Soil-water management performance and layout optimization of an innovative bamboo-drip system in West-Africa

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Abstract: An attempt to bring drip irrigation closer to small vegetable farmers of rural and peri-urban West-Africa was recently made through the successful test of an innovative bamboo-drip system, with regards to hydraulics, uniformity, yield and water productivity, and in comparison to the conventional plastic-drip and the traditional watering can systems in south-west Benin. This study enters the same testing line and aimed to assess the soil-water management performance of the bamboo system, after which its layout was optimized for minimum water loss through deep percolation and maximum fresh yields. For soil-water management performance, content and matric potential were determined at five positions in and around plants' rooting area. One-way ANOVA was used for comparisons between the three irrigation systems, and T-test was employed to compare soil-water content to major characteristics of soil storage behaviour for water in each experiment plot. Results show that soil-water content went slightly above field capacity in the vicinity of the rooting front, during mid and late seasons where over-irrigation was more pronounced. Ranges and fluctuations of soil-water matric potential were higher in areas closer to where the plant sits, laterally and vertically and lower close to the rooting front. They were also higher in the bamboo-drip system, compared to the watering can system. Overall, soil-water content and potential were in acceptable ranges for crop growth under the bamboo system, sign of good soil-water management performance. For layout optimization, HYDRUS 2D and AquaCrop v.5.0 software packages were linked through daily water stress level and used to simulate hydrologic and agronomic behaviours of the bamboo system at spacings decreasing by increments of 1 cm from 60 cm onwards. Then under the GAMS model, CONOPT Solver was used to integrate those behaviours, and identified 34 cm as optimal spacing of drippers and laterals, where the best deep percolation - fresh yield compromise is observed on sandy loam soil. Useful life, economic analysis and performance improvement possibilities of the bamboo system must still be looked into through additional long-term time-series studies, but yet, this system enables a better soil-water management and holds promises of a better rural and peri-urban economy.

Key words: Water content; water potential; spacing

1. INTRODUCTION

Drip irrigation is a localized irrigation method which slowly and frequently provides water directly to the plant root zone. Despite its high potential to use scarce water resources most efficiently to produce vegetables, it is still too expensive for small vegetable farmers of West Africa who are still watering their gardens with cans, buckets or calabashes (Dittoh *et al.*, 2010). An attempt to bring drip irrigation closer to those farmers was done by creating an innovative bamboo-drip system, which was successfully tested in south-west Benin and showed performance (in terms of hydraulics, uniformity, yield and water productivity) similar to that of the conventional plastic-drip system, and nearly doubled water productivity of the traditional watering can system (Agossou *et al.*, 2017).

Used daily in field conditions, the bamboo system, like the other drip irrigation systems, would provide water to a portion of the root zone only (beneath the emitters), creating a wetted shape which would influence the balance between liquid and gas phases, roots and microbes' respiration and activities as well. If this system applies water excessively, root development would be limited, root hair damaged and soil oxygen reduced, as well as the ability of gas to diffuse (Bouma and Bryla, 2000). Soil microbial respiration would then be inhibited (Skopp *et al.*, 1990). At plant level, stomatal conductance would decrease with a resultant reduction in photosynthetic carbon assimilation. On the contrary, if the bamboo-drip system applies water in deficit, plant metabolisms

would be affected as a result of (a) the reduction of tissue water potential and water channel activity of membrane aquaporins caused by dehydration at cellular level (Dichio *et al.*, 2007), (b) the inhibition of photosynthesis caused by stomatal closure or non-stomatal limitations (Lawlor, 2002), (c) disturbances in carbohydrate and amino acid metabolism (Santos and Pimentel, 2009), (d) a limited supply of substrates to roots caused by a lower diffusion rates in the soil pore space and the dehydration of microorganisms. An adequate soil moisture condition under the bamboo system would enhance soil organic matter mineralization by increasing microbial activity and the mineralization of easily decomposable organic substrates (Wu *et al.*, 2010). These substrates would then be allowed to diffuse within a greater proportion of the soil pore volume, making them more available to microorganisms (Amador *et al.*, 2005). Thus, the soil-water management performance of the bamboo system (i.e. how much water it applies to the root zone and how available that water is for plant uptake) needs to be answered through field tests, to determine how it uses soil storage at different positions and times, in and around the plant's root zone, and in comparison to the traditional watering can system and the conventional plastic-drip system. That would show if any threats to roots and plant's metabolism under the bamboo system in case it applied water in deficit or in excess. Furthermore, this performance should be improved through layout optimization (optimization of emitters and laterals spacing), to make best use of the advantages of the bamboo system on a given soil type. For a given drip-irrigated plot, many layout variations (spacing of drippers and drip-lines) exist which are directly linked to root zone water pattern and yield. When spacing is large, plant density is low and excessive amounts of water are added to the root zone. This influences the root zone water pattern, increases deep percolation (share of irrigation water percolating below the plant root zone) and reduces fresh yields. Reducing spacing tends to increase plant density and fresh yields while reducing deep percolation, but causes higher total investment costs. In the light of the above, this study was initiated to assess the soil-water management performance of the bamboo system and optimize its layout for minimum water loss through deep percolation, and maximum fresh yields.

2. MATERIALS AND METHODS

An experiment was carried out in a farmer's field, south-west Benin (latitude 6°24′27″ North, longitude 1°52′55″ East, altitude 69 m) in 2015 (January 3 – March 13) and repeated in 2016 (January 17 – March 25) (Agossou *et al.*, 2017). It compared the bamboo-drip system to the conventional plastic-drip system and the traditional watering can system.

2.1 Assessment of soil-water management performance

In a cropped soil, water diffuses along gradients from high to low energy status. In the transpiration process, water moves along the potential gradient as stomata open. Plant responses to soil-water depend not only on its content (i.e. how much water is present in the soil at a given position and time), but more importantly on its potential (i.e. how readily available the water present in the soil is for movement or for plant uptake). Hence soil-water management performance of the bamboo system was assessed through soil-water content and potential. Data were collected weekly in a random block, making sure three blocks were covered in three weeks (Table 1). In each plot of the selected block, a random plant was chosen and soil-water content and potential around where it sits monitored at five positions: P1, P2, P3, P4 and P5 (Figure 1).

Soil-water content can be expressed as mass (gravimetric) or volume (volumetric) of water occupying the space within soil pores. Gravimetric water content (mass wetness or water content by weight) was first determined. To that end, soil samples were taken at the five measurement points, before and after irrigation. After drying them to a constant mass at 105 °C and 21h, gravimetric water content was calculated as the ratio of water mass (wet sample mass minus dry sample mass) to dry sample mass. Thereafter, volumetric water content was deduced by multiplying the

gravimetric water content by bulk density. For bulk density determination, undisturbed soil samples were taken in each plot at 30 cm depth using cutting rings, at the beginning of each cropping season. Soil-water content was compared to major characteristics of soil storage behaviour for water in each experiment plot, i.e. Saturation (Sat), Field Capacity (FC), Readily Available Water (RAW) and Permanent Wilting Point (PWP). *FC* is the water content held in the soil matrix after the gravitational water and the readily-displaced water have drained (i.e. soil macropores are empty). *PWP* is the water content at which plant roots can no longer compete with the binding forces between the soil matrix and water, and their leaves wilt irreversibly. *RAW* is the fraction of the Total Available Water (TAW) that plants can extract from the root zone without suffering water stress.

Table 1. Monitoring process

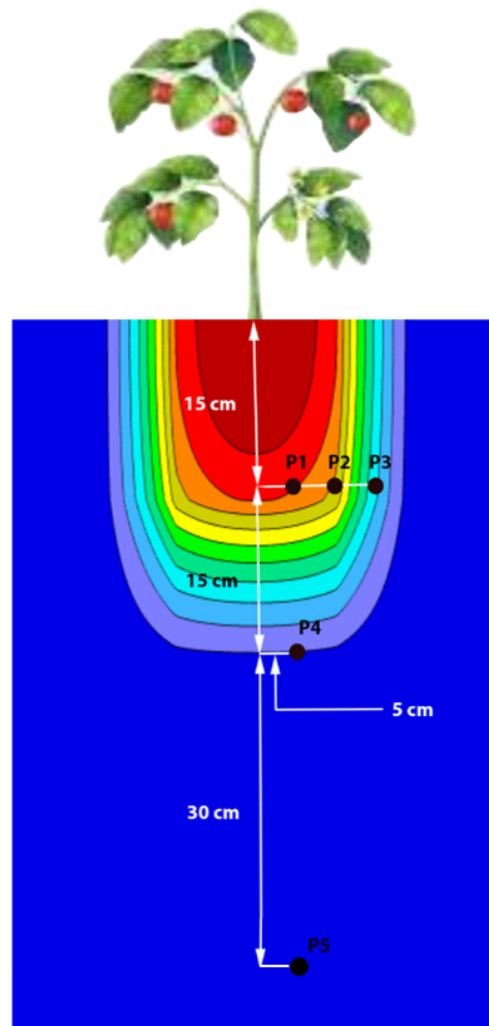| Week	DAT[*] interval	Block	Growth Phase
1	14-20	2	2 (Development)
2	21-27	3	
3	28-34	1	
4	35-41	3	3 (Mid-season)
5	42-48	1	
6	49-57	2	
7	56-62	1	
8	63-69	3	4 (Late season)

* DAT = days after transplanting

Figure 1. Monitored positions in and around plant's rooting area

When soil-water content is sufficient, no stress is observed, indicated by actual evapotranspiration at potential level. When it goes below *RAW* (which is the critical value), actual evapotranspiration is reduced depending on the difference between the critical value and the current soil moisture, i.e. the plant experiences water stress. *RAW* is calculated based on the Management Allowable Depletion (MAD), maximum decrease of soil-water content that a farmer allows between irrigations. A *MAD* value of 30% was considered, accordingly to FAO 56 requirements, i.e. *RAW* was 70% of *TAW*. Between *MAD* and *FC*, soil-water content is optimum, and higher or lower water content would result in suboptimal yields due to water stress (deficit or waterlogging). Below *MAD*, soil-water can no longer be transported quickly enough toward the roots to respond to transpiration demand. Saxton method was used to calculate *FC* and *PWP* for each plot, as mentioned by Agossou *et al*. (2017). *Sat* was determined using the Soil Water Characteristics Program (https://hrsl.ba.ars.usda.gov/soilwater/Index.htm).

Soil-water potential was measured with tensiometers (14.04.03 Tensiometer; https://www.eijkelkamp.com/download.php?file=M11404e_Tensiometers_ee6b.pdf), porous, permeable ceramic cup connected through a water-filled tube (kept saturated) to a vacuum gauge. Water moves through the cup into the soil, thereby creating suction / tension in the tube, tension which is sensed by the gauge. Water flows until the suction in the tube equals the matric potential in the soil. Positions of the tensiometers (P1, P2, P3, P4 and P5) are shown in Figure 1.

2.2 Layout optimization

An optimally designed drip-irrigation system delivers water to the plants just as they require in time and quantity, and in a manner so that all the delivered water is utilized by the plants and none is wasted. Optimization of the bamboo system's layout consists of improving its spacing, i.e. identifying, for a given soil type (sandy loam in this case; Agossou *et al.*, 2017), the spacing where the best trade-off between reduced deep percolation and increased fresh yields is observed. The process requires integration of the hydrologic (spacio-temporal soil-water dynamics of the root zone) and agronomic (crop-water productivity) behaviours of the bamboo system, which were simulated with HYDRUS 2D and AquaCrop v.5.0, respectively. As a prerequisite for application, HYDRUS 2D and AquaCrop v.5.0 were calibrated and validated comparing observed and fitted (simulated) data. First and second cropping season data were used respectively for calibration and validation. For simulations, the second season was randomly selected, and the third replicate (in block 3) of the bamboo-drip system considered, as being the only one (among the three replicates) having been monitored until late season phase (see Table 1).

HYDRUS 2D is a two-dimensional finite element model (Šimůnek *et al.*, 2011) based on the mass conservative iterative scheme, and allowing for the analysis of both vertical and lateral fluxes of water from a source with particular geometrical boundaries. This is specifically important for irrigation situations such as drip and watering can irrigations where flux directions change over time due to changing boundary fluxes and local variations in water pressure head gradients. Under high frequency irrigation scheduling (such as in the experiment carried out by this study), the soil layer used by roots as storage remains at near field capacity throughout the cropping season. Of the two models commonly used to describe soil moisture behavior, the van Genuchten analytical model (Mualem, 1976; van Genuchten, 1980) is the most appropriate for such soils, and was chosen to numerically simulate soil hydraulic properties. Hysteresis was not considered for the same near Field Capacity reason. Since direct field or laboratory measurement of soil hydraulic parameters (r, s, K_{sat}, n and l) is time consuming and costly, they were estimated with the built-in pedotransfer function ROSETTA (Schaap *et al.*, 2001), by inputting particle size distribution and dry bulk density data (determined from soil samples). Potential evapotranspiration (ET_c) was estimated using the dual-coefficient approach (Allen *et al.*, 1998), as mentioned by Agossou *et al.* (2017). In

HYDRUS 2D, potential transpiration and evaporation are transformed into actual values by affecting them a stress factor, according to soil matric potentials and salinity condition. Yet, salinity stress is assumed to be absent at the study site as the irrigation water was sourced from a 36 m-deep groundwater. Evaporation is modelled by Darcy's law when the soil surface is dry, having a water potential below a critical pressure head (hCritA), considered −15000 cm in this study. Transpiration is according to FAO 56 and allocated to soil layers according to root architecture/Feddes model (Feddes *et al.*, 1978) embedded in HYDRUS 2D. The Feddes model assigns root water uptake rates according to local soil-water pressure head (h) at any finite element node point in the root zone. It defines how transpiration is reduced below potential value when the soil is dry (i.e. no longer able to supply plant demand under the prevailing climatic conditions). Soil-water infiltration was considered two-dimensional axisymmetric, as the lack of horizontal spatial heterogeneity produces a symmetrical irrigation bulb which extends radially after irrigation has ceased. The computational flow region (Figure 3) was a homogeneous and isotropic one-layer rectangular profile, 60 cm deep and 30 cm wide, representing the cross-sectional space between two plants. It was discretized into a structured triangular finite element mesh of 8530 nodes.
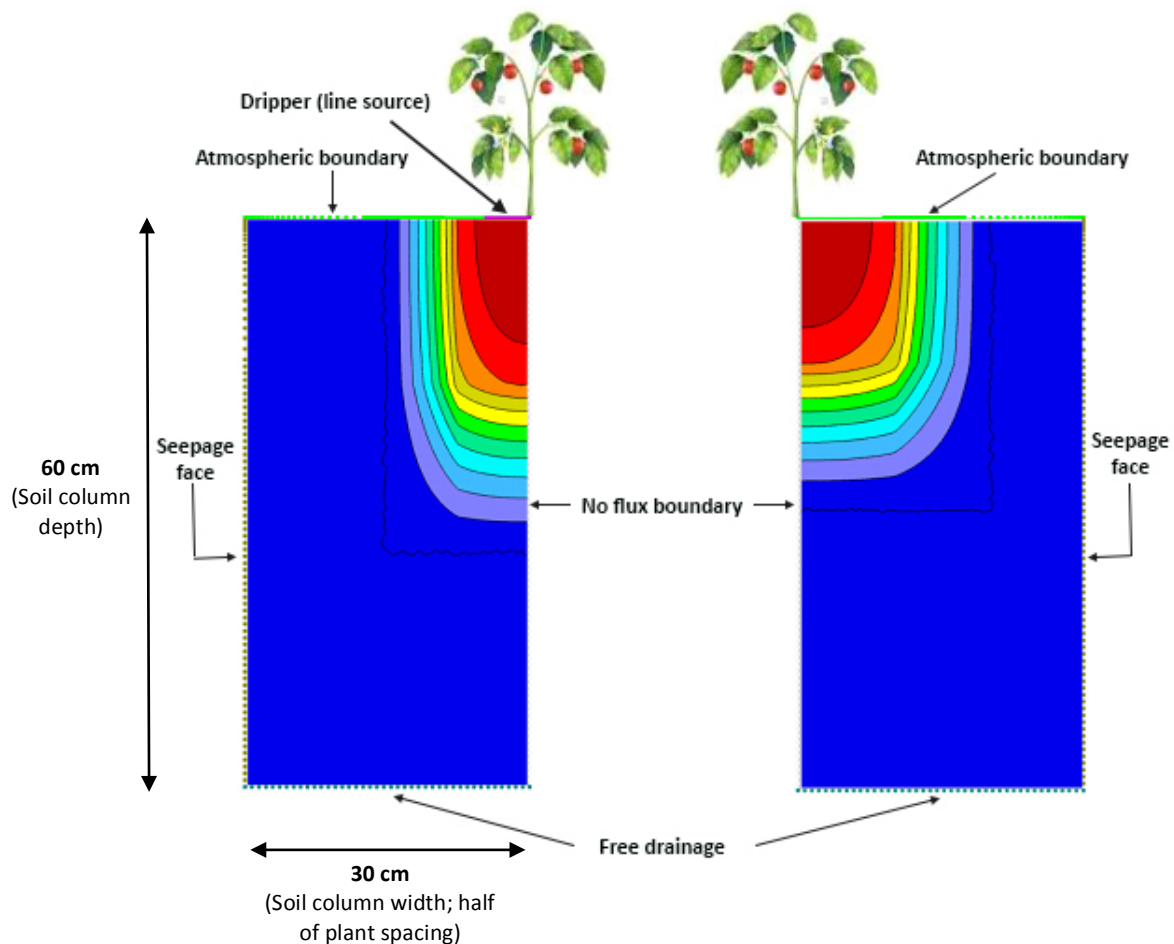

Figure 3. Flow region and boundary conditions for drip (left) and watering can (right) plots

The grid was very fine (0.05 cm) around where the plant sits (where the hydraulic gradient is higher, i.e. more active flow is expected) and increased gradually, farther from where the plant sits, up to 0.24 cm. As the soil material is relatively coarse (sandy loam), this fine spatial discretization was appropriate to avoid numerical oscillations and achieve acceptable mass balance errors (Šimůnek *et al.*, 2008). The top surface was assigned an ''atmospheric boundary'' condition to allow for interactions between the soil and the atmosphere. These interactions are evaporation, watering can irrigation or rainfall. In the case of evaporation, a flux is prescribed when water

pressure head at the boundary is above a threshold value (hCrit = 15000 cm), whereas a constant pressure head equal to *hCrit* was prescribed otherwise. Water is then allowed to evaporate from the soil at a potential rate when the surface is wetter than the threshold value, and at a lower rate (calculated based on soil conditions) when the soil dries to wetness threshold.

For drip-irrigated plots (bamboo-drip and plastic-drip), a single surface dripper represented by a line source (4.94 cm long) was placed at the corner of the flow region where the plant sits. For each daily irrigation event, dripper flux (q) was estimated as:

$$q\ (cm.day^{-1}) = \frac{Dripper\ discharge\ flow\ rate\ (cm^3.day^{-1})}{Drip\ tubing\ surface\ area\ (cm^2)} \qquad (1)$$

The vertical side of the flow region below where the plant sits (see Figure 3) was assigned a no flux boundary condition (impermeable and not allowing water into or out of the flow region through it), as soil-water movement will be symmetrical along it. Opposite to it was a seepage face (having zero pressure head along both unsaturated and saturated portions of its nodes) to enable lateral flow of water through the flow region. The lower boundary was set to be free drainage condition (pressure head gradient equal to zero), assuming that the deep water table (36 m) has no impact on moisture dynamics of the flow region.

AquaCrop v.5.0 is a water-driven crop growth model (Steduto *et al.*, 2009; Raes *et al.*, 2009b). Its choice was motivated by its ability to maintain optimal balance between accuracy (lower error probabilities), robustness and simplicity (i.e. it requires minimum explicit and mostly intuitive input data), its moderate input requirements and the availability of default values for a wide range of crops. It presents the advantage (over radiation-driven models) to normalize water productivity for climate, and can thus be applied in different locations under varying climatic and spatio-temporal settings. Although simple, it pays particular attention to the fundamental processes involved in crop productivity and yield response to water, from physiological and agronomic perspectives. AquaCrop v.5.0 software consists of four sub-menus: *Climate* (minimum and maximum air temperature, rainfall, evapotranspiration and CO_2 concentration), *Crop* (development, growth and yield processes), *Management* (irrigation and major agronomic practices such as planting dates and fertilizer application) and *Soil* (fertility and water balance) (Raes *et al.*, 2009b; Steduto *et al.*, 2009). Pests, diseases, and weeds are not considered (Raes *et al.*, 2009a). It was executed at daily time steps, to allow a realistic accounting of the dynamic nature of water stress effects and crop responses. Mauna Loa Observatory record (369.47 ppm, included in the model structure) was used as CO_2 concentration, and reference evapotranspiration (ET_o) calculated daily, using FAO Penman-Montheith equation (Agossou *et al.*, 2017). To allow for accurate root zone water content simulation by the model, the soil profile was divided into four layers 15 cm each, whose water content was determined gravimetrically at the beginning of the cropping seasons, and supplied as model input. To simulate soil evaporation, the Readily Evaporable Water (REW) value was taken from the soil textural and hydraulic properties as defined by Allen *et al.* (1998). The default Field Capacity value for sandy loam was used. No impervious or restrictive layer was observed, which could obstruct root growth expansion. There was no surface runoff, as no rainfall was recorded during both growing seasons, and plots were bordered by bricks. Saturated hydraulic conductivity was taken as provided by HYDRUS 2D model. Furthermore, default values in AquaCrop v.5.0 for infiltration and redistribution were used. Dry yield was simulated from its formation onset, and as a portion of the aboveground biomass, employing a user-defined reference harvest index *HI_o* (Raes *et al.*, 2009b), which was adjusted from 55% until 49% during model calibration. At maturity, root depth was measured from all plots, by excavating the soil close to the plants and measuring the depth to which roots grew from the soil surface. The effective rooting depth (depth at which the crop conducts most of its water uptake; Raes *et al.*, 2009b) was considered as the lowest level where roots were clearly visible. The maximum rooting depth was considered twice the effective rooting depth (Evans *et al.*, 1996).

HYDRUS 2D was linked to AquaCrop v.5.0 through daily water stress level defined as the ratio

between actual and potential plant water uptakes. AquaCrop v.5.0 provided the daily relative evaporations and transpirations (Actual value / Maximum value) which were multiplied by the daily evaporation and transpiration values to be used as inputs in HYDRUS 2D (to adjust for water stress level ratios). HYDRUS 2D then simulated soil-water dynamics and computed deep percolation (DP) for the top-35 cm, representing the maximum root depth of the bamboo-drip plots. Spacing was reduced step-wise and marginally (1 cm decrement) from 60 cm to 30 cm, minimal possible spacing which prevents the touching of lateral roots. After dry yield (15% of fresh yield, as from FAO) simulations with AquaCrop v.5.0, fresh yields were calculated by multiplying dry yields by 6.67 (100/15), as from FAO. Layout optimization was done with CONOPT solver under the General Algebraic Modeling System (GAMS), developed in the 1980s to facilitate development of complex operation research models, and used widely in the water resources and agricultural research communities. Components of the model are:

- The *decision variable*: best spacing (x).
- The *objective*: minimize deep percolation (DP) while maximizing fresh yield (Y).
- The *constraints*:

$$x_{min} \leq x \leq 60 \text{ cm,}$$
$$DP_{min} \leq DP \leq DP_{max}, \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (2)$$
$$Y_{min} \leq Y \leq Y_{max}.$$

2.3 Statistical analysis

2.3.1 Soil-water management performance

Soil-water content comparisons were done between monitored positions, under STATA 13.0 program and at 5% significance level. T-test was used to compare measured values to the major characteristics of soil storage behaviour (*Sat*, *FC*, *RAW* and *PWP*), and one-way ANOVA used for spatio-temporal comparisons. For spatial variations, replicates were compared per season to one another, whereas they were compared season-wise for temporal variations.

2.3.2 Layout optimization

HYDRUS 2D and AquaCrop v.5.0 were calibrated and validated by comparing observed and fitted (simulated) data of soil-water content and soil-water matric head (SWMH; measured matric head values (cm of water) were obtained by dividing tensiometer values (matric potentials expressed in KPa) by 10.2, according to specifications in the operating manual) (in the case of HYDRUS 2D), and of dry yield (for AquaCrop v.5.0). First and second season data were used respectively for calibration and validation.

- Calibration and validation of HYDRUS 2D

As plot soils were all the same type (sandy loam), differences in wetting patterns would come mainly from saturated soil hydraulic conductivity (K_{sat}). First and second season soil-water content and matric potential data were used respectively for calibration and validation. Calibration of HYDRUS 2D model consisted of fine-tuning K_{sat} by trial and error, for each plot and each growth phase. Three statistical estimators were used: the Pearson coefficient of determination (R^2), the Normalized root mean square error (*NRMSE*) and the Nash–Sutcliffe efficiency (*NSE*) (Nash and Sutcliffe, 1970).

R^2 is used to assess the degree of association (or error variance) between measured and simulated values. It ranges between 0 and 1, describing how much of the observed dispersion is explained by the prediction. A value of zero means there is no correlation at all between observed and predicted values and values close to 1 indicate a good correlation. R^2 was calculated as:

$$R^2 = \left(\frac{\sum_{i=1}^{N}(Mi - \bar{M})(Si - \bar{S})}{\sqrt{\sum_{i=1}^{N}(Mi - \bar{M})}\sqrt{\sum_{i=1}^{N}(Si - \bar{S})}} \right)^2 \qquad (3)$$

where *M* and *S* are observed (or measured) and simulated values respectively.

NRMSE expresses the overall mean deviation between observed and simulated values as a measure for the relative model uncertainty. A simulation can be considered excellent when *NRMSE* is less than 10%, good between 10 and 20%, fair between 20 and 30% and poor when more than 30%. *NRMSE* was calculated as:

$$NRMSE = \frac{1}{\bar{M}}\sqrt{\frac{\sum(Si - Mi)^2}{n}} \times 100 \qquad (4)$$

where *M* and *S* are observed (or measured) and simulated values respectively, and *n* the number of observed (or simulated) values.

NSE ranges from $-\infty$ to 1, the latter indicating a perfect agreement between simulated and observed values. Negative values mean that observations' mean value would have been a better predictor than the model, and 0.5 (or higher values) is generally viewed as acceptable levels of performance (Moriasi *et al.*, 2007). *NSE* was calculated as:

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Mi - Si)^2}{\sum_{i=1}^{N}(Mi - \bar{M})^2} \qquad (5)$$

Final values of saturated soil hydraulic conductivity (K_{sat}) were those giving not only the best values of the statistical estimators considered, but also the best visual fit between observed and simulated curves.

Validation of HYDRUS 2D model consisted of keeping K_{sat} values as determined after calibration, simulating soil-water data and comparing simulated values to observed ones (from season 2). The same statistical estimators used for calibration were also used for validation.

  - Calibration and validation of AquaCrop v.5.0

First and second season observed yields were used respectively for calibration and validation. For AquaCrop v.5.0, calibration consisted of minimizing the difference between predicted and observed yields. The Harvest Index was adjusted by trial and error from 55% after initial simulations, until 49% where the closest match between simulated and observed yields was reached. Validation was done using calibrated parameters unaltered. The accuracy of the model was evaluated with *NRMSE* and visual observation of residual plots. STATA 13.0 was used for analysis, with 5% significance level. For hydraulics and uniformity performance, t-test was used for comparisons to thresholds. For yield and water productivity performance, one-way analysis of variance (ANOVA) was performed to determine the effect of irrigation treatment on fresh yield and water productivity.

3. RESULTS AND DISCUSSION

3.1 Soil-water management performance

3.1.1 Soil-water content

At all five positions monitored, soil-water content was above *PWP* and below *Sat* (Table 2).

Table 2. Comparisons of measured soil-water contents to saturation, field capacity, readily available water and permanent wilting point (both seasons combined)

Position	Phase	Irrigation system	< Sat	> Sat	< FC	> FC	< RAW	> RAW	< PWP	> PWP
P1	Dev	B	0**	1	0.0732*	0.9268	0.9916	0.0084**	1	0**
		C	0**	1	0.8447	0.1553	1	0**	1	0**
		P	0**	1	0.0355**	0.9645	0.9716	0.0284**	1	0**
	Mid	B	0**	1	0.0484**	0.9516	0.9924	0.0076**	1	0**
		C	0**	1	0.0975*	0.9025	0.9999	0.0001**	1	0**
		P	0**	1	0.0035**	0.9965	0.9085	0.0915*	1	0**
	Late	B	0.0019**	0.9981	0.3389	0.6611	0.9609	0.0391**	0.9965	0.0035**
		C	0.0008**	0.9992	0.1442	0.8558	0.8417	0.1583	0.9892	0.0108**
		P	0.0044**	0.9956	0.8425	0.1575	0.9817	0.0183**	0.9974	0.0026**
P2	Dev	B	0**	1	0.441	0.559	0.9986	0.0014**	1	0**
		C	0**	1	0.9753	0.0247**	1	0**	1	0**
		P	0**	1	0.2371	0.7629	0.9916	0.0084**	1	0**
	Mid	B	0**	1	0.7042	0.2958	0.9998	0.0002**	1	0**
		C	0**	1	0.4086	0.5914	1	0**	1	0**
		P	0**	1	0.5511	0.4489	0.9997	0.0003**	1	0**
	Late	B	0.0018**	0.9982	0.3848	0.6152	0.9764	0.0236**	0.9977	0.0023**
		C	0.0009**	0.9991	0.2425	0.7575	0.8828	0.1172	0.9893	0.0107**
		P	0.0047**	0.9953	0.893	0.107	0.9816	0.0184**	0.9969	0.0031**
P3	Dev	B	0**	1	0.8749	0.1251	1	0**	1	0**
		C	0**	1	0.9986	0.0014**	1	0**	1	0**
		P	0**	1	0.5623	0.4377	0.9995	0.0005**	1	0**
	Mid	B	0**	1	0.9889	0.0111**	1	0**	1	0**
		C	0**	1	0.9996	0.0004**	1	0**	1	0**
		P	0**	1	0.9137	0.0863*	0.9999	0.0001**	1	0**
	Late	B	0.0021**	0.9979	0.9771	0.0229**	0.9951	0.0049**	0.9989	0.0011**
		C	0.0009**	0.9991	0.7738	0.2262	0.9672	0.0328**	0.994	0.006**
		P	0.0049**	0.9951	0.9774	0.0226**	0.9938	0.0062**	0.9986	0.0014**
P4	Dev	B	0**	1	0.6029	0.3971	0.9994	0.0006**	1	0**
		C	0**	1	0.9975	0.0025**	1	0**	1	0**
		P	0**	1	0.4068	0.5932	0.9987	0.0013**	1	0**
	Mid	B	0**	1	0.9736	0.0264**	1	0**	1	0**
		C	0**	1	0.9998	0.0002**	1	0**	1	0**
		P	0**	1	0.8391	0.1609	0.9995	0.0005**	1	0**
	Late	B	0.0022**	0.9978	0.9716	0.0284**	0.9935	0.0065**	0.9986	0.0014**
		C	0.0011**	0.9989	0.9011	0.0989*	0.9753	0.0247**	0.9941	0.0059**
		P	0.0052**	0.9948	0.9853	0.0147**	0.9952	0.0048**	0.9988	0.0012**
P5	Dev	B	0**	1	0.9828	0.0172**	1	0**	1	0**
		C	0**	1	0.9994	0.0006**	1	0**	1	0**
		P	0**	1	0.8167	0.1833	0.9997	0.0003**	1	0**
	Mid	B	0**	1	0.9994	0.0006**	1	0**	1	0**
		C	0**	1	0.9998	0.0002**	1	0**	1	0**
		P	0**	1	0.9775	0.0225**	0.9999	0.0001**	1	0**
	Late	B	0.0027**	0.9973	0.9506	0.0494**	0.9856	0.0144**	0.9967	0.0033**
		C	0.0011**	0.9989	0.7545	0.2455	0.9588	0.0412**	0.9926	0.0074**
		P	0.0053**	0.9947	0.9874	0.0126**	0.9957	0.0043**	0.9989	0.0011**

*Dev = development phase; Mid = mid-season phase; Late = late season phase; P = position (Figure 1); ** highly significant; * significant; P-value = probability of being wrong when saying there is a difference between the groups compared.*

Overall, soil-water content was in the acceptable range for plants (i.e. between *RAW* and *FC*) in the three systems, but went above *FC* at some particular positions and growth phases summarized in Table 3. Hence, irrigation scheduling could be improved by lowering irrigation input or introducing longer time between irrigation events (to lower soil moisture to or a bit below *FC*). This would prevent irrigation water from reaching the lower end of the root zone, and avoid deep percolation. Table 3 shows that soil-water content (SWC) above *FC* was observed at P3 and P4 located in the maximum rooting front, and P5 which is completely below the root zone, but at different growth phases. At P3 and P5 in both drip systems, *SWC* was above *FC* during mid and late seasons. This could be explained by hydraulic redistribution (mechanism by which, after an irrigation or precipitation event, soil-water is redistributed by vascular plants that have roots in both wet and

extremely dry soil) or internal drainage which occurs after infiltration has ceased and brings water from the wetting pattern to the drier part of the soil ahead of the wetting front (e.g. from P2 to P3), or from moist to drier parts of the sol profile (e.g. deep percolation from P4 to P5). In case of frequent non-deficit irrigation practiced in this study, the redistribution process is likely to be dominated by deep percolation observed during mid and late seasons. At P4 in both drip systems, *SWC* above *FC* was more obvious during late season, due to the combined effect of excessive irrigation (Figure 4) and a lesser water absorption by roots, as compared to mid-season where their density and activity are reduced as senescence starts. The relationship between soil-water content and roots under drip irrigation was studied by Michelakis *et al*. (1993) who found that root density is generally higher in areas with low and moderate soil-water content (P4 during mid-season), and lower in areas with medium and high soil-water content ranges (P4 during late season). At P3 and P5 in the watering can system, *SWC* was above *FC* during mid-season like the two drip systems, but also during development phase where water content was below *FC* in the drip systems. Excessive water content at P3 and P5 as early as during development phase could be explained by excessive irrigation and water movement rather one dimensional, downward from the soil surface in watering can irrigation, as opposed to drip systems where it is two dimensional laterally and vertically from the wetting bulb. At P4 in the watering can system, *SWC* above *FC* was observed during late season like the two drip systems, but also during development and mid-season phases, like P3 and P5 in the same system. This is, as mentioned before, due to infiltration of excessive irrigation water and root gradient-related redistribution to P4 which is closer to the roots' maximum intensity zone than P3 and P5.

Table 3. Particular positions and growth phases where soil-water content exceeded field capacity

Position	Bamboo-drip system	Plastic-drip system	Watering can system
P3	Mid-season phase	Mid-season phase	Development phase Mid-season phase
	Late season phase	Late season phase	
P4	Mid-season phase		Development phase Mid-season phase
	Late season phase	Late season phase	Late season phase
P5	Development phase		Development phase
	Mid-season phase	Mid-season phase	Mid-season phase
	Late season phase	Late season phase	

Shading highlights growth phases where the two drip systems have the same pattern (soil-water content above field capacity), and how they both differ from the watering can system; P = position (Figure 1).
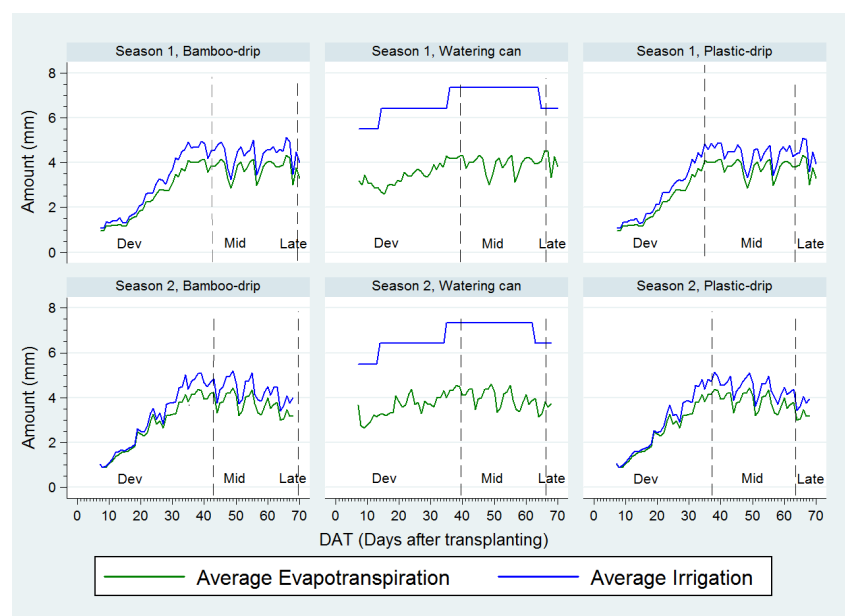

Figure 4. Seasonal averages of evapotranspiration and irrigation amounts per irrigation system
(Dev = development phase; Mid = mid-season phase; Late = late season phase)

Overall, no spatial difference was observed between the monitored positions, within the irrigation treatments and during each cropping season. But during season 1, there is a slight spatial difference within the plastic-drip treatment, due to its third replicate. This could be explained by minor particularities in soil characteristics rather than by different performance of the system. No temporal difference was also observed overall between the monitored positions, within the irrigation systems and from one season to the other. Yet, in the bamboo-drip system, there is a slight temporal difference in the first block due, as in the case previously mentioned, not to a different irrigation performance, but to minor particularities in soil characteristics.

3.1.2 Soil-water matric potential

Soil-water matric potential (SWMP) interval and range per monitored position and irrigation system are presented in Table 4. Overall, *SWMP* fluctuated around a constant value and in a narrow intervall at each monitored position. Between the two drip-irrigation systems (bamboo-drip and plastic-drip), fluctuation intervalls and ranges of *SWMP* are very similar, and higher than in the watering can system. The intervals and their ranges also decrease laterally from emitter position (i.e. from P1 to P3). This was to be expected since P1, P2 and P3 are located in the rooting bulb at places of decreasing moisture levels. Fluctuation intervals and their ranges also decrease vertically from emitter position (i.e. from P1 to P4 and from P4 to P5). This too is not surprizing, since roots are denser and more active closer to the emitter where irrigation input (and in turn soil moisture) is higher and roots are denser, as reported by Cheng *et al.* (2009). P3 and P4 show nearly similar fluctuation intervalls and ranges, meaning nearly similar wetting levels and root activity. In the watering can system, fluctuation intervals and ranges of *SWMP* also decrease laterally from where the plant sits (i.e. from P1 to P3). This too was to be expected, since P1, P2 and P3 are located at places in the rooting bulb with decreasing root density and activity. Fluctuation intervals and their ranges also decrease vertically from where the plant sits i.e. from P1 to P4, but remained nearly constant from P4 to P5. This shows again that roots are denser and more active closer to where the plant sits, where evapotranspiration fluxes are more important. The nearly similar fluctuation intervall and range between P4 and P5 suggests that roots did not reach P4 where water movements are due solely to soil matric gradients.

Table 4. Soil-water matric potential interval and range per monitored position and irrigation system

| Position | Irrigation system | Soil-water Matric potential (KPa) | |
		Interval	Range
P1	Bamboo-drip	[-30 ; -8]	22
	Plastic-drip	[-29 ; -9]	20
	Watering-can	[-25 ; -12]	13
P2	Bamboo-drip	[-24 ; -9]	15
	Plastic-drip	[-22 ; -10]	12
	Watering-can	[-22 ; -12]	10
P3	Bamboo-drip	[-21 ; -10]	11
	Plastic-drip	[-20 ; -10]	10
	Watering-can	[-19 ; -12]	7
P4	Bamboo-drip	[-22 ; -11]	11
	Plastic-drip	[-21 ; -10]	11
	Watering-can	[-18 ; -13]	5
P5	Bamboo-drip	[-20 ; -9]	11
	Plastic-drip	[-20 ; -9]	11
	Watering-can	[-17 ; -12]	5

Shading highlights that interval and range of soil-water matric potential in the two drip systems (bamboo-drip and plastic-drip) are nearly the same at positions P3 and P4 located at the rooting front; P = positions (Figure 1)

Research on drip irrigation indicated that good soil moisture condition can be maintained in the root zone throughout the crop growing season when the soil-water matric potential at 20 cm depth immediately under the emitters is kept higher than -20 KPa (Kang *et al.*, 2010). As far as tomato plant is concerned, Wang *et al.* (2007) found that fruit yield is not negatively influenced when *SWMP* varied in a range of -10 to -50 KPa. Kirda *et al.* (2004) and Wang *et al.* (2013) observed that tomato plants growing under a *SWMP* threshold of -35 KPa during the vegetative growth stage could achieve higher yield. Under the bamboo system, *SWMP* was in the above-mentioned ranges, making this system very conducive to good plant growth and yield, water management-wise. Hence, when operated appropriately, the bamboo-drip irrigation system can achieve good soil-water management.

3.2 Layout optimization

3.2.1 Calibration and validation of HYDRUS 2D

For *SWC* and soil-water matric head (SWMH), statistic estimators R^2, *NRMSE* and *NSE* are summed-up in Table 5, before calibration, after calibration and at validation. They show that values of *NRMSE* were at least good (i.e. $\leq$ 20%), at calibration and at validation. This indicates low mean deviation between observed and simulated values of *SWC* and *SWMH*. Also were *NSE* values above 0.5 overall, indicating a good agreement between observed and simulated values, meaning that HYDRUS 2D model has shown an acceptable modelling performance. Values of R^2 were above 75% overall, indicating a good correlation between observed and predicted values. As observed and predicted *SWC* values before calibration were already pretty well correlated (i.e. high R^2 values), calibration aimed essentially to reduce deviation (*NRMSE*) and improve agreement (*NSE*) and visual fit. HYDRUS 2D model was then able to predict soil-water content and matric head throughout both cropping seasons and the three irrigation systems, with a quite small bias of estimation. Hence, it can be used to simulate soil-water dynamics and deep percolation of the bamboo-drip system with non-significant errors.

Table 5. Summary of statistic estimators per irrigation system, before calibration, after calibration and at validation

		R^2 (no unit)			NRMSE (%)			NSE (no unit)		
		Cb	Ca	V	Cb	Ca	V	Cb	Ca	V
Soil-water content	Bamboo-drip system	0.842	0.854	0.862	3.155	2.641	2.870	0.627	0.743	0.777
(SWC)	Plastic-drip system	0.863	0.865	0.866	2.936	2.410	2.469	0.512	0.714	0.811
	Watering can system	0.815	0.839	0.857	3.825	2.260	1.847	0.165	0.785	0.779
Soil-water matric head	Bamboo-drip system	0.860	0.869	0.870	7.753	6.352	6.512	0.731	0.843	0.853
(SWMH)	Plastic-drip system	0.855	0.860	0.865	7.769	6.739	6.541	0.763	0.845	0.854
	Watering can system	0.851	0.865	0.873	5.770	3.803	3.905	0.551	0.817	0.852

Cb = before calibration; Ca = after calibration; V = at validation; R^2 = pearson coefficient of determination;
NRMSE = normalized root mean square error; NSE = Nash-Sutcliffe efficiency.

3.2.2 Calibration and validation of AquaCrop v.5.0

Observed and simulated yields for calibration and validation, and *NRMSE* as well are shown in Table 6. Residuals between simulated and observed yields are also presented in Figure 5. The satisfactory performance of the simulations led to a reasonable fit of yields in the three irrigation systems. Values of *NRMSE* are excellent (i.e. below 10%) overall. Additionally, the residuals' distribution is homoscedastic, meaning that the spread is about the same, and no systematic patterns were observed. AquaCrop v.5.0 was then well calibrated and validated and can be used to simulate yields in our experimental conditions with high reliability.

Table 6. Dry yields (observed and simulated) and NRMSE (after calibration and at validation)

Irrigation system	Plot	After calibration			At validation		
		Observed dry yields (t.ha^{-1})	Simulated dry yields (t.ha^{-1})	NRMSE (%)	Observed dry yields (t.ha^{-1})	Simulated dry yields (t.ha^{-1})	NRMSE (%)
B	1	0.669	0.643	3.850	0.594	0.646	8.724
	2	0.662	0.643	2.882	0.640	0.646	1.003
	3	0.579	0.643	11.102	0.659	0.646	1.935
P	1	0.695	0.643	7.427	0.600	0.646	7.592
	2	0.572	0.643	12.396	0.620	0.646	4.194
	3	0.617	0.643	4.200	0.652	0.646	0.933
C	1	0.636	0.643	1.061	0.659	0.646	1.935
	2	0.605	0.643	6.354	0.685	0.646	5.636
	3	0.650	0.643	1.013	0.672	0.646	3.821

NRMSE = normalized root mean square error
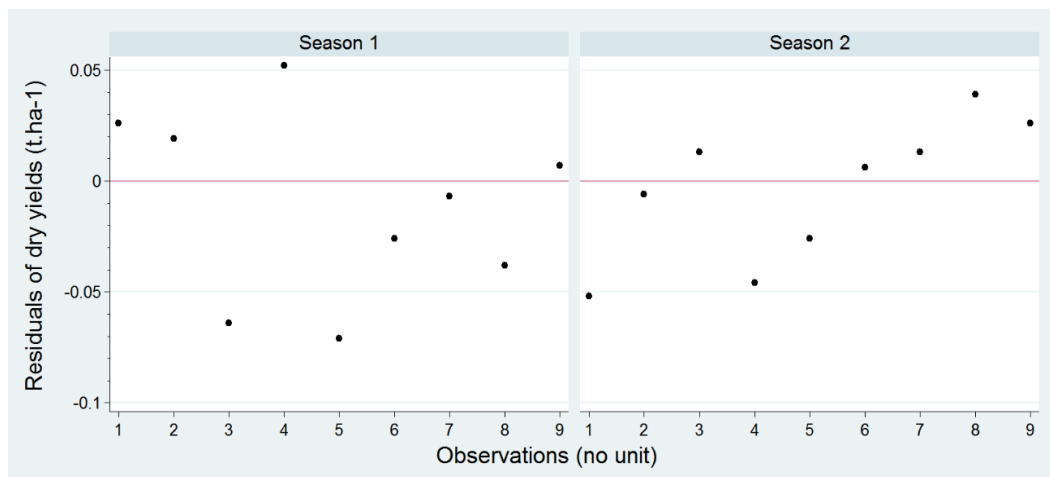
Figure 5. Residuals of dry yields after calibration (left) and at validation (right)

3.2.3 Layout optimization

As spacing was progressively reduced (with 1 cm steps from 60 cm down to 30 cm), plant density and evapotranspiration increased, while gross irrigation was kept the same. As a result, fresh yields also increased, while deep percolation decreased. But the increase of fresh yields would reach a limit where competition between plants (for resources) is maximum and further spacing reduction would result in lower yields. Deep percolation (DP) and fresh yield (Y) were line-charted at log-scale, and a polynomial trend line fit to their curve (Figure 6). The chart equations were used as objective functions in GAMS:

$$OF_1 \text{ (For DP): min } DP = 759.06x^2 - 550x + 101.87$$
$$OF_2 \text{ (For Y): max } Y = -95.231x^2 + 69.759x - 3.5419 \tag{6}$$

where x is the spacing of emitters and laterals, ranging from 0.3 m to 0.6 cm.

After running the model, feasible solutions were identified as 2.47 mm for deep percolation and 9.19 kg.plot^{-1} for fresh yield. For deep percolation, the feasible solution corresponds to 30 cm spacing where a reduction of 93.5% is observed from the value at 60 cm spacing. For fresh yield, the feasible solution lies in-between 8.82 kg.plot^{-1} (fresh yield at 32 and 33 cm spacings), and 9.264 kg.plot^{-1} (fresh yield at 34 cm spacing), but is closer to 9.264 kg.plot^{-1}. 34 cm spacing was then identified as best spacing where the most interesting compromise between fresh yield and deep percolation is observed under the bamboo-drip system, and for sandy loam soil.
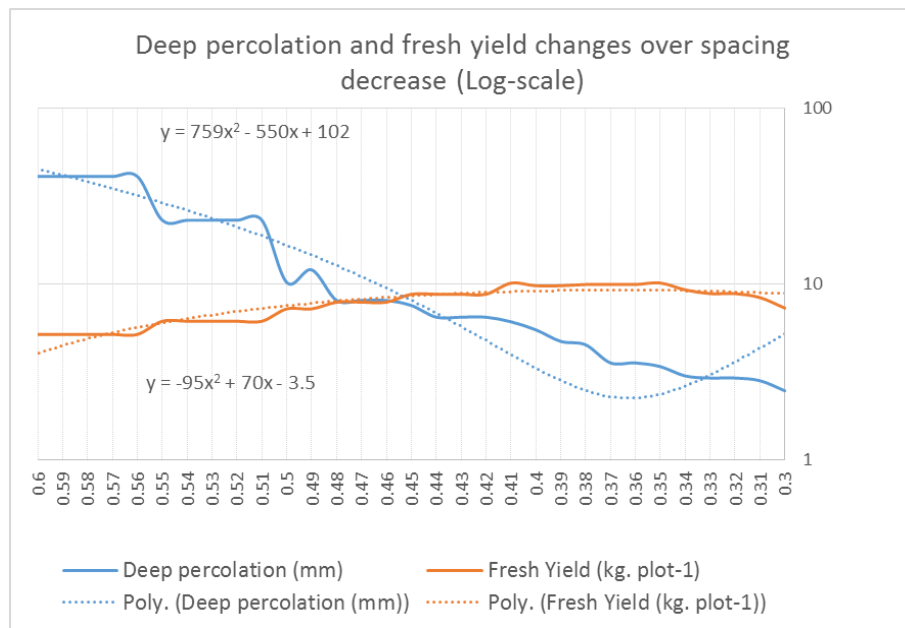
Figure 6. Deep percolation and fresh yield changes over spacing decrease

3. CONCLUSION

Overall, soil-water management under the bamboo system is good. Like the plastic-drip system, the bamboo system succeeded in maintaining soil-water content and matric potential in acceptable ranges for crop growth, during two cropping seasons. Soil-water content under this system went slightly above field capacity in the vicinity of the rooting front during mid and late seasons, where the gap between irrigation and evapotranspiration was highest. When it comes to soil-water matric potential, fluctuation intervals and ranges were higher in areas closer to where the plant sits, laterally and vertically and lower close to the rooting front. They were also higher in the bamboo-drip system, compared to the watering can system. By showing good and constant soil-water management performance in space and time, the bamboo-drip system proved to be able to keep a good balance between liquid and gas phases of the soil. Integration of its hydrologic and agronomic behaviours on sandy loam soil revealed 34 cm spacing as where the best compromise of deep percolation and fresh yield is observed.

Higher performance of the bamboo-drip system could be obtained by using one lateral per two cropping rows, and integrating water and nutrient managements through fertigation (process that combines fertilization and irrigation by injecting soil amendments, fertilizers and other water-soluble products into an irrigation system) and deficit irrigation. The cost savings between the bamboo-drip and plastic-drip systems could also be investigated through longer time-series studies, but yet, this system holds promises to enable a more productive use of water for smallholder farmers, allow them produce vegetables under dry spells and changing climate, and improve food security at household level and in water-scarce areas of West Africa.

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