W. Dorgbetor (GHA), C. Grewe (USA)	Project review

2) Training

Training of technicians

Two technicians were trained to install, handle and maintain the LPD equipment in Ghana at the beginning of the project by the representative of the company (Netafim) that manufactures the LPD system.

Mr. Anipa, the Ghanaian chief-technician involved in the project, was in Israel during May and June 2005. He attended a 5-weeks international course on Advanced Irrigation Systems. He also visited the Israeli field experiment at Besor and learned about the high-frequency drip system used for irrigation and fertigation. The following two days, Mr. Anipa stayed at the laboratory of the Israeli investigators, where he synthesized the new information gained in the international irrigation course and at the experimental site. The Israeli project partners answered his remaining question and gave recommendations for improved maintenance and repair work at the LPD system in Ghana.

Training of Ph.D. student

Mr. W. Dorgbetor, a Ghanaian Ph.D. student at Prof. Adiku's group, stayed with the Israeli research group at the Volcani Center from July 2005 through July 2006. Mr. Dorgbetor participated in all aspects of the field work and has learned some of the data analysis techniques, including application of the P-M model to climate data (Allen et al., 1998) and statistics using the JMP software (JMP, 2002). Furthermore, he participated in the construction of thermal dissipation (TDP) type sap flow sensors and their power boards. He installed the TDP sensors in the field experiment at Besor and compared their measurements with those from older compensation type heat pulse sensors (Cohen, 1994) with good results. He took some of these sensors back to Ghana and it is hoped that he will be able to build more there and deploy them in subsequent research on crop water relations. Mr. Dorgbetor's experience gained in Israel is expected to help him in analyzing data collected in Ghana and produce a report and hopefully a paper for publication.

Training of Scientist

Dr. S. Asuming-Brempong, the co-principal investigator, under went training in Israel from 12th November to 4th December 2003 at the Volcani Center, Bet Dagan. She participated in the International Course on Research and Development in Irrigation and Fertigation in Controlled Environment. Components of the training had practical parts in using the LPD systems in controlled environment. Knowledge gained was used to enhance the advancement of the project work. New skills acquired include the use of LPD systems in the soil less culture medium and manipulating the irrigation water (fertigation) for high quality output in crops.

3) Publications and patents

Both research teams have actively been pursuing the dissemination of the gained knowledge by means of publications in international peer-reviewed journals. The following research papers were already accepted for publication:

Assouline S, Möller M, Cohen S, Ben-Hur M, Grava A, Narkis K, Silber A (2006) *Soil-Plant System Response to Pulsed Drip Irrigation and Salinity: Bell Pepper Case Study*. Soil Science Society of America Journal 70: 1556-1568.

Möller M, Assouline S (2006) *Effects of a shading screen on microclimate and crop water requirements*. Irrigation Science (accepted for publication). http://www.springerlink.com/content/36676g127v07rp17/fulltext.pdf

In addition, based on this CDR project, the following research paper is currently in preparation:

Möller M, Assouline S, Cohen S, Silber A (2006) *The effect of drip irrigation frequency and growing media on root distribution of young sweet pepper: Qualitative and quantitative estimates*. Soil Science Society of America Journal (research paper in preparation).

Furthermore, the Ghanaian and Israeli research groups are currently working jointly on the following two papers:

Assouline S, Cohen S, Möller M, Dorgbetor W, Adiku S (2006) *Modelling and predicting the Soil-Plant Response to Irrigation Frequency and Salinity*. Plant and Soil (research paper in preparation)

Dorgbetor W, Cohen S, Möller M, Adiku S, Assouline (2006) *Comparing the Granier heat compensation method and the heat pulse method for measuring sap flow at variable salinity and irrigation frequencies*. Plant and Soil (research paper in preparation)

F) Project Productivity

The Israeli research group achieved its research objectives. In Ghana several obstacles and external influences beyond the control of Prof. Adiku's group occurred during the field experiments: (i) during the 2003 field trials, the control treatments (surface irrigation) could not be installed due to technical difficulties with the hydraulic design, (ii) during the 2004 experiment, field trials at the saline site had to be terminated prior to fruit harvest due to the onset of heavy rains and subsequent flooding of these fields and (iii) during the field trials in early 2005, the experiments had to terminated prematurely (at the plant flowering stage), due to a severe drought and the resulting cessation of the water supply to the experimental plots. There was only one main successful trial out of three (October 2004 to May 2005).

As a consequence, the Ghanaian research group could not achieve all research objectives set out prior to the project. But there was a considerable learning curve that they have crossed and the experience gained should now enable them to carry out such projects with much more ease in future. Apart from the limited successful trial, it is noted that physiological crop data, soil and climate data is available for the periods of the trials that can be used as reference material for future projects.

G) Future Work

The knowledge gained from this project has enabled the Ghanaian research group to commence a new wind-pump low-pressure drip irrigation experiment of irrigated vegetables at village of Anloga, Ghana (Fig. 11). The site is located on the sandy shore between the southern Atlantic and an inland lagoon. Irrigation water is abstracted from a fresh water lens which floats on the dense salty water. The volume of this water lens changes from season to season and is recharged during the rainy season. The soils are predominantly sandy, with very high infiltration rates and very low water holding capacity. Traditionally, water is drawn from shallow hand-dug wells and irrigation was by manual sprinkling. Currently, intensified irrigation using sprinklers powered by diesel engines or electricity is becoming very common. The exploitation of this fresh water lens requires special care to prevent a overdrawing the fresh water resource. Therefore, a study using the LPD technology powered by wind pumps begun late 2005. This work is currently supported by the Ghana Council for Scientific and Industrial Research through a one year grant. Prof. Adiku's research group conjectures, that the wind pump-LPD system will be the most appropriate technology at this site due to the slow water extraction rate by the wind pump and the slow water delivery rates by the drip system.

Figure 11. Wind pump powered LPD system for okra production.

In Israel, both output and acquired knowledge emanating from this CDR project fit well into the department's efforts for improving our understanding and modeling of the dynamic processes of the soil-plant-atmosphere with the aim of increasing irrigation water use efficiencies and crop yield. In this respect, the findings presented herein will represent the basis for funded projects in the near future and will be developed further during the course of these future research activities.

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