Performance assessment of a bamboo-drip irrigation system

a contribution to water productivity improvement West Africa

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To my parents and siblings

"You should not be afraid of failures, and
not get enamored by success."

- *H.H. Shri Adi Shakti Nirmala Devi*

ABSTRACT

Despite its high efficiency and productivity potential in regions subject to scarce water supply, conventional drip irrigation is still expensive and therefore only being adopted slowly in West Africa where 80% of vegetable gardens and small farms are still watered by hand. Much effort has been made so far, and some less costly drip kits were implemented in the region, but are rare due to the still high investment cost. As an alternative and further-going option, a novel bamboo-drip system was created and assessed in terms of performance with regard to hydraulics and uniformity in the laboratory, and yields, water productivity and soil-water management *in situ* under field conditions. Then the layout of the system was optimized in order to identify a spacing with the best compromise between deep percolation and fresh yields on a sandy loam soil.

In the laboratory, the bamboo system was tested at four pressure heads. For hydraulic performance assessment, coefficients of variation of emitter flow were determined with regard to bamboo material, emitter precision and emitter plugging, and compared to the ASAE EP405.1 standards. The analyses reveal that plugging is the most important factor causing emitter flow to vary in the system. For uniformity performance assessment, the Christiansen uniformity coefficient was determined and compared to ASABE EP458 standards. Results show that the bamboo-drip system has good performance, and hydraulic characteristics similar to conventional drip systems under suitable pressure conditions.

An *in-situ* test was conducted in a farmer's field (south-west Benin) in 2015 and repeated in 2016. Tomato was selected as the test crop due to its relevance for smallholder farmers and its suitability for drip systems. The experimental design was a three-plot randomized block with three repetitions, and each block in the bamboo-drip system was compared to plastic-drip and watering-can systems. The bamboo system was compared to the two systems with regard to yield, irrigation water productivity, soil-water potential and soil-water content, which were also compared to the main characteristics of soil-water storage behavior in each plot. Comparisons were performed with STATA 13.0 at 5% significance level.

For assessment of yield and water productivity performance, one-way analysis of variance (ANOVA) was used, and results show that the bamboo system led to yields in the range of the two other systems in both cropping seasons. Its water productivity was found to be similar to that of the plastic-drip system in both seasons, but 99% (2015) and 85% (2016) higher than that of the can system.

For soil-water management performance assessment, soil-water content and matric potential were determined at five positions in and around the plants' rooting area, and one-way ANOVA used for comparisons between irrigation treatments. T-test was also employed to compare soil-water content to major characteristics of soil-water storage behavior in each plot. Results show that soil-water management under the bamboo system is good. Soil-water content and potential in the bamboo system were in acceptable ranges for crop growth during both cropping seasons. Soil-water content under this system was slightly above field capacity in the vicinity of the rooting front during mid and late seasons, where over-irrigation was more pronounced. Soil-water matric potential fluctuation intervals and ranges under the bamboo system 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 this system compared to the watering-can system.

For layout optimization, HYDRUS 2D and AquaCrop software packages were used to simulate hydrologic and agronomic behavior of the bamboo system with spacing decreasing by increments of 1 cm from 30 to 60 cm. Then, under the GAMS model, CONOPT Solver was used to integrate hydrologic and agronomic behavior of the system, and identified 34 cm as best spacing where the best *deep percolation - fresh yield* compromise on sandy loam soil was observed.

Useful life, economic analysis and performance improvement possibilities of the bamboo system need to be investigated in long-term time-series studies. However, this system promises a more productive use of water on a small scale, improved food security, and increased income at the household level, culminating in a better rural and peri-urban economy.

Leistungsbewertung und Verbesserung eines Bambus-Tropfenbewässerungssystems: Ein Beitrag zur Verbesserung der Wasserproduktivität im ländlichen und peri-urbanen Westafrika

KURZFASSUNG

Obwohl die Tropfenbewässerung hohe Effizienz und Produktivität in der Wassernutzung ermöglicht, was vor allem in Gebieten mit knappen Wasserdargeboten vorteilhaft ist, erweist sich die konventionelle Tropfenbewässerung immer noch als teuer. Sie wird daher in Westafrika nur vergleichsweise langsam in größerem Umfang eingesetzt, obwohl dort 80% der Gemüsegärten und kleinen Farmen noch mit Handkannen bewässert werden. Es her wurden zwar große Anstrengungen (zur Entwicklung (Kosten-) günstiger Tropfsysteme) unternommen, und in der Region wurden auch einige weniger kostspielige Tropfsysteme implementiert; einer weiten Verbreitung stehen allerdings die noch immer hohen Investitionskosten entgegen. In dieser Arbeit wurde eine alternative und weitergehende Option in Form eines innovativen Tropfsystems aus Bambus konzipiert, konstruiert und getestet, und zwar in Bezug auf: hydraulische Kennwerte und Gleichmäßigkeit (Laboruntersuchungen), Ertrag der bewässerten Anbaukulturen, Wasserproduktivität und Bodenwassermanagement (Felduntersuchungen). Darauf aufbauend wurde der Entwurf eines Bambus-Systems optimiert , um den Abstand (zwischen den Tropferleitungen) mit der besten Relation aus (verringerten) Sickerverlusten und (gesteigertem) Ertrag auf sandigem Lehm zu finden.

Im Labor wurde das Bambus-System für vier Druckhöhen getestet. Zur Beurteilung der hydraulischen Eigenschaften des Bambus-Systems wurden Variationskoeffizienten der Tropferdurchflüsse ermittelt, und zwar in Bezug auf das (Bambus-) Material , die Dosiergenauigkeit und die Anfälligkeit für Verstopfungen; Untersuchungsergebnisse wurden und mit dem Standard ASAE EP405.1 verglichen. Die Untersuchungen zeigten, dass das Verstopfen der Einfluss-stärkste Faktor ist, der die Gleichmäßigkeit der Tropferleistung bei dem Bambus-System beeinträchtigt. Die Gleichmäßigkeit wurde mit dem Christiansen-Koeffizienten beurteilt und mit dem Standard ASABE EP458 verglichen. Die Ergebnisse belegen, dass das Bambus-System ähnlich gute hydraulische Eigenschaften aufweist wie konventionelle Tropfsysteme, vorausgesetzt das Bambus-System wird mit angemessenem Druck betrieben.

In situ-Untersuchungen wurden auf dem Feld eines Farmers im südwestlichen Benin in 2015 durchgeführt und in 2016 wiederholt. Tomaten wurden für den Test ausgewählt, und zwar aufgrund ihrer Bedeutung für Kleinbauern und der Eignung für Tropfenbewässerung. Das Experiment wurde als randomisierter Block-Versuch (Varianten: Bambus-System, konventionelles Tropfsystem, Kannenbewässerung; drei Wiederholungen) konzipiert. Der Vergleich des Bambus-System mit den beiden anderen Methoden erfolge nach den Kriterien Ertrag, Wasserproduktivität und Bodenwasserpotenzial sowie Bodenfeuchte; letztgenannte Kriterien wurden in Relation zu den Speichereigenschaften des Bodens gesetzt. Die Auswertung erfolgte mit der STATA 13.0 software und einem Signifikanzniveau von 5%.

Zur Beurteilung des Ertrages und der Wasserproduktivität wurde die einfache Varianzanalyse (ANOVA) verwendet. Die dabei ermittelten Ergebnisse zeigen, dass die mit dem Bambus-System erreichten Erträge mit denen der beiden anderen Systemen vergleichbar sind (in beiden Testzeiträumen); die Wasser-Produktivität beim Bambus-System war genauso hoch wie bei dem konventionellen System und um 99% sowie 85% (2015 und 2016) höher als bei der Kannenbewässerung.

Zur Beurteilung der Beeinflussung des Bodenwasserhaushalts wurden die Bodenfeuchte und das Matrixpotenzial an fünf Stellen in, am Rand und unterhalb der Wurzelzone bestimmt; bei der Auswertung mit ANOVA (einfach) wurde ein Vergleich der

Bewässerungssysteme vorgenommen. Darüber hinaus fand der t-Test Anwendung, um die Bodenfeuchtewerte mit den Kenngrößen zur Erfassung des Bodenspeichers in jedem Plot zu vergleichen. Dabei wurden mit dem Bambus-System gute Ergebnisse erzielt, denn mit dem Bambus-System konnten die Bodenfeuchte und das Matrixpotenzial für beide Untersuchungszeiträume in Bereichen gehalten werden, die für das Pflanzenwachstum akzeptable Bedingungen schaffen. Bei diesem System ergaben sich in der mittleren sowie späten Vegetationsphase am unteren Ende der Wurzelzone Bodenfeuchtewerte leicht über der Feldkapazität (stärker ausgeprägte Überbewässerung in diesen späten Phasen). Die Fluktuation des Matrixpotenzials (nach Dauer und Betrag) unter dem Bambus-System waren größer im Bereich an der Pflanze (vertikal und lateral) und geringer am unteren Ende der Wurzelzone; insgesamt waren sie höher als bei dem System der Kannenbewässerung.

Um die Optimierung des Entwurfs (Abstand der Tropferleitungen) vorzunehmen, wurden die Modelle hydrus (dreidimensionale Version) und AquaCrop genutzt; damit konnten wasserwirtschaftliche und agronomische Effekte des Bambussystems für unterschiedliche Entwürfe simuliert werden (ausgehend von 60 cm wurde der Abstand in Schritten von einem cm verringert und das Verhalten des Systems simuliert). Die Simulationsergebnisse wurden genutzt, um mit GAMS (CONOPT Solver) die wasserwirtschaftlichen und agronomischen Kriterien für die Bewertung des Systems zu integrieren. Dabei erwies sich der Abstand von 34 cm zwischen den Tropferleitungen als optimal, um für sandigen Lehm die beste Relation aus (verringerten) Sickerverlusten und (gesteigertem) Ertrag zu erreichen.

Es sind weitere - und vor allem langfristige - Tests mit dem Bambus-System nötig, um insbesondere die Dauerhaftigkeit, die ökonomische Analyse und die Optionen zur Steigerung Handhabung dieses innovativen Systems weiter zu untersuchen. Die im Rahmen der Arbeit durchgeführten Untersuchen zeigen jedoch deutlich das Potenzial dieses Systems auf, und zwar im Hinblick auf die Steigerung der Produktivität in der Wassernutzung in kleinen Betrieben, die Verbesserung der Nahrungssicherheit und Erhöhung der Haushaltseinkommen, was in der Gesamtwirkung die wirtschaftliche Situation in urbanen und peri-urbanen Räumen begünstigen kann.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASABE	:	American Society of Agricultural and Biological Engineers
ANOVA	:	Analysis of variance
ASAE	:	American Society of Association Executives
B	:	Cumulative aboveground biomass production
C/N	:	Carbon to nitrogen ratio
CC	:	Canopy cover at time t
CC_0	:	Initial canopy cover
CC_X	:	Maximum canopy cover
CDC	:	Canopy decline coefficient
CGC	:	Canopy growth coefficient
cm	:	Centimeters
cm^2	:	Square centimeters
CO_2	:	Carbon dioxide
CONOPT	:	Non-linear numerical solver generally used for non-linear optimization
DAT	:	Days after transplanting
D_e	:	Cumulative depth of evaporation
DP	:	Deep percolation
dS/m	:	deciSiemens per meter
e_a	:	Actual vapor pressure
e_s	:	Saturation vapor pressure
e_s-e_a	:	Saturation vapor pressure deficit
ET_a	:	Actual evapotranspiration
ET_c	:	Crop evapotranspiration
ET_m	:	Maximum evapotranspiration
ET_o	:	Reference crop evapotranspiration
FAO	:	Food and Agriculture Organization
FC	:	Field capacity of the soil

fcDecline	:	Average daily decline of canopy cover once maximum canopy cover is reached
f_{ew}	:	Fraction of the soil surface not covered by vegetation and from which most evaporation occurs, as wetted by precipitation or watering-can irrigation
F-value	:	Ratio of the variance between the groups compared and the variance within those groups
G	:	Soil heat flux density
GAMS	:	General algebraic modeling system
$g.m^{-2}$	:	Grams per square meter
H	:	Local soil-water pressure head
h_1	:	Arbitrary anaerobiosis pressure head of the root zone above which water uptake is assumed to be zero
h_2 and h_3	:	Lower and upper limits of root zone pressure head between which water uptake is considered optimal
h_4	:	Wilting point pressure head of the root zone below which plants wilt irreversibly
hCrit	:	Threshold value of water pressure head at the boundary of the flow domain in the case of evaporation
hCritA	:	Minimum allowed pressure head at the soil surface (atmospheric boundary) for the evaporation flux to be at its potential value
HI	:	Dynamic harvest index
HI_o	:	Reference harvest index
HYDRUS 2D	:	Two dimensional finite element hydrological model
ID	:	Inner diameter
K	:	Unsaturated hydraulic conductivity
K+	:	Potassium ion
K_c	:	Crop coefficient
K_{cb}	:	Basal crop coefficient

$K_{cb(Tab)}$	:	Tabulated value of basal crop coefficient
K_{cmax}	:	Maximum value of crop coefficient following rain or irrigation
K_e	:	Soil evaporation coefficient
$kg.ha^{-1}$	:	Kilograms per hectare
$kg.m^{-3}$	:	Kilograms per cubic meter
KPa	:	Kilopascals
K_r	:	Dimensionless evaporation reduction coefficient
$K_s.CC_x$	:	Soil fertility stress coefficient for maximum canopy cover
K_s.exp,f	:	Soil fertility stress coefficient for canopy expansion
K_s.WP	:	Soil fertility stress coefficient for water productivity
K_{sat}	:	Saturated soil hydraulic conductivity
k_y	:	Proportionality factor between relative yield decline and relative reduction in evapotranspiration.
L	:	Pore connectivity (tortuosity) parameter
m	:	Meter
MAD	:	Management Allowable Depletion of soil-water content
$mol.mol^{-1}$	:	Mole per mole
MPa	:	Megapascals
N	:	Nitrogen
NRMSE	:	Normalized root mean square error
NSE	:	Nash–Sutcliffe efficiency
P	:	average emitter flow reduction observed after CV (HMP) test
P	:	Phosphorus
P1, P2, P3, P4 and P5	:	Positions in the root zone around where the plant sits, and where the wetting pattern was monitored
pH water	:	pH value in drinking water
ppm	:	Parts per million
P-value	:	Probability of being wrong when saying there is a difference between compared groups
PVC	:	Polyvinyl chloride

PWP	:	Permanent wilting point of the soil
R^2	:	Pearson coefficient of determination
RAW	:	Readily available water of the soil
REW	:	Readily evaporable water of the soil
RH_{min}	:	Mean value for daily minimum relative humidity during mid or late season growth stage
R_n	:	Net radiation at crop surface
S	:	Distributed sink function representing water uptake by the roots
SDI	:	Surface drip irrigation
S_e	:	Effective fluid saturation
STATA	:	Data analysis and statistical software
SWC	:	Soil-water content
SWMH	:	Soil-water matric head
SWMP	:	Soil-water matric potential
T	:	Mean daily air temperature at 2 m height over grass
T_{avg}	:	Observed average daily temperature
TAW	:	Total amount of water that a crop can extract from its root zone, ranging from field capacity to permanent wilting point
TEW	:	Total evaporable water
T_r	:	Crop transpiration
T_{ri}	:	Daily actual crop transpiration
T-test	:	Student’s test
$t.ha^{-1}$	:	Tons per hectare
u_2	:	Mean value for daily wind speed at 2 m height over grass
UCC	:	Christiansen uniformity coefficient
USA	:	United States of America
US$	:	United States dollar
USDA	:	United States Department of Agriculture
vol%	:	Percent volume below soil saturation

WP	:	Crop water productivity
WP*	:	Crop water productivity normalized for CO_2 concentration and local climate
WPi	:	Increase of irrigation water productivity from the traditional watering-can system (reference situation)
X	:	Spacing of emitters and laterals in a bamboo-drip irrigation system
Y	:	Fresh yield
Y_a	:	Actual fresh yield
Y_m	:	Maximum (potential) fresh yield
Z	:	Vertical coordinate with positive upwards
Γ	:	Psychrometric constant
Δ_Deep percolation	:	Variation of deep percolation from that of 60 cm spacing
Δ_Fresh yield	:	Variation of fresh yield from that of 60 cm spacing
% WP*	:	Percent of WP*
θ	:	Soil volumetric water content
θ_r	:	Soil residual water content
θ_{sat}	:	Soil volumetric water content at saturation
$1-ET_a/ET_m$	:	Relative water stress (relative reduction in evapotranspiration)
$1-Y_a/Y_m$	:	Relative yield decline (loss)

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1. CHAPTER 1: INTRODUCTION AND OBJECTIVES

Freshwater resources are limited and expected to become more variable due to climate and land-use changes, while demand is forecasted to rise, and therefore gaps between supply and demand might occur (Hall *et al.*, 2008). Irrigated agriculture, by far the biggest (70%) water user globally (Rosegrant *et al.*, 2002), has rather low efficiencies which urgently need to be improved.

A promising approach to improving water use efficiency is drip irrigation, which is a precise and frequent application of water as discrete drops, tiny streams or miniature sprays through pressure-reducing water paths and emitters (Ngigi *et al.*, 2000). One of its main advantages is the reduction in conveyance loss and water use for growing crops (Ngigi *et al.*, 2001) through a water application targeted to the location of use (i.e. the crop), a high dosage precision, and the option to apply irrigation water frequently without high water losses due to non-uniform wetting patterns as with surface irrigation methods. Indeed, its field application efficiency can be as high as 90% compared to 75% for sprinkler and 60% for surface irrigation methods such as border, furrow and basin irrigation (http://www.fao.org/docrep/t7202e/t7202e08.htm). Apart from improving water distribution uniformity, drip irrigation also increases plant yields and decreases risks of soil degradation and salinity (Karlberg and Penning de Vries, 2004). Phene *et al.* (1986) demonstrated significant yield increases in tomato production with the use of high frequency Surface Drip Irrigation (SDI) and precise fertility management. Yield increases were also demonstrated in production of, for example, alfalfa (Hutmacher *et al.*, 1996) and cotton (Ayars *et al.*, 1998) using drip systems.

Yet, despite their numerous advantages and the urgent need for advanced irrigation systems for crops such as vegetables, drip systems are only adopted by very few producers in developing countries for various reasons among which the main is high equipment cost. Indeed, conventional drip systems have capital costs ranging between US$ 1500 and 2500 per hectare, whereas the vast majority of farmers in developing countries have small landholdings and limited financial resources (Postel *et al.*, 2001). This lack of financial resources for purchase and installation, operation and maintenance is one of the major reasons for the low application of drip systems in developing countries (Gerards, 1992), and they are economically and technically unavailable to the farmers. In this context, developing low-cost drip systems while maintaining the advantages of conventional drip systems in terms of water saving is of great interest for smallholder farmers in general and vegetable producers in particular.

Low-cost drip systems are commensurate drip technologies for low-income farmers. Such systems would create opportunities that might support a substantial improvement of the farmers' economic situation and contribute to achieving food security in developing countries. Considerable research was therefore conducted in this domain with much success (Musonda, 2000) and some less costly systems are available nowadays, the most common being drum and bucket kits (Cornish and Brabben, 2001) and the Nica irrigation kit. Recently in Nigeria, a more affordable system incorporating electrical conduit pipes as laterals and medical perfusion sets as emitters was successfully designed and evaluated (Mofoke *et al.*, 2004). Its hydraulic performance was satisfactory (96% application efficiency, 91% irrigation efficiency, 93 distribution uniformity, and 94% irrigation adequacy), as the emitters had provisions for flow regulation and were adjusted to deliver the pre-calculated water flow. Yet, this system still is expensive as PVC and electrical conduit pipes are used, which can hardly be afforded by smallholder farmers.

An alternative to this system is to use bamboo instead of PVC pipes, and handmade pen tube emitters instead of perfusion sets. Bamboo (*Bambusa vulgaris* Schrad) is widely distributed in tropical zones (Dierick *et al.*, 2010), and has stable characteristics making it suitable for various uses (Lee *et al.*, 2012), e.g. drip irrigation (Singh, 2010). In West Africa, the species *Oxytenanthera abyssinica* (A. Rich) Munro is very abundant. It is a lowland, drought-resistant and woody perennial bamboo with hollow internodes and interesting mechanical properties (Lin *et al.*, 2002). Internodes can reach 7-15 cm diameter and 15-40 cm length (Ohrnberger and Goerrings, 1988), and can therefore be used to form water pipes of different sizes. Ball-pen tubes are cheap and easily accessible to smallholder farmers, who can make emitters out of them.

But although the bamboo system has several advantages over other irrigation systems, it is not possible for it to achieve 100% water application uniformity across the fields (like conventional drip systems), due to the inherent variabilities in its hydraulics (Zhu *et al.*, 2009), and to the low but still existing non-uniformity of water application in the root zone. The inherent variabilities in hydraulics and their effect on the uniformity of water application to the plants must therefore be investigated in order to correctly assess the bamboo system.

Among other advantages that drip irrigation offers over surface and sprinkler systems is the reduction in evaporation (Mathieu, Wang and Goldy, 2007), the prevention of soil-water stress, and the increase in yields as a soil moisture level is maintained which avoids water stress due to frequent irrigation with high efficiency (Liao *et al.*, 2008). Drip irrigation also presents direct advantages for plant health, since it applies water under the canopy and keeps the foliage dry, thus reducing the incubation and development of many pathogens. By reducing the soil-wetted area and creating a drier soil surface, pest and weed invasion is also reduced (Simonne *et al.*, 2008). These advantages mean that drip irrigation has a high yield and water productivity potential, and a broader set of production opportunities in regions subject to scarce water supply such as West Africa. Especially under conditions of small-scale irrigation such as gardens, where 80% are still hand-watered using watering cans, buckets or calabashes (Dittoh *et al.*, 2010), drip irrigation and particularly the bamboo-drip system has the potential to boost yield and water productivity with quite low costs, in case of the bamboo system. This potential should be investigated under field conditions and compared to the current practice as the reference situation (traditional watering-can system) and the ideal one (conventional plastic-drip system).

Used daily under field conditions, drip irrigation systems provide water to a part of the root zone only (beneath the emitters), creating a wetted shape (wetting pattern) and making best use of the soil storage. Content and availability of soil-water thus influence the balance between liquid and gas phases, and roots and also microbe respiration and activities. If water is applied excessively, as is often the case with surface irrigation methods, root development is limited, root hairs are damaged, and soil oxygen as well as the ability of gas to diffuse is reduced (Bouma and Bryla, 2000). Soil microbial respiration is then inhibited (Skopp *et al.*, 1990). At plant level, stomatal[1] conductance decreases with a resulting reduction in photosynthetic carbon assimilation. If the bamboo system applies water in deficit, plant metabolisms are affected as a result of (a) the reduction in tissue water potential and water channel activity of membrane aquaporins caused by dehydration at the 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), and (d) a limited supply of substrates to roots caused by a lower diffusion rates in the soil pore space and the dehydration of microorganisms. Adequate soil moisture conditions 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 easily available to microorganisms (Amador *et al.*, 2005). The question of whether the bamboo system provides the afore-mentioned advantages compared to conventional drip systems needs to be answered through field tests. This was one of the aims of this study.

For optimal soil-water management performance and making best use of the advantages of the bamboo system on a given soil type, its layout should be optimized. 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 the 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 had three major objectives:

[1] Small apertures in the epidermis of leaves, stems, etc., through which gases are exchanged. (http://www.dictionary.com/browse/stomata)

- Assess hydraulics and uniformity performance of the bamboo-drip system,
- Assess the yield and water productivity performance of the bamboo-drip system,
- Assess soil-water management performance of the bamboo-drip system and optimize its layout for minimum water loss through deep percolation, and for maximum fresh yields.

2. CHAPTER 2: ASSESSMENT OF HYDRAULICS AND UNIFORMITY PERFORMANCE

2.1. Materials and methods

2.1.1. Construction of the bamboo-drip system

In the bamboo-drip system, bamboo internodes (20 cm length) were used to construct lines. They were first heated in candle wax for leaching the starch, increasing the drying time, reducing water absorption during future use, and increasing resistance to micro-organisms. Second, the inner parts were very thinly coated with wax to protect the bamboo from rotting and to reduce friction head losses during irrigation. After these treatments, they were glued together with strong and waterproof glue to form the irrigation lines. The main and laterals were constructed with bamboo internodes of 16 mm and 8 mm inner diameter, respectively, and were 2.4 m and 5 m long. Emitters were tortuous-path G type, regulatory, non-pressure compensating and directed upward. They were handmade from ball-pen tube pieces of 2 mm diameter. The basal opening was closed and three small V-openings made alongside to regulate flow by up and down movement into the bamboo pipes (Figure 2.1). To ease handling of bamboo pipes during laboratory tests and prevent breaking during transportation to the field (for *in situ* test), junctions between consecutive internodes were protected later on.

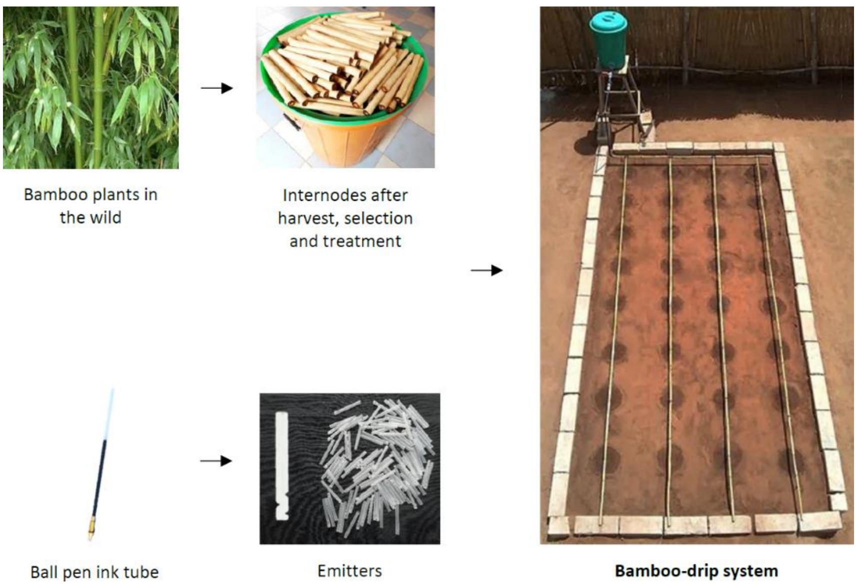

Figure 2.1 *Bamboo-drip system and its main components*

2.1.2. Assessment of inherent variabilities in hydraulics

Variabilities in a drip system's hydraulics are generally due to pipe material (bamboo material in this case), emitter precision, temperature effects and potential plugging of emitters. But temperature effects can be neglected as emitters are turbulent flow (Wu and Phene, 1984). Coefficients of variation of emitter flow were then determined for the three remaining factors, i.e. bamboo material, emitter precision and plugging of emitters, and compared to ASAE EP405.1 standards (ASAE EP405.1, 2000). Tests were conducted at 4 pressure heads (20, 40, 60 and 80 cm), as emitter flow rates of drip systems have different responses to pressure variations (Badr *et al.*, 2009). Parameters and test methods were:

- **CV (H)**: This expresses how much emitter flow variation is caused by the bamboo material. Three 5-m laterals were tested three times each for 30 minutes. The volumetric method was used to determine lateral outlet flow and CV (H) calculated as:

$$CV\,(H) = \frac{Sl}{\overline{ql}} \qquad (2.1)$$

$\overline{ql}$ being average, and *Sl* standard deviation of lateral outlet flow.

Testing conditions were as shown in Figure 2.2.

Figure 2.2 *Test of emitter flow variation caused by bamboo material*

- **CV (M)**: This expresses how much emitter flow variation is caused by emitter precision. Three emitters were tested three times each for 30 minutes. The volumetric method was used to determine emitter outlet flow and CV (M) calculated as:

$$\boldsymbol{CV\ (M) = \frac{Se}{\overline{qe}}} \qquad (2.2)$$

$\overline{qe}$ being average and *Se* standard deviation of emitter flow.

Testing conditions were as shown in Figure 2.3.

Weighing of empty cans before test | Test of emitters: volumetric method | Weighing of collected water

Figure 2.3 *Test of emitter flow variation caused by emitter precision*

- **CV (P)**: This expresses how much emitter flow variation is caused by emitter plugging. It was deduced from the coefficient of variation of emitter flow due to the combination of bamboo material, emitter precision and emitter plugging CV (HMP) as follows:

$$\boldsymbol{CV\ (P) = \sqrt{CV^2(HMP) - CV^2(HM)}} \qquad (2.3)$$

with $CV\ (HMP) = \sqrt{\frac{CV^2(H)+CV^2(M)}{1-P} + \frac{P}{1-P}}$

and $CV\ (HM) = \sqrt{CV^2(H) + CV^2(M)}$ (Bralts *et al.*, 1981a).

CV (H) and *CV (M)* are as previously defined. *CV (HM)* expresses how much emitter flow variation is caused by the combination of bamboo material and emitter precision. *P* is the average emitter flow reduction observed for the 8 emitters after the 6 tests. It is expressed as:

$$P = \frac{\sum_{i=1}^{8}[(qi_{max} - qi_{min})/qi_{max})]}{8}$$

qi_{max} being maximum value and qi_{min} minimum value of emitter flow.

Testing conditions were as shown in Figure 2.4.

Test set-up Water collection

Figure 2.4 *Test of emitter flow variation caused by emitter plugging*

2.1.3. Assessment of emitter flow uniformity

Emitter flow uniformity in the bamboo-drip system shows how much water flow varies from one emitter to the other. At the same pressure heads as previously defined (i.e. 20, 40, 60 and 80 cm), the bamboo-drip system was tested for 30 minutes. Emitter flows were determined using the volumetric method. Uniformity was assessed with the Christiansen uniformity coefficient (UCC) (Christiansen, 1941) and compared to ASABE EP458 standards (ASABE EP458, 1999).

$$UCC = 1 - \frac{\overline{\Delta q}}{\bar{q}} \qquad (2.4)$$

$\bar{q}$ being average emitter flow and $\overline{\Delta q}$ mean deviation of emitter flow from average.

Testing conditions were as shown in Figure 2.5.

Figure 2.5 *Test of emitter flow uniformity in the bamboo-drip system*

2.2. Results and discussion

2.2.1. Inherent variabilities in hydraulics of the bamboo-drip system

Emitter flow variations caused by inherent variabilities in hydraulics, i.e. bamboo material, emitter precision and emitter plugging, and their interpretation criteria are shown in Figure 2.6 and Table 2.1. Results show that flow variations due to bamboo material and emitter precision are excellent at the four pressure heads, whereas flow variations due to emitter plugging were overall unacceptable. Emitter plugging is then the strongest factor causing emitter flow to vary in the bamboo-drip system. Emitter plugging has been proved to be a major problem in micro-irrigation systems in general (Nakayama and Boman, 2007). Several authors studied its effect on emitter flow variation, and most conclude an adverse correlation. Indeed, after many field studies, Pitts *et al*. (1996b) showed that emitter plugging can be the major cause of emitter flow variation within a micro-irrigation system. Wu (1993a) and Wu *et al*. (2007) were more affirmative and indicated that plugging was not just a possible cause, but rather the most significant factor affecting emitter flow uniformity. This has a direct adverse effect on water application efficiency and useful life[2] of drip systems, even when plugging percentage is small (Nakayama and Bucks 1981). Besides their position on drip laterals, plugging of emitters depends on their passageway size, the flow velocity at their position, and their internal factors (physical, chemical and biological hazards) (Ravina *et al.*, 1992), which depend on the quality of the irrigation water. In the laboratory test of the bamboo system, internal factors were irrelevant, as tap water was used for the test. Also, passageway size of the handmade emitters was large enough. Flow velocity was then the only plugging inducer left, which may have varied due to singularities in both the bamboo internodes and junctions. The bamboo internodes used to construct the laterals were from culms harvested in different locations/shrubs. This resulted in imperfect uniformity regarding straightness, sectional shape and inner roughness, even though inner diameters were the same. Thus, the way to reduce emitter flow variations due to flow velocity is to construct pipes with bamboo internodes coming from the same shrub. This would require cultivation of bamboo in a controlled and uniform environment.

Table 2.1 *Criteria for micro-irrigation component manufacturing variability values (Adapted from ASAE EP405.1, 2000)*

Coefficient of variation (%)	**Interpretation**
5 or less	Excellent
5 – 10	Average
10 – 15	Marginal
15 or more	Unacceptable

[2] Time the system can be used.

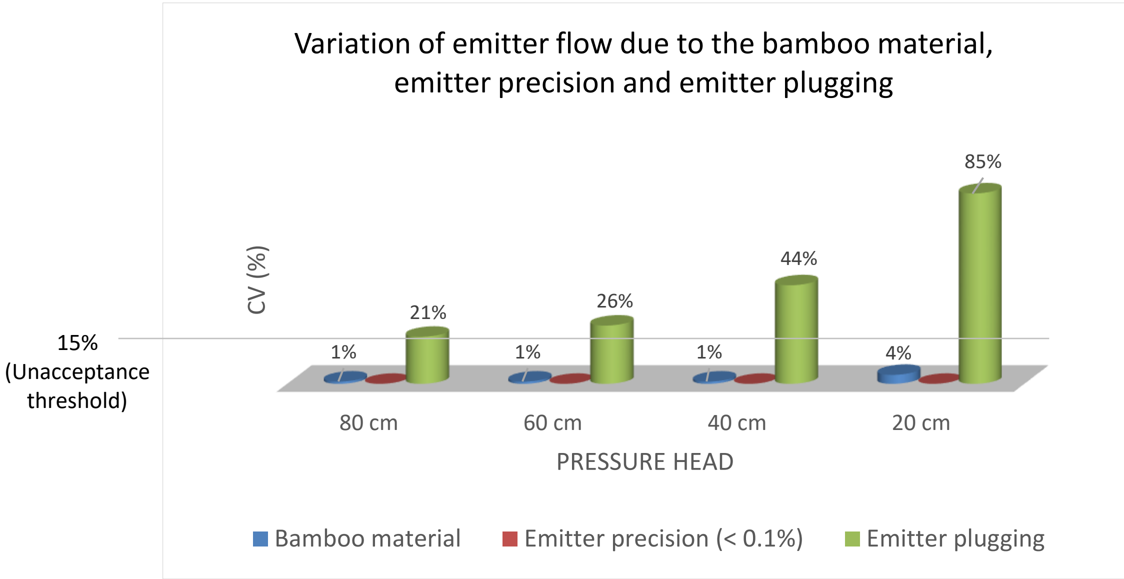

Figure 2.6 *Inherent variabilities in hydraulics at 80, 60, 40 and 20 cm pressure heads*

2.2.2. Emitter flow uniformity in the bamboo-drip system

Emitter flow uniformity in the bamboo-drip system, and interpretation criteria are shown in Figure 2.7 and Table 2.2. Results show that emitter flow uniformity in the bamboo-drip system is unacceptable only at the 20-cm pressure head. Pressure head being directly proportional to water flow velocity (even driving velocity), this means water flow velocity in the system at 20-cm head varies too much from one emitter position to another. As identified previously, this is because singularities in bamboo internodes and junctions are very relevant at 20-cm pressure head. Achieving a good uniformity would then mean either reducing these singularities by using more identical bamboo internodes, or running the system at higher pressure heads, which would require high, strong and relatively costly tank-holding structures. The first option seems more feasible, and only requires bamboo segments from a uniform shrub. The second option would be more difficult because of the costs for construction of high tank-holding structures.

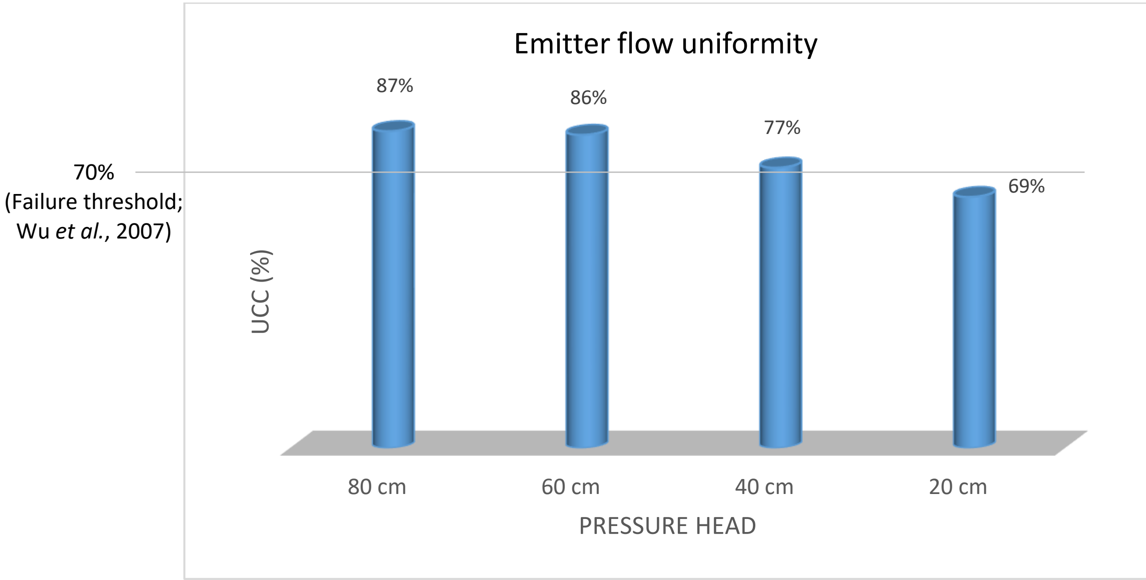

Figure 2.7 *Emitter flow uniformity at 80, 60, 40 and 20 cm pressure heads*

Table 2.2 *Standards for uniformity in micro-irrigation systems*
(Adapted from ASABE EP458, 1999)

Uniformity coefficient (%)	**Classification**
Above 90	Excellent
90 – 80	Good
80 – 70	Fair
70 – 60	Poor
Below 60	Unacceptable

3. CHAPTER 3: ASSESSMENT OF YIELD AND WATER PRODUCTIVITY PERFORMANCE

3.1. Materials and methods

3.1.1. Experimental design and conditions

An experiment was conducted in a farmer's field in 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). It compared the bamboo-drip system to the conventional plastic-drip and the traditional watering-can systems (Figure 3.1), and also served as demonstration site, thereby facilitating the dissemination of the alternative bamboo technology.

Bamboo-drip system (Desired situation) *Plastic-drip system (Ideal situation)* *Watering-can system (Reference situation)*

Figure 3.1 *Irrigation systems compared during the field test*

The experimental design (Figure 3.2) was a 3-plot randomized block[3] with three replications. The irrigation treatments comprised the three abovementioned irrigation systems. Plots were 12 m^2 (2.4 m x 5 m) and bordered with bricks to ensure stability and prevent run-off from can-irrigated plots.

[3] The randomized block was a group of three experimental plots randomly assigned to the irrigation systems.

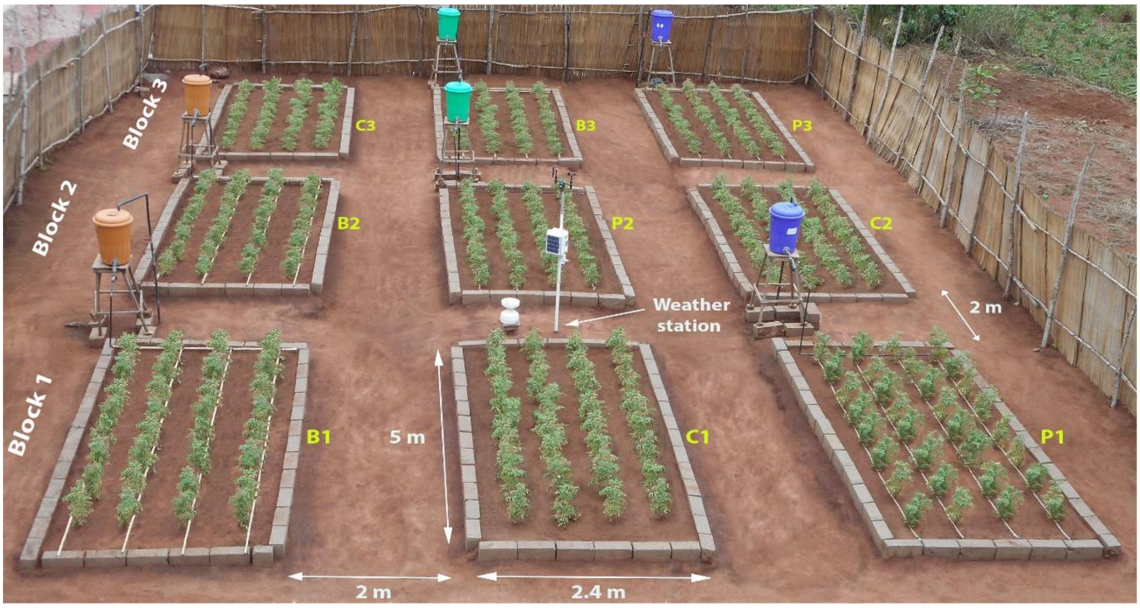

Figure 3.2 *Experimental design*
Note: B = bamboo-drip system; P = plastic-drip system; C = watering-can system; 1 = first replicate; 2 = second replicate; 3 = third replicate

A Basic Weather Station (BWS200, https://www.campbellsci.eu/bws200) was installed on the site coupled to a rain gauge, which provided hourly data to calculate evapotranspiration. Data were relative humidity (%), dewpoint (°C), wind speed and its maximum (m/s), wind direction (degrees), total rainfall (mm), total wind run (m), air temperature (°C) and solar radiation (W/m^{-2}) and barometric pressure (mBar). Soil samples were taken at the beginning of the experiments and analyzed at the Soil Sciences Laboratory of the University of Abomey-Calavi, Benin. Plot soils were sandy loam (according to USDA soil textural classification system) and rich in essential nutrients. The Saxton method was used to calculate water content at field capacity and at permanent wilting point. Characteristics of the soils are presented in Table 3.1. The extra-early tomato variety NADIRA F1 (*Lycopersicon esculentum* Mill.) was transplanted at 60 cm x 60 cm spacing, and no mineral fertilizer was applied during cultivation to clearly see the effect of the irrigation systems on crop yield and water productivity. Pesticides were used when necessary for pest control, and weeding was done manually.

Table 3.1 *Soil characteristics in experimental plots*

Season	System	Plot	Silt (%)	Clay (%)	Sand (%)	C/N (No unit)	N (%)	P (ppm)	K+ (meq/100g)	pH water	FC (No unit)	PWP (No unit)
1	Bamboo	1	6.59	13.61	79.17	9.43	0.07	80.59	0.71	6.42	0.186	0.104
		2	4.52	14.69	80.51	9.5	0.06	80.53	0.77	6.31	0.188	0.109
		3	4.27	17.13	78.1	9.43	0.07	87.99	0.76	6.31	0.200	0.120
	Plastic	1	2.9	15.9	80.75	9.14	0.07	89.14	0.79	6.45	0.192	0.114
		2	6.34	13.37	79.7	8.29	0.07	81.63	0.71	6.43	0.184	0.102
		3	3.41	17.57	78.11	9	0.07	84.5	0.71	6.47	0.201	0.122
	Can	1	4.98	14.48	80.52	9	0.07	80.96	0.77	6.3	0.187	0.108
		2	4.54	15.54	79.19	9.17	0.06	86.97	0.78	6.42	0.193	0.112
		3	5.66	13.25	80.18	9.29	0.07	88.21	0.79	6.2	0.183	0.102
2	Bamboo	1	4.78	13.94	80.67	8	0.07	83.57	0.77	6.26	0.185	0.105
		2	5.69	15.92	78.14	9.14	0.07	83.47	0.74	6.25	0.195	0.114
		3	5.56	15.2	78.85	7.86	0.07	83.29	0.74	6.27	0.192	0.111
	Plastic	1	7.81	14.51	78.39	7.86	0.07	85.82	0.73	6.44	0.190	0.108
		2	4.99	13.74	80.61	8	0.07	84.35	0.75	6.37	0.184	0.104
		3	5.45	15.52	79.72	9.5	0.06	87.08	0.75	6.4	0.192	0.112
	Can	1	3.55	16.97	78.59	11	0.06	85.3	0.77	6.35	0.198	0.119
		2	4.73	16.55	78.26	9.43	0.07	85.43	0.72	6.43	0.197	0.117
		3	2.42	17.4	79.87	9.33	0.06	82.03	0.71	6.44	0.199	0.121

C/N = carbon to nitrogen ratio; N = nitrogen; P = phosphorus; K+ = potassium ion; FC = field capacity of the soil; PWP = permanent wilting point of the soil.

3.1.2. Yield and water productivity

Plots were harvested at 69 days after transplanting (DAT) and fresh yields determined. Dry yields were then considered 15% of fresh yield (FAO; (http://www.fao.org/nr/water/cropinfo_tomato.html). Water productivity (WP_i) was calculated with respect to gross irrigation as follows:

$$\boldsymbol{WP_I} = \frac{\boldsymbol{Dry\ yield\ (kg/ha)}}{\boldsymbol{Gross\ irrigation\ (m3/ha)}} \qquad (3.1)$$

Irrigation was applied daily at 5:30 p.m. For watering-can plots, the amounts were set according to the farmers' common practice. For drip plots, net irrigation requirements were first determined from crop evapotranspiration (FAO Irrigation and Drainage Paper 56) and rainfall; capillary rise was not relevant due to the deep groundwater at 36 m). Next, the theoretical gross irrigation was calculated from net irrigation and estimated application efficiency (90%;

http://www.fao.org/docrep/t7202e/t7202e08.htm#TopOfPage), and the corresponding irrigation duration determined using the dripper discharge. The system was then opened and left to work till the end of the irrigation duration, and application of the expected gross irrigation cross-checked by volume change in the irrigation tank, which was calculated from water level observations (Figure 3.3).

Figure 3.3 *Water level difference in a water tank after drip irrigation*

Crop evapotranspiration was estimated using the dual-crop coefficient (Allen *et al.*, 1998), which separates transpiration (productive component) from evaporation (unproductive component) as follows:

$$ET_c = (K_{cb} + K_e) \times ET_o \qquad (3.2)$$

K_{cb} being the basal crop coefficient, K_e the evaporation coefficient and ET_o the reference crop evapotranspiration.

ET_o was calculated using the FAO Penman-Monteith equation (Allen *et al.*, 1998):

$$ET_o = [[0.408\ \Delta\ (R_n - G)] + [900 \gamma u_2\ (e_s - e_a) / (T+273)]] / [\Delta + \gamma\ (1+0.34\ u_2)] \qquad (3.3)$$

R_n $(MJ.m^{-2}.day^{-1})$ being net radiation at crop surface, G $(MJ.m^{-2}.day^{-1})$ soil heat flux density, T (°C) mean daily air temperature at 2-m height, u_2 $(m.s^{-1})$ mean value for daily wind speed at 2-m height, e_s (kPa) saturation vapor pressure, e_a (kPa) actual vapor pressure, e_s-e_a *(kPa)* saturation vapor pressure deficit, *Δ (kPa.°C^{-1})* slope of vapor pressure curve, and *γ (kPa.°C^{-1})* psychrometric constant.

K_{cb} is defined as the ratio of crop transpiration over reference evapotranspiration (ET/ET_o) when the soil surface is dry (i.e. evaporation is zero) but transpiration is fully met (i.e. occurring at the potential rate). Therefore, $K_{cb}.ET_o$ represents primarily the transpiration component of *ET*. It includes a residual diffusive evaporation component supplied by soil water below the dry surface and by soil water from beneath dense vegetation. K_{cb} was calculated as:

$$K_{cb}= K_{cb\,(tab)} + [0.04\,(u_2-2) - 0{,}004\,(RH_{min} - 45)]\,(\frac{h}{3})^{0.3} \tag{3.4}$$

$K_{cb\,(Tab)}$ being the tabulated value of K_{cb}, u_2 the mean value for daily wind speed at 2-m height over grass during mid or late season growth stage [$m.s^{-1}$] for $1\ m.s^{-1} \le u_2 \le 6\ m.s^{-1}$, RH_{min} the mean value for daily minimum relative humidity during mid or late season growth stage [%] for $20\% \le RH_{min} \le 80\%$, and *h* the mean plant height during mid or late season stage [m] for $20\% \le RH_{min} \le 80\%$.

$K_{cb\,(Tab)}$ values (Figure 3.4) were as follows: 0.2 (initial phase), linearly increasing from 0.2 to 1.1 (development phase), 1.1 (mid-season phase) and linearly decreasing from 1.1 to 0.75 (late season phase).

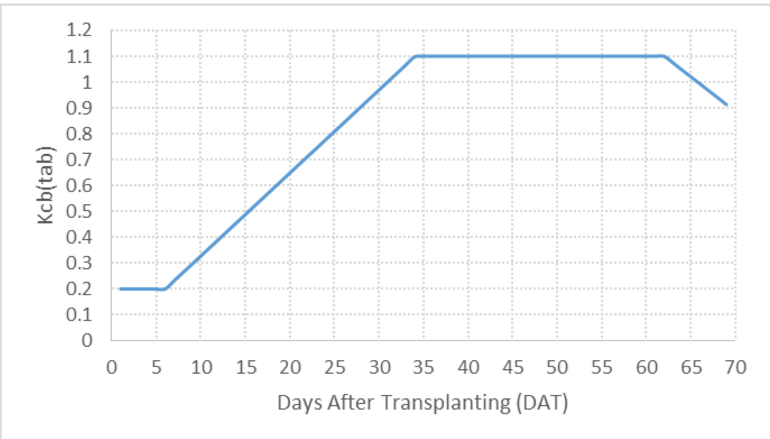

Figure 3.4 *$K_{cb\,(Tab)}$ values used during the experiment*

K_e describes the evaporation component of ET_c. When the topsoil is wet (following rain or watering can irrigation), K_e is at its maximum/potential value (i.e. =1), and evaporation determined only by the energy available. When the soil surface is drying, K_e decreases and reaches zero when no water is left for evaporation in the soil layer relevant for evaporation. However, K_c $(K_{cb} + K_e)$ can never exceed a maximum value $K_{c\ max}$, which is determined by the energy available for evapotranspiration at the soil surface $(K_{cb} + K_e \leq K_{c\ max})$. When the topsoil dries out, less water is available for evaporation which gets reduced in proportion to the amount of water remaining, and:

$$K_e = K_r\,(K_{c\ max} - K_{cb}) \leq f_{ew}\,K_{c\ max} \qquad (3.5)$$

$K_{c\ max}$ being the maximum value of K_c following rain or irrigation, f_{ew} the fraction of the soil surface not covered by vegetation and from which most evaporation occurs because it is wetted by precipitation or watering-can irrigation, and K_r the dimensionless evaporation reduction coefficient, dependent on the cumulative depth of water evaporated from the topsoil. Following rain or watering-can irrigation, the soil surface is wet and stage 1 of the drying process (energy limiting stage) starts. K_r is then considered 1 until the end of this stage where the cumulative depth of evaporation (D_e) reaches the Readily Evaporable Water (REW) (Allen *et al.*, 1988). After stage 1 is complete, stage 2 of the drying process (falling rate stage) starts where D_e exceeds *REW* and reaches a value where the soil surface is visibly dry. For watering-can plots, evaporation was considered at the energy limiting stage, and a K_r value of 1 was used. For drip-irrigated plots (bamboo-drip and plastic-drip), evaporation was considered at the falling rate stage, and a K_r value of 0.085 was used, meaning that the cumulative depth of evaporation (D_e) is 95% of the Total Evaporable Water (TEW).

3.1.3. Statistical analysis

To determine the effect of the irrigation system on fresh yield and water productivity, the three irrigation systems (bamboo-drip, plastic-drip and watering-can) were compared using one-way analysis of variance (one-way ANOVA) under STATA13.0

software and at 5% significance level. One-way ANOVA is a technique used to compare the means of three or more groups using the F-distribution[4]. It determines whether any of those means are significantly different from the others, but does not tell which specific groups are different from each other. A post-hoc test (Bonferoni) was then associated to the one-way ANOVA, which made a pair-wise comparison of the groups, and identified where the difference was.

3.2. Results and discussion

Crop evapotranspiration as a whole, and split in evaporation and transpiration, and gross irrigation amounts of the two cropping seasons are shown in Table 3.2.

Table 3.2 *Evapotranspiration, evaporation, transpiration and gross irrigation amounts per irrigation system and per cropping season*

Season	Irrigation system	Evapotranspiration (mm)	Evaporation (mm)	Transpiration (mm)	Gross irrigation (mm)
Season 1	Bamboo-drip	194.6	5.1	189.4	228.1
	Plastic-drip	194.6	5.1	189.4	226.1
	Watering-can	249.2	59.8	189.4	449.2
Season 2	Bamboo-drip	199.2	5.5	193.7	228.4
	Plastic-drip	199.2	5.5	193.7	227.9
	Watering-can	258.4	64.8	193.7	449.2

3.2.1. Fresh yields

Seasonal fresh yields per irrigation system and yield-wise comparisons of the three irrigation systems within and between cropping seasons are presented in Figure 3.5 and Table 3.3, respectively.

[4] Statistical parameter that identifies significant difference amongst means.

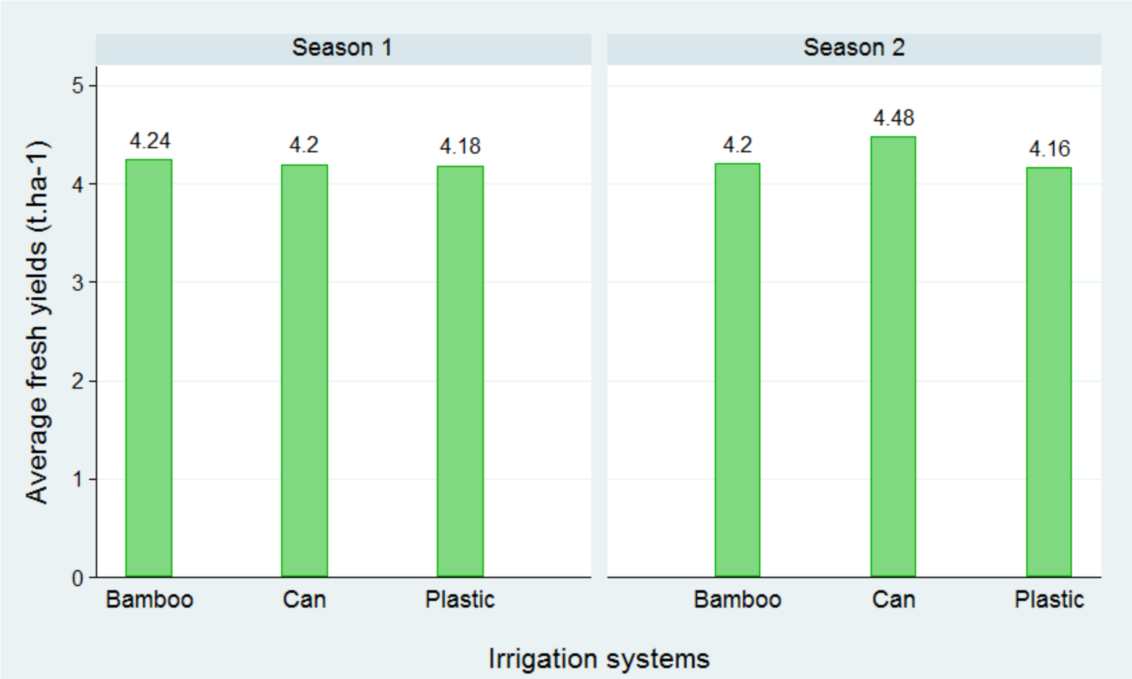

Figure 3.5 *Fresh yields per irrigation system per cropping season*
Note: Yield values extrapolated from $kg.plot^{-1}$ to $t.ha^{-1}$

Table 3.3 *Comparison of yields of three irrigation systems within and between cropping seasons*

Comparison		Irrigation system	F-value	P-value
Within seasons	Season 1	B vs P vs C	0.03	0.9743
		B vs C	-6.3889	1
		B vs P	-8.6111	1
		P vs C	-2.2222	1
	Season 2	B vs P vs C	3.06	0.1215
		B vs C	40.8333	0.292
		B vs P	-6.6667	1
		P vs C	-47.5	0.188
Between seasons	Season 1	B	-5.6944	1
	vs	C	41.5278	1
	Season 2	P	-3.75	1

B = bamboo-drip system; P = plastic-drip system; C = watering-can system; F-value is the ratio of the variance between the groups compared and the variance within those groups. P-value is the probability of being wrong when saying there is a difference between the groups compared.

The results show that yields are overall low (Figure 3.5), which could be due to the absence of mineral fertilization during cultivation and the low planting density. A slight pruning was also performed during cultivation to improve plant health, but this led to a lower stem density and fruit number per plant. Another possible yield reduction factor is heat stress due to the relatively high air temperature observed, specifically during harvest index development (Figure 3.6).

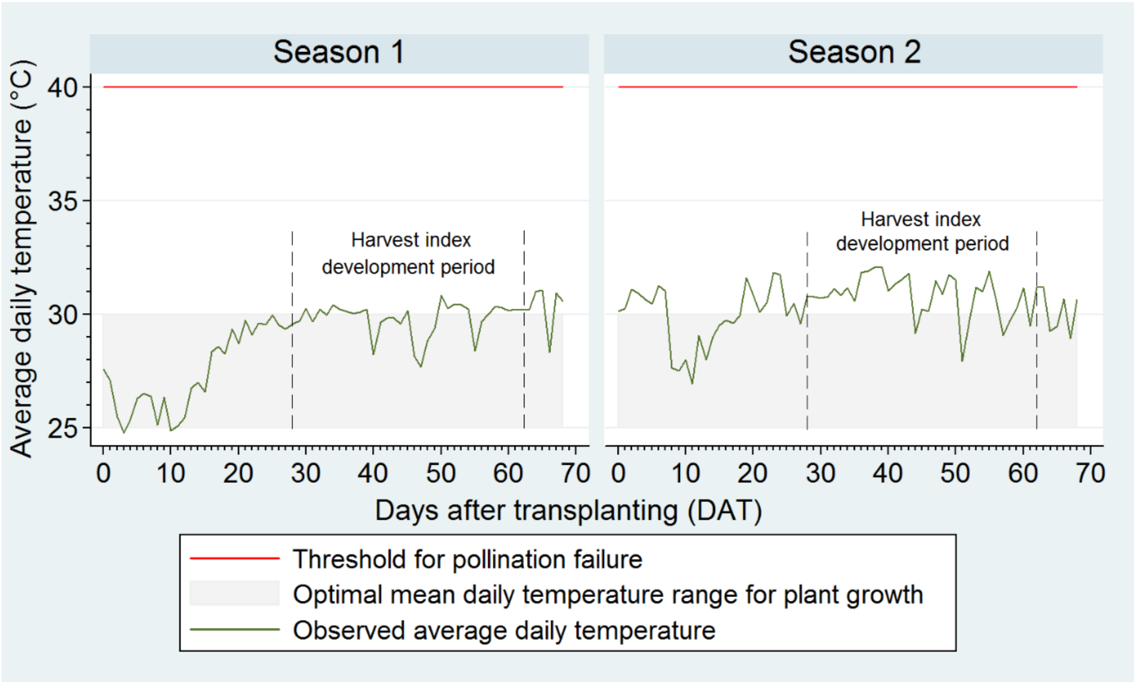

Figure 3.6 *Average daily temperatures during experiment*
Note: Optimum range for tomato plant growth and threshold for pollination failure according to Cirad, G (2002)

The observed average daily temperature was around the upper limit of the optimum crop growth range during season 1, and was slightly but significantly above the optimum range during season 2 (Table 3.4).

Table 3.4 *Observed average daily temperatures in relation to 30°C (upper limit of optimum temperature range for tomato plant growth)*

	T_{avg} (°C) < 30°C	**T_{avg} (°C) > 30°C**
	P-value	**P-value**
Season 1	0**	1
Season 2	0.9951	0.0049**

T_{avg} = observed average daily temperature; ** highly significant. P-value is the probability of being wrong when saying there is a difference between the groups compared.

The plants were then subject to heat stress, which was more pronounced during season 2, and might have reduced pollination and hence yields. The adverse effect of high temperature on tomato yield was confirmed by Adams *et al.* (2001) in tropical and sub-tropical parts of the world where they observed 18 and 17% yield reduction at mean temperatures of 26°C and 29°C, respectively, as compared to 22°C and 25°C. Zhang, Li and Xu (2008) also observed a very high yield decrease (-46.1%) at a day temperature of 35°C when compared to 25°C.

Yields were also similar between the three irrigation systems and between cropping seasons (Table 3.3), which implies that the bamboo system successfully competed with both conventional plastic-drip and watering-can systems with regard to soil moisture conditions suitable for crop growth without water stress. The availability of adequate soil moisture at critical stages of the plant cycle optimizes the metabolic processes of the cells and increases the effective absorption of soil mineral nutrients. As a consequence, any degree of water stress may have a negative effect on plant growth and yield. When irrigation frequencies are too low, the root zone becomes too dry (El-Hendawy and Schmidhalter, 2010), whereas too high frequencies tend to create excessive soil water, losses via evaporation, and oxygen limitation, because the application rate exceeds the root extraction rate. Oxygen limitation in the root zone creates hypoxia paradox (Bhattarai *et al.*, 2005), and impedes uptake of water and nutrients by the roots. Under severe conditions, it leads to the loss of membrane integrity, indiscriminate salt movement into the plants, and salt accumulation and subsequent injury to the leaves and to the whole plant (Barrett-Lennard, 2003). By creating a soil moisture level below field capacity and above the limit of the allowable depletion, the bamboo system favored a well-aerated root zone and avoided deficit or excess water content, which would limit root growth and development and reduce their absorbing capacity (Ehdaie *et al.,* 2010). This will be discussed in more detail in Chapter 4 through the analysis of soil-water content and matric potential.

3.2.2. Irrigation water productivity

Seasonal irrigation water productivity per irrigation system was determined and productivity of the three irrigation systems within and between cropping seasons compared (Figure 3.7 and Table 3.5).

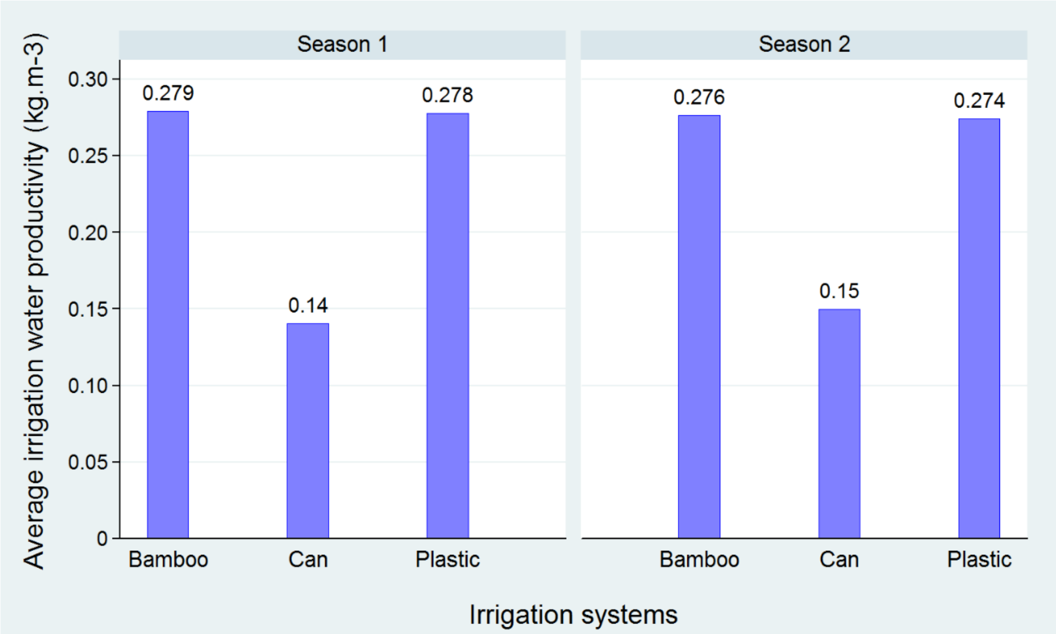

Figure 3.7 *Water productivity per irrigation system and cropping season*

Table 3.5 *Comparison of water productivity of irrigation systems within and between cropping seasons*

Comparison	Season	Irrigation system	F-value	P-value
Within season	Season 1	B vs P vs C	8.87	(0.0162)**
		B vs C	-0.0743	(0.028)**
		B vs P	-0.0044	1
		P vs C	0.0699	(0.037)**
	Season 2	B vs P vs C	19.26	(0.0024)**
		B vs C	-0.0567	(0.004)**
		B vs P	-0.0033	1
		P vs C	0.0534	(0.006)**
Between seasons	Season 1	B	-0.0105	1
	vs	C	0.0071	1
	Season 2	P	-0.0094	1

** highly significant; B = bamboo-drip system; P = plastic-drip system; C = watering-can system; F-value is the ratio of the variance between the groups compared and the variance within those groups. P-value is the probability of being wrong when saying there is a difference between the groups compared.

Table 3.6 *Increase in irrigation water productivity in bamboo-drip (desired situation) and plastic-drip (ideal situation) systems compared to traditional watering-can system (reference situation)*

		Δ WP_i
Season 1	Bamboo-drip system	+ 99 %
	Plastic-drip system	+ 98 %
	Bamboo-drip system	+ 85 %
Season 2	Plastic-drip system	+ 83 %

Δ WP_i = increase in irrigation water productivity compared to traditional watering-can system (reference situation)

Results show that irrigation water productivity under the three irrigation systems is overall low (0.276 $kg.m^{-3}$ and 0.145 $kg.m^{-3}$ for drip and watering-can systems, respectively) (Figure 3.7) compared to the common average of 1.3 $kg.m^{-3}$ determined by Battilani (2006) in climates of high evaporative demand and low canopy cover with frequent wetting of the exposed soil surface by rain or irrigation. This is based on the overall low yields observed.

Irrigation water productivity of the bamboo-drip system was similar to that of the ideal situation (plastic-drip system) (Table 3.5), and nearly the double of that of the reference situation (99% season 1, and 85% season 2) (Table 3.5 and 3.6). This was expected, since the water supply by the bamboo-drip system is targeted, thus reducing losses via evaporation and deep percolation without negatively affecting yields.

Yield and irrigation water productivity of the bamboo-drip system could be increased by optimizing its layout and combining it with controlled deficit irrigation or partial root drying technique. In the case of deficit irrigation, 50% of the root zone under the bamboo system would be irrigated at less than the maximum crop evapotranspiration, creating some minor stress at appropriate growth and development stages. This was used by Battilani *et al.* (2000) in processing tomatoes and proved to save irrigation water. For the partial root drying technique, only one side of the root zone would be irrigated, creating a drying which would affect biomass and not yield, i.e. trigger a continuous production of sufficient amounts of root-based chemical signals, hence reducing stomatal conductance and leaf expansion without significantly reducing yields. This was experienced by Zegbe *et al.* (2004) who reported 70% water productivity increase in tomato fields with the partial root drying technique compared to full irrigation. Kirda *et al.* (2004) also used partial root drying in greenhouse tomatoes and saved 50% of the irrigation water with only a marginal yield reduction.

4. CHAPTER 4: ASSESSMENT OF SOIL-WATER MANAGEMENT PERFORMANCE AND LAYOUT OPTIMIZATION

4.1. Materials and methods

4.1.1. 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 the stomata open. Plant responses to soil-water depend not only on content of water in the soil, but more importantly on potential, i.e. how readily available the water present is for movement or for plant uptake. An experiment was conducted where the bamboo-drip system was compared to conventional plastic-drip and traditional watering-can systems (see Chapter 3 for details). Soil-water management of the bamboo-drip system was assessed through soil-water content and soil-water potential, which were compared to the major characteristics of soil-water storage in each experimental plot. Data collection was done weekly in a random block/replicate, making sure three blocks were covered in three weeks (Table 4.1).

Table 4.1 *Monitoring process*

Week	DAT	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

In each plot of the selected block (Figure 3.2.), a random plant was selected and the wetting pattern around where it sits monitored at five positions, i.e. P1, P2, P3, P4 and P5 (Figure 4.1).

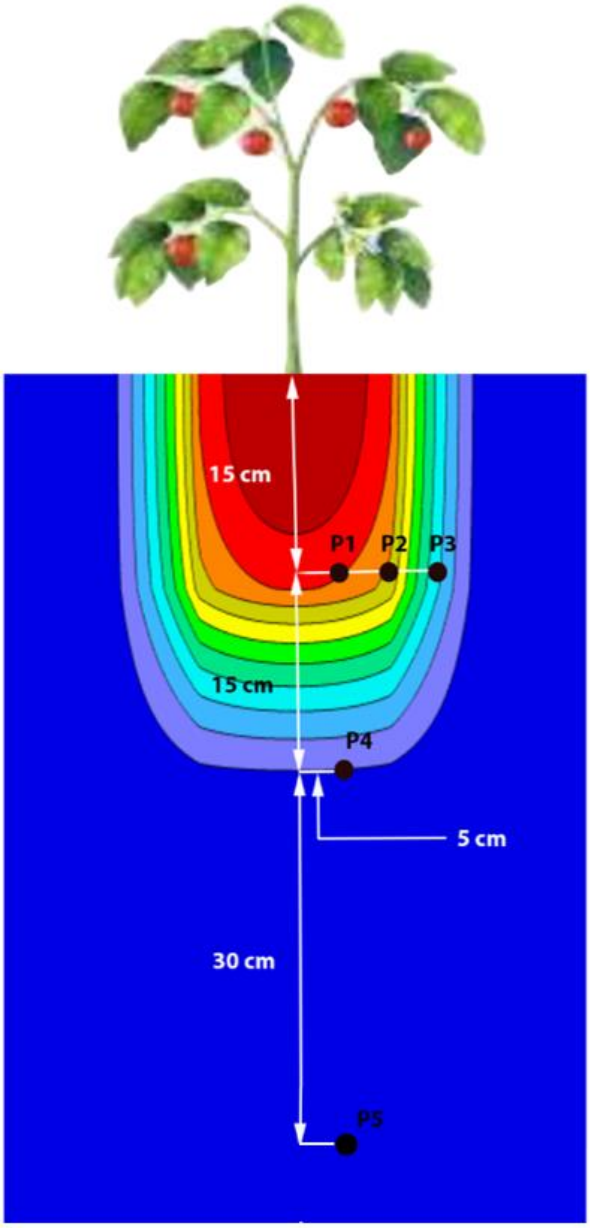

Figure 4.1 *Monitored positions in and around the rooting area*

4.1.1.1. Soil-water content

Soil-water content tells how much water is present in the soil at a given position and time. It 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 positions (P1, P2, P3, P4 and P5) before and after irrigation. After drying to a constant mass at 105°C for 21 h, the gravimetric water content was calculated as the ratio of water mass (wet sample mass minus dry sample mass) to dry sample mass. Then, the volumetric water content (water by volume) 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.

4.1.1.2. Soil-water potential

Soil-water potential tells how readily available the water present in the soil is for movement or for plant uptake. It is the potential energy status of a small parcel of water in the soil. In the soil, water is subjected to forces originating from the matrix (solid phase), gravity, dissolved salts and external gas. The soil-water matric potential is the portion of the water potential attributed to the attraction of the matrix only. It is caused by capillary action similar to the rise of water in small cylindrical capillary tubes and is a good indicator for water availability to roots and microorganisms (Gleeson *et al*., 2008).

Tensiometers (14.04.03 Tensiometer[5]) were used to measure the soil-water matric potential. They consist of a porous, permeable ceramic cup connected through a water-filled tube (to be kept saturated) to a vacuum gauge. Water moves through the cup into the soil, thereby creating suction/tension in the tube, 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 with regard to drip emitter (drip plots) and to where the plant sits (watering-can plots) are shown in Figure 4.2.

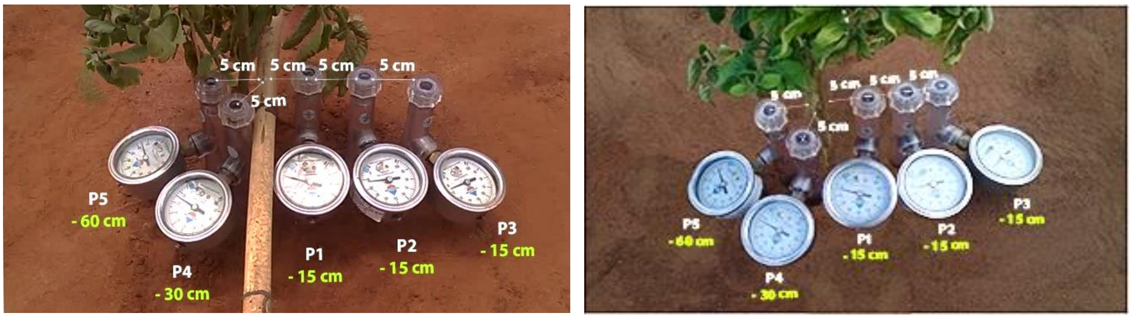

Figure 4.2 *Tensiometers in drip (left) and watering-can (right) plots*

[5] https://www.eijkelkamp.com/download.php?file=M11404e_Tensiometers_ee6b.pdf

4.1.1.3. Soil-water characteristics

The major characteristics for describing water storage behaviour of the soil are saturation (Sat), field capacity (FC), readily available water (RAW) and permanent wilting point (PWP). These characteristics provide basic information for irrigation scheduling and are employed in this study. *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. The total available water (TAW) is the amount of water that a crop can extract from its root zone, ranging from *FC* to *PWP*. The *RAW* is the fraction of the *TAW* that plants can extract from the root zone without suffering water stress. When the soil-water content is sufficient, no stress is observed, which is indicated by actual evapotranspiration at potential level. When it goes below the *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. The *RAW* is calculated based on the management allowable depletion (MAD), i.e. the maximum decrease in soil-water content that a farmer allows between irrigation events. A *MAD* value of 30 % was considered (FAO 56 requirements), i.e. *RAW* was 70% of *TAW*. Between *MAD* and *FC*, soil-water content is at an optimum, and a higher or lower water content would result in suboptimal yields due to water stress (deficit or waterlogging). Below the *MAD* value, soil-water can no longer be transported quickly enough towards the roots to respond to transpiration demand. The Saxton method was used to calculate *FC* and *PWP* for each plot (Chapter 2). *Sat* was determined using the Soil Water Characteristics Program[6].

4.1.2. Layout optimization

An optimally designed drip system delivers water to the plants exactly when required, in the necessary quantity, and in a manner that all the delivered water is utilized by the

[6] The Soil Water Characteristics Program estimates soil-water tension, conductivity and water-holding capacity based on the soil physical properties, texture, organic matter, gravel , salinity and compaction (https://hrsl.ba.ars.usda.gov/soilwater/Index.htm).

plants and none is wasted. Optimization of the layout of the bamboo system consists of improving its spacing, i.e. identifying for a given soil type (sandy loam in this study) the spacing where the best trade-off between reduced deep percolation and increased fresh yields is observed. The process requires integration of the agronomic and hydrologic behaviors of the bamboo system through the use of numerical models. For this purpose, the models HYDRUS 2D (hydrologic behavior) and AquaCrop v.5.0 (agronomic behavior) were applied. As a prerequisite for simulation, these models were calibrated and validated using data from the field experiments.

4.1.2.1. HYDRUS 2D for soil-water dynamics modeling

- **Overview**

Spacio-temporal soil-water dynamics (i.e. infiltration and redistribution; capillary rise did not occur due to deep groundwater) of the root zone under the bamboo system were simulated using HYDRUS 2D, which is a two-dimensional finite element model (Šimůnek *et al.*, 2011) based on the mass conservative iterative scheme, and allowing the analysis of both vertical and lateral fluxes of water from a source with particular geometrical boundaries. This is specifically important for watering-can and drip irrigations, where flux directions change over time due to changing boundary fluxes and local variations in water pressure head gradients. The model has been thoroughly tested and proven to numerically solve the modified Richards' convection-dispersion equation for water flow in variably saturated porous media using the Galerkin finite element method (or numerical techniques). It has been extensively used to simulate water flow in agricultural fields with different crops and various irrigation schemes. Assuming homogeneous and isotropic soil, the governing equation for water flow can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[rK(h)\frac{\partial h}{\partial r}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial K(h)}{\partial z} - S \qquad (4.1)$$

where θ is the soil volumetric water content ($cm^3.cm^{-3}$), *t* is time (day), *r* is the radial coordinate (cm), *K (h)* is the hydraulic conductivity ($cm.\ day^{-1}$), *h* is the pressure head (cm), *z* is the vertical coordinate with positive upwards (cm), and *S* is a distributed sink function representing water uptake by the roots ($1.day^{-1}$).

➢ **Inputs and parametrization**

- **Estimation of soil hydraulic parameters**

The soil layer used by roots as storage under high frequency irrigation scheduling (such as in the experiment carried out by this study) remains near field capacity throughout the cropping season. Of the two models commonly used to describe soil moisture behavior, the van Genuchten analytical model (van Genuchten, 1980) is the most appropriate for such soils, and was chosen to numerically simulate soil hydraulic properties:

$$\Theta(h) = \theta r + \frac{\theta sat - \theta r}{[1+(\alpha h)^n]^m} \qquad h < 0$$

$$\Theta(h) = \theta sat \qquad h \geq 0 \qquad (4.2)$$

$$K(h) = Ksat\ Se^l\ [1-(1-Se^{\frac{1}{m}})^m]^2$$

$$Se = \frac{\theta - \theta r}{\theta sat - \theta r}$$

where θ is soil-water content, *α* root water uptake rate, *h* local soil-water pressure head, *Se* effective fluid saturation (dimensionless), θr and θ*sat* residual and saturated water content, respectively ($L^3.L^{-3}$), *K (h)* unsaturated hydraulic conductivity function ($L.T^{-1}$), K_{sat} saturated hydraulic conductivity ($L.T^{-1}$), *n* and *m* (both dimensionless) are empirical shape parameters where m = 1−(1/n), and *l* is pore connectivity (tortuosity) parameter (dimensionless). ***l*** (from $Se^{\,l}$) was considered 0.5, the average for many soils (Mualem, 1976).

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, their values were estimated with the built-in pedotransfer function ROSETTA[7] (Schaap *et al*., 2001) by inputting the particle size distribution and dry bulk density data determined from the soil samples.

- **Evapotranspiration**

Potential evapotranspiration (ET_c) was estimated using the dual-coefficient approach (Allen *et al*., 1998; Chapter 3). In HYDRUS 2D, potential transpiration and evaporation are transformed into actual values by affecting them with a stress factor according to soil matric potentials and salinity condition. However, salinity stress is assumed to be absent at the study site, as the relatively low salt content in the irrigation water would have lead to only low salt accumulation, leachable by a high rainfall. Evaporation was modeled by Darcy's law when the soil surface is dry with a water potential below a critical pressure head (hCritA[8]), i.e. −15000 cm in this study. Transpiration was according to FAO 56 and allocated to soil layers based on root architecture/Feddes model (Feddes *et al*., 1978) embedded in HYDRUS 2D. The Feddes model assigns root-water uptake rates according to the local soil-water pressure head (h) at any finite element node point in the root zone. It defines how transpiration is reduced below the potential value when the soil is dry, i.e. no longer able to fulfill plant demand under the prevailing climatic conditions. It is expressed as:

$$\alpha(h) = \begin{cases} 0, & h > h_1 \text{ or } h \leq h_4 \\ \frac{h-h1}{h2-h1}, & h_2 < h \leq h_1 \\ 1, & h_3 < h \leq h_2 \\ \frac{h-h4}{h3-h4}, & h_4 < h \leq h_3 \end{cases} \tag{4.3}$$

[7] ROSETTA is an artificial neural network-based model which predicts soil hydraulic parameters from texture and related data.
[8] hCritA is the minimum allowed pressure head at the soil surface (atmospheric boundary) for the evaporation flux to be at its potential value. When the soil surface pressure head is lower than hCritA (h < hCritA), evaporation is reduced from potential to actual value. The value of hCritA is usually selected based on the soil texture, using lower values (-50000 cm) for fine-textured soils, about -15000 cm for moderately-textured and coarse soils (field experiment), and about -1000 cm for sandy soils or gravel (https://www.pc-progress.com/forum/viewtopic.php?f=3&t=1876).

where α is the root-water uptake rate, h local soil-water pressure head, h_1 (-10 cm), h_2 (-25 cm), h_3 (-1500 cm for a potential transpiration rate of 10%, and -800 cm for a rate of 50%), and h_4 (-8000 cm) are threshold soil-water pressure heads imbedded in HYDRUS 2D for tomato crop.

Water uptake is assumed to be zero when the root zone water content is close to saturation (i.e. wetter than the anaerobiosis pressure head "h_1") or less than the wilting point pressure head "h_4". In the first case, the roots are short of oxygen, and in the second, they are short of water. Water uptake is considered optimal between two pressure heads (h_2 and h_3), and decreases or increases linearly when h lies between h_3 and h_4 or between h_1 and h_2.

- **Flow region and boundary 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 4.3) was a homogeneous and isotropic one-layer rectangular profile, 60-cm deep and 30-cm wide, representing the cross-sectional space between two plants. The flow region was discretized into a structured triangular finite element mesh of 8530 nodes. 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 was relatively coarse (sandy loam), this fine spatial discretization was appropriate to avoid numerical oscillations and to achieve acceptable mass balance errors (Šimůnek *et al.*, 2008). The top surface was assigned an ''atmospheric boundary'' condition to allow interactions between the soil and the atmosphere. These interactions are either evaporation, watering-can irrigation or rainfall. In the case of evaporation, a flux is prescribed when the 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 plots, a single surface dripper represented by a line source (4.94 cm length) was placed at the corner of the flow region where the plant sits.

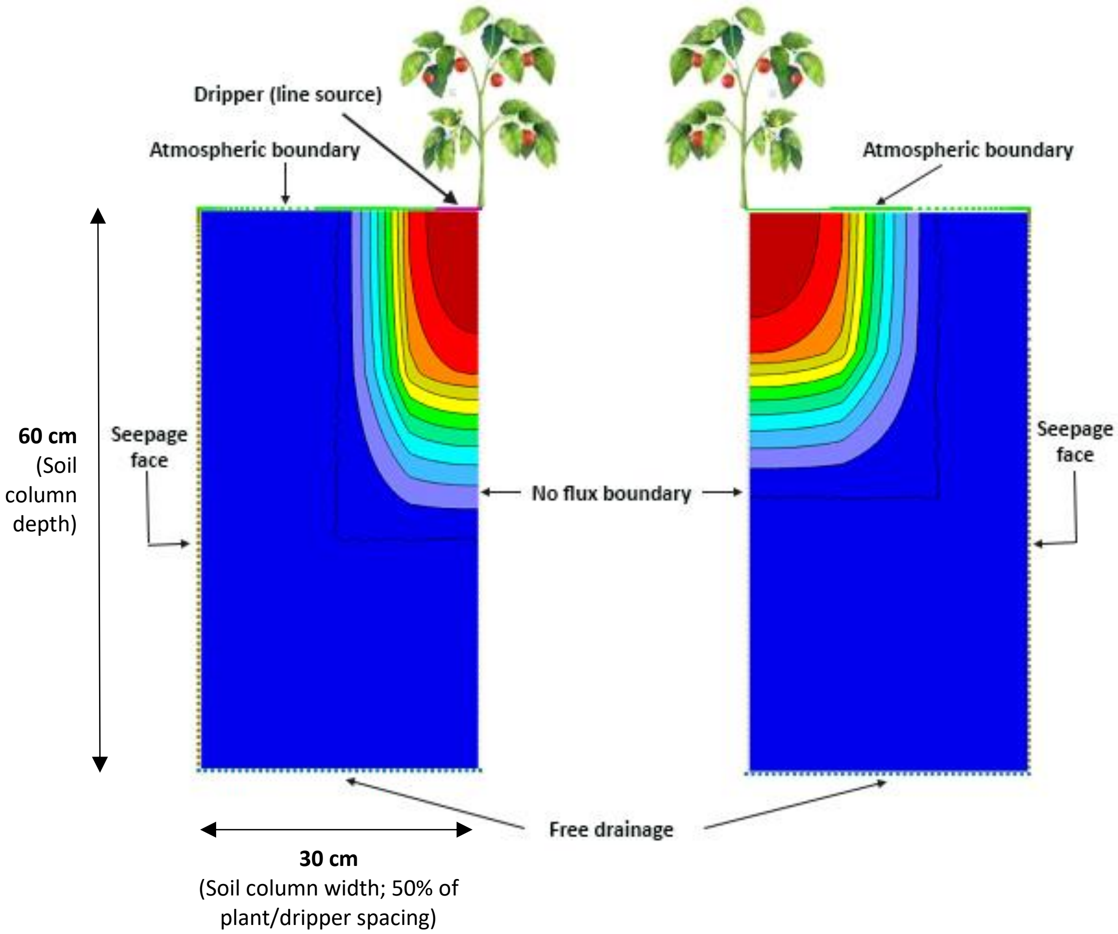

Figure 4.3 *Flow region and boundary conditions for drip (left) and watering-can (right) plots*

For each daily irrigation event, the dripper flux (q) was estimated as:

$$q\ (cm.day^{-1}) = \frac{Dripper\ discharge\ flow\ rate\ (cm^3.day^{-1})}{Drip\ tubing\ surface\ area\ (cm^2)} \tag{4.4}$$

The vertical side of the flow region (Figure 4.3) below where the plant sits was assigned a no-flux boundary condition (impermeable and not allowing water into or out of the flow region), as soil-water movement is symmetrical there. Opposite to this was a seepage face with 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 a free-drainage condition (pressure head gradient equal to zero), assuming that the deep water table (36 m) had no impact on moisture dynamics of the flow region.

4.1.2.2. AquaCrop for crop-water productivity modeling

- **Overview**

Crop-water productivity under the bamboo system was modelled using AquaCrop (Steduto *et al*., 2009). The choice of this model was motivated by its ability to maintain an optimal balance between accuracy (lower error probabilities), its robustness and simplicity (requires minimum explicit and mostly intuitive input data) (García-Vila and Fereres, 2012), its moderate input requirements, and the availability of default values for a wide range of crops. Furthermore, AquaCrop is water driven and has the advantage over radiation-driven models of being able to normalize water productivity based on climate. It can thus be applied in different locations under varying climatic and spatio-temporal settings (Steduto and Albrizio, 2005). Although simple, it pays particular attention to the fundamental processes involved in crop productivity and yield response to water from physiological and agronomic perspectives. Among other specificities, its features are:

- the use of ground canopy cover instead of leaf area index,
- the expression of root development in terms of effective rooting depth changing over time, the calculation of yield as a product of biomass and harvest index, and
- the expression of water stress through stress coefficients specific for leaf expansion, stomata closure, canopy senescence and change in harvest index.

AquaCrop is a decision-support tool which aims to assist researchers and field practitioners (farmers, agricultural consultants, water managers, and policymakers) with developing irrigation management strategies, planning projects and carrying out future climate scenario analyses for a location. So far, it has been successfully used to determine crop response to water stress and irrigation levels (Araya *et al*., 2010a,b), improve on-farm irrigation management (Garcia-Vila and Fereres 2012), develop deficit irrigation scheduling (Paredes *et al*., 2014), design irrigation strategies (Geerts *et al*., 2010), evaluate sowing strategies (Abrha *et al*., 2012), evaluate the potential increase in crop production by field management (Mhizha *et al*., 2014), develop economic models for farm-scale decision support (García-Vila and Fereres, 2012), assess climate change impact on crop production (Vanuytrecht *et al*., 2014b), and evaluate water salinity effects on crop production (Kumar *et al*., 2014). It has been used to simulate growth of over 15 cultivated crops among which are cotton (Farahani *et al*., 2009), maize (Paredes *et al*., 2014), wheat (Andarzian *et al*., 2011), sunflower (Todorovic *et al*., 2009), potato (Garcia-Vila and Fereres, 2012), and tomato (Katerji *et al*., 2013).

AquaCrop evolved from concepts of stage yield response to water (Doorenbos and Kassam, 1979) to the concept of normalized crop water productivity where relationships are based on a daily time step (Steduto *et al*., 2009). The empirical approach of Doorenbos and Kassam is:

$$1 - \frac{Ya}{Ym} = k_y \left(1 - \frac{ETa}{ETm}\right) \quad (4.5)$$

where Y_m and Y_a are the maximum (potential) and actual yields, $1-Y_a/Y_m$ the relative yield decline (loss), ET_m and ET_a the maximum and actual evapotranspiration (dependent on soil moisture availability), $1-ET_a/ET_m$ the relative water stress (relative reduction in evapotranspiration) and k_y[9] the proportionality factor between relative yield decline and relative reduction in evapotranspiration. Y_a is the product of biomass and a dynamic harvest index, which evolves during the yield formation phase until reaching a maximum value.

AquaCrop relies on the conservative behavior of biomass per unit transpiration relationship and splits the actual evapotranspiration (ET_a) into soil evaporation (E_s) and crop transpiration (T_r) to avoid the confounding effect of non-productive consumptive use of water. Splitting also enables targeted determination of irrigation scheduling data,

[9] k_y values are crop specific and vary over the growing season according to growth stages. For tomato, Aquacrop considers ky equal to 1.05, i.e. yield reduction is almost directly proportional to reduced water use (Doorenbos and Kassam, 1979).

as it allows directly referring to crop transpiration. Furthermore, partial wetting of the soil surface is considered, which is especially relevant in the case of drip irrigation. In AquaCrop, actual crop transpiration is calculated first (from canopy cover), then translated into biomass using the biomass water productivity, a conservative crop-specific parameter normalized for evaporative demand and air CO_2 concentration. This is represented by the following conceptual equation, i.e. the core of AquaCrop model:

$$B = WP^{*}. \sum_{1}^{n}\left(\frac{Tri}{ETo_i}\right) \quad (4.6)$$

where B is the cumulative aboveground biomass production (g.m^{-2}), Tr_i the daily crop transpiration (mm.day^{-1}), and ET_{oi} the daily reference evapotranspiration (mm.day^{-1}). It can be determined with the FAO Penman-Monteith equation using meteorological data (Allen *et al.*, 1998). n is the sequential days spanning the period when B is produced, and WP^* crop water productivity (g.m^{-2}) normalized for CO_2 concentration and local climate.

WP^* is a crop-specific parameter that is typically constant for a given crop species (Steduto *et al.*, 2009). It considers the crop-water productivity for a reference CO_2 concentration of 369.41 mol.mol^{-1} (i.e. the average CO_2 concentration for the year 2000 measured at the Mauna Loa Observatory in Hawaii, USA), and tends to remain robust under both well-watered and water-deficit conditions, and also variable soil nutrient status. Its indicative range for C_3 plants[10] is 15-20 g.m^{-2}, and the default value of 17 g.m^{-2} was considered in this study.

- **Inputs and parametrization**

AquaCrop 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 main agronomic practices

[10] Plants in which the CO_2 is first fixed into a compound containing three carbon atoms before entering the Calvin cycle of photosynthesis (https://www.biology-online.org/dictionary/C3_plant)

such as planting dates and fertilizer application), and *Soil* (fertility and water balance) (Hsiao *et al*., 2009). Pests, diseases, and weeds are not considered (Raes *et al*., 2009a).

- **Climate**

AquaCrop was executed at daily time steps to allow a realistic accounting of the dynamic nature of water stress effects and crop responses. The Mauna Loa Observatory value (369.47 ppm, included in the model structure) was used as the CO_2 concentration, and reference evapotranspiration (ET_o) was calculated daily using the Penman-Montheith equation (Equation 3.3; Chapter 3).

- **Management**

Management inputs are *field management* and *actual irrigation* (amount and timing). Field management includes soil fertility (which affects crop canopy development and biomass production), mulches (which reduce soil evaporation), field surface practices (tillage and soil bunds, which affect soil surface storage and runoff) and soil structure management (the presence or absence of a restrictive soil layer that would affect root zone expansion).

- **Soil**

AquaCrop simulates root zone water content by keeping track of incoming (rainfall and irrigation) and outgoing (runoff, evaporation, transpiration and deep percolation) water fluxes at its boundaries, considering the soil as a water storage reservoir with different layers. Infiltration and internal drainage are estimated by an exponential drainage function, which takes into account initial wetness and drainage characteristics of the different soil layers. To allow accurate root zone water content simulation by the model, the soil profile was divided into 4 layers of 15 cm each, where the water content was determined gravimetrically at the beginning of the cropping season and supplied as model input. Other layer input parameters are texture (sandy loam in this study), field capacity (FC), permanent wilting point (PWP), saturated hydraulic conductivity (K_{sat}), and volumetric water content at saturation (θ_{sat}). 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 have obstructed 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 the HYDRUS 2D model. Furthermore, the default values in AquaCrop for infiltration and redistribution were used (see Table 4.2).

- **Crop**

  ✓ **Phenology**

Crop input parameters are of two types: *conservative* and *non-conservative* (cultivar specific). *Conservative* parameters are nearly constant and do not change with time, management practices or geographic location. They seldom need to be adjusted during AquaCrop simulations (Raes *et al.*, 2009), are applicable to a wide range of conditions and are not specific for a given crop cultivar (Steduto *et al.*, 2012). Among them are canopy cover growth and decline, crop coefficient for transpiration at full canopy, water productivity for biomass and soil water depletion thresholds. *Non-conservative* parameters (e.g. plant density and time to maturity) are affected by the climate, field management or soil profile conditions. They were calibrated according to cultivar characteristics observed during the field experiment, and included time to emergence, start and end of flowering, date of maximum canopy cover, start of senescence (time at which the canopy cover started to decline), and physiological maturity.

  ✓ **Biomass production**

Biomass production is associated with crop parameters such as stomatal conductance, canopy senescence and harvest index (Steduto *et al*., 2009). As previously mentioned, the aboveground biomass is estimated in AquaCrop as the product of the seasonal cumulated ratio between actual transpiration (Tr_i), evapotranspiration (ET_o) and crop water productivity normalized for CO_2 concentration and local climate (WP*).

- **Harvestable yield**

Dry yield is simulated in AquaCrop from its formation onset, and as a portion of the aboveground biomass employing a user-defined reference harvest index HI_o[11] (Raes *et al.*, 2009), which was adjusted from 55% until 49% during model calibration. The harvest index is a non-conservative parameter which varies depending on the irrigation water deficit experienced by the crop, depending on crop stage and stress severity (Steduto *et al.*, 2009). It is simulated by a linear increase from flowering up to physiological maturity (Steduto *et al*., 2009). It is also adjusted by the model in response to five water stress coefficients, namely for inhibition of leaf growth, for inhibition of stomata, for reduction in green canopy duration due to senescence, for reduction in biomass due to pre-anthesis[12] stress and for pollination failure (Steduto *et al.*, 2009).

- **Maximum rooting depth**

At maturity, root depth was measured on all plots by excavating the soil close to the plants and measuring the depth to which roots grew. The effective rooting depth (depth at which the crop conducts most of its water uptake; Raes *et al.*, 2009) 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).

- **Fertility and spikelet sterility**

AquaCrop provides categories of soil fertility levels ranging from *non-limiting* to *severely limiting*. It calibrates crop response to soil fertility according to the chosen level of fertility by adjusting the maximum canopy cover, the canopy growth coefficient, the canopy decline coefficient, and the normalized water productivity. This adjustment is done through the soil fertility stress coefficient for canopy expansion (Ks.exp,f ≤1), maximum canopy cover (Ks.CCx ≤1), water productivity (Ks.WP ≤1) and average daily decline of canopy cover once the maximum canopy cover is reached (fcDecline ≥0).

---

[11] The reference Harvest Index (HIo) is the ratio of the dry yield mass to the total dry aboveground biomass that will be reached at maturity for non-stressed conditions. HIo is a cultivar-specific crop parameter.
http://www.fao.org/3/a-br248e.pdf

[12] Period before the expansion (opening) of flowers. http://www.dictionary.com/browse/anthesis

Spikelet sterility is the phenomenon by which the spikelets[13] scheduled to pollinate on a day when the panicle water potential[14] is low (-1.8 MPa for example, meaning water molecules can move relatively freely in the panicles) do not open to shed pollen, which reduces the harvest index. AquaCrop models the negative effects of high temperature on spikelet sterility at flowering time.

- ✓ **Crop coefficients and aerial canopy**

The crop coefficients take into account crop characteristics and averaged effects of soil evaporation. Crop aerial canopy is the source for actual transpiration, which is translated in a proportional amount of biomass produced through the water productivity parameter. AquaCrop calculates canopy cover based on several input parameters, in particular canopy growth coefficient (CGC), maximum canopy cover (CC_X) and canopy decline coefficient (CDC). Environmental factors such as water stress and temperature influence crop development stage and leaf growth, and thus affect the time course of the canopy cover. Using observed key phenological dates (time to emergence, maximum canopy cover, senescence and maturity), AquaCrop computes canopy cover through three phases (Raes *et al*., 2012). The first one is exponential, uses an exponential time function, starts at crop emergence and ends at $0.5\ CC_X$. It is proportional to the existing canopy size for photosynthesis, and its growth rate is defined by the parameter *CGC*. The second phase applies another exponential function until the maximum canopy cover (CC_x) is reached. It starts when plants start to shade each other, and is not proportional to the existing canopy size. Its shape is given by the same *CGC* parameter. The last phase refers to the exponential decline of green canopy cover after senescence started (Hsiao *et al*., 2009). Its shape is defined by the parameter *CDC* (Raes *et al*., 2012). The overall canopy development function is:

[13] Flower clusters, or units of inflorescence consisting of two or more flowers and subtended by one or more glumes variously disposed around a common axis. http://www.dictionary.com/browse/spikelet

[14] Measure of how freely water molecules can move in a particular environment or system (here in the panicles). https://biologydictionary.net/water-potential/

$$\begin{cases} \boldsymbol{CC = CC_o \cdot e^{CGC * t}} \\ \boldsymbol{CC = CC_x \left[1 - 0.5 \left(e^{CDCt / CCx} - 1\right)\right]} \\ \boldsymbol{CC = CC_x - (CC_x - CC_o) \cdot e^{-CGC * t}} \end{cases} \qquad (4.7)$$

where CC is the canopy cover at time t, expressed in fraction of ground cover. CC_0 is initial canopy cover (at t = 0) in fraction, proportional to plant density and mean initial canopy size per seedling. CGC is canopy growth coefficient in fraction per day. CDC is canopy decline coefficient (in fraction reduction per day).

Crop sub-model inputs are shown in Table 4.2.

Table 4.2. *Inputs of crop sub-model*

Parameter	Type	Determination	Unit	Value
Base temperature below which crop development does not progress	CGA	Default	°C	7
Upper temperature above which crop development no longer increases with an increase in temperature	CGA	Default	°C	28
Soil water depletion factor for canopy expansion (p-exp) - Upper threshold	CGA	Estimated	-	0.15
Soil water depletion factor for canopy expansion (p-exp) - Lower threshold	CGA	Estimated	-	0.55
Shape factor for water stress coefficient for canopy expansion (0.0 = straight line)	CGA	Estimated	-	3
Soil water depletion fraction for stomatal control (p - sto) - Upper threshold	CGA	Estimated	-	0.5
Shape factor for water stress coefficient for stomatal control (0.0 = straight line)	CGA	Estimated	-	3
Soil water depletion factor for canopy senescence (p - sen) - Upper threshold	CGA	Estimated	-	0.7
Shape factor for water stress coefficient for canopy senescence (0.0 = straight line)	CGA	Estimated	-	3
Soil water depletion factor for pollination (p - pol) - Upper threshold	CGA	Default	-	0.92
Vol% for anaerobiotic point at which deficient aeration occurs	CS, DE/M	Default	vol%	5
Minimum air temperature below which pollination starts to fail (cold stress)	CGA	Default	°C	10
Maximum air temperature above which pollination starts to fail (heat stress)	CGA	Default	°C	40
Electrical conductivity of soil saturation extract at which crop starts to be affected by soil salinity	CGA	Literature	dS/m	2
Electrical conductivity of soil saturation extract at which crop can no longer grow	CGA	Literature	dS/m	72
Crop coefficient when canopy is complete but prior to senescence (KcTr,x)	CGA	Literature	-	1.1
Decline of crop coefficient as a result of ageing, nitrogen deficiency, etc.	CGA	Default	%/day	0.15
Minimum effective rooting depth	DE/M	Measured	m	0.1
Maximum effective rooting depth	DE/M	Measured	m	0.35 (for bamboo-drip and plastic-drip) 0.3 (for watering-can)
Shape factor describing root zone expansion	CGA	Estimated	-	15
Effect of canopy cover in reducing soil evaporation in late season stage	CGA	Estimated	-	50
Soil surface covered by an individual seedling at 90 % emergence	C-CS	Measured	cm^2	5
Number of plants per hectare	DE/M	Measured	-	26667
Canopy growth coefficient (CGC): Increase in canopy cover	CGA	Estimated	Fraction of soil	0.21443

			cover per day	
Maximum canopy cover (CCx)	DE/M	Measured	Fraction of soil cover	0.24
Canopy decline coefficient (CDC): Decrease in canopy cover	CGA	Estimated	Fraction per day	0.06094
Calendar Days: from transplanting to recovered transplant	DE/M	Measured	Days	6
Calendar Days: from transplanting to maximum rooting depth	CS	Measured	Days	34
Calendar Days: from transplanting to start of senescence	CS	Measured	Days	63
Calendar Days: from transplanting to maturity	CS	Measured	Days	75
Calendar Days: from transplanting to flowering	CS	Measured	Days	28
Length of flowering stage	CS	Measured	Days	15
Excess of potential fruits	C-CS	Default	%	50
Building up of harvest index starting at flowering	CS	Measured	Days	47
Water productivity normalized for ET_o and CO_2 (WP*)	CGA	Default	$g.m^{-2}$	17
Water productivity normalized for ET_o and CO_2 during yield formation	CGA	Default	% WP*	100
Crop performance under elevated atmospheric CO_2 concentration	CGA	Default	%	50
Reference harvest index (HI_o)	CS	Calibrated	%	49
Possible increase in HI due to water stress before flowering	CGA	Estimated	%	5
Coefficient describing positive impact on HI of restricted vegetative growth during yield formation	CGA	Estimated	-	10
Coefficient describing negative impact on HI of stomatal closure during yield formation	CGA	Estimated	-	8
Allowable maximum increase in specified HI	CGA	Estimated	%	15

CGA = conservative generally applicable; CS = cultivar specific; DE/M = dependent on environment and/or management; C-CS = conservative but can/may be cultivar specific. Shading highlights where the inputs for drip-irrigated (plastic and bamboo) and can-watered plots differ.

4.1.2.3. Layout optimization process

Hydrologic and agronomic behaviors of the bamboo-drip system were integrated to identify the best spacing, thereby maximizing fresh yields and minimizing deep percolation (DP). The second of the two cropping seasons was randomly selected, and the third replicate of the bamboo-drip system was considered for simulations, as it was the only one (among the three replicates of the bamboo-drip system) having been monitored until late season phase (see Table 4.1). HYDRUS 2D was linked to AquaCrop through the daily water stress level defined as the ratio between actual and potential plant water uptakes. AquaCrop provided the daily relative evaporation and transpiration values $(\frac{Actual\ value}{Maximum\ value})$ 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 *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, the minimal possible spacing which prevents the touching of lateral roots. For each of the resulting new spacings (30 in total), laterals per plot, emitters per lateral and emitters (also plants) per plot were calculated (Table 4.3). After dry yield[15] simulations with AquaCrop, fresh yields were calculated by multiplying dry yields by 6.67 (100/15).

Layout optimization[16] 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:

- **Decision variable**: best spacing (x).
- **Objective**: minimize deep percolation (DP) while maximizing fresh yield (Y).
- **Constraints**:

[15] Dry yield is the mass of the harvested tomato fruits after all water is removed by gravimetric method. It is considered 15% of fresh yield (mass of the fruits still containing water), (http://www.fao.org/nr/water/cropinfo_tomato.html).

[16] Results are shown and discussed in sub-chapter 4.2.2.

$\mathbf{x_{min} \leq x \leq 60\ cm,}$

$\mathbf{DP_{min} \leq DP \leq DP_{max},}$

$\mathbf{Y_{min} \leq Y \leq Y_{max}.}$

Table 4.3 *Number of laterals, emitters and plants per spacing in bamboo-drip plot*

Spacing (cm)	Laterals per plot	Emitters per lateral	Emitters (also plants) per plot
60	4	8	32
59	4	8	32
58	4	8	32
57	4	8	32
56	4	8	32
55	4	9	36
54	4	9	36
53	4	9	36
52	4	9	36
51	4	9	36
50	4	10	40
49	4	10	40
48	5	10	50
47	5	10	50
46	5	10	50
45	5	11	55
44	5	11	55
43	5	11	55
42	5	11	55
41	5	12	60
40	6	12	72
39	6	12	72
38	6	13	78
37	6	13	78
36	6	13	78
35	6	14	84
34	7	14	98
33	7	15	105
32	7	15	105
31	7	16	112
30	8	16	128

4.1.3. Statistical analysis

4.1.3.1. Soil-water management performance

Soil-water management performance of the bamboo system was assessed to determine how it uses soil storage, compared to the watering-can and the plastic-drip systems, i.e. content and availability of soil-water at different positions and times in and around the plant's root zone. This would reveal threats to root and plant metabolism under this system in case it applied water in deficit or in excess.

Comparisons of soil-water content 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 main characteristics of soil-water storage behavior (*Sat*, *FC*, *RAW* and *PWP*) and one-way ANOVA done for spatio-temporal comparisons. For spatial variations, replicates were compared per season to one another, whereas they were compared season-wise for temporal variations.

4.1.3.2. Layout optimization

HYDRUS 2D and AquaCrop were calibrated and validated by comparing observed and fitted (simulated) data of soil-water content and soil-water matric head (HYDRUS 2D), and of dry yield (AquaCrop). Measured matric head values (cm of water) were obtained by multiplying tensiometer values (matric potentials expressed in KPa) by 10.2, according to specifications in the operating manual[17]. 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 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). They were calculated as:

[17] https://www.eijkelkamp.com/download.php?file=M11404e_Tensiometers_ee6b.pdf

- **Pearson coefficient of determination (R^2)**

It is used to assess the degree of association (or error variance) between measured and simulated values according to:

$$R^2 = \left(\frac{\sum_{i=1}^{N}(Mi-\bar{M})(Si-\bar{S})}{\sqrt{\sum_{i=1}^{N}(Mi-\bar{M})}\sqrt{\sum_{i=1}^{N}(Si-\bar{S})}} \right)^2 \tag{4.9}$$

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

R^2 values range between 0 and 1, describing how much of the observed dispersion is explained by the prediction. A zero value means there is no correlation at all between observed and predicted values and values close to 1 indicate a good correlation.

- **Normalized root mean square error** (**NRMSE**)

It is calculated as:

$$NRMSE = \frac{1}{\bar{M}} \sqrt{\frac{\sum(Si-Mi)^2}{n}} \; x \; 100 \tag{4.10}$$

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

NRMSE expresses the overall mean deviation between observed and simulated value 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%.

- **Nash-Sutcliffe efficiency** (**NSE**) (Nash and Sutcliffe, 1970).

It is calculated as:

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Mi - Si)^2}{\sum_{i=1}^{N}(Mi - \bar{M})^2} \quad (4.11)$$

NSE values range from -∞ to 1, the latter indicating a perfect agreement between simulated and observed values. Negative values mean that the observed mean value would have been a better predictor than the model, and 0.5 (or higher) is generally viewed as an acceptable level of performance (Moriasi *et al.*, 2007).

Final values of saturated soil hydraulic conductivity (K_{sat}; Table 4.4) were those giving not only the best values of the statistical estimators considered, but also the best visual fit between observed and simulated curves (Figures 4.10 and 4.11).

Validation of HYDRUS 2D 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 here.

Table 4.4 *Values of K_{sat} per plot and per growth phase, before and after calibration*

	K_{sat} bc (cm.day^{-1})	**K_{sat} ac** (cm.day^{-1})			
		Dev	Mid	Late	Range of K_{sat} for very fine sandy loam (cm.day^{-1})
B1	86	75	74	74	
B2	96	68	66	66	
B3	82	64	62	63	
P1	73	63	61	61	
P2	103	82	79	79	37 – 122
P3	98	66	64	64	
C1	122	77	75	74	
C2	72	61	60	59	
C3	104	85	83	81	

K_{sat} bc = saturated hydraulic conductivity before calibration for each plot, determined with the built-in pedotransfer function ROSETTA by inputting particle size distribution and dry bulk density data of soil samples; K_{sat} ac = saturated hydraulic conductivity after calibration. It differs between growth phases because it was adjusted at each phase for simulated values of soil-water content and matric potential to match observed ones the most possible. Dev = development phase; Mid = mid-season phase; Late = late-season phase.

- **Calibration and validation of AquaCrop**

First and second-season observed yield data were used respectively for calibration and validation of AquaCrop. Calibration consisted of minimizing the difference between predicted and observed yields. The harvest index (HI) 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.

4.2. Results and discussion

4.2.1. Soil-water management performance

4.2.1.1. Soil-water content

For each plot, measured soil-water contents in each cropping season and comparisons to *FC* and *RAW* are shown in Figures 4.4, 4.5 and Table 4.5.

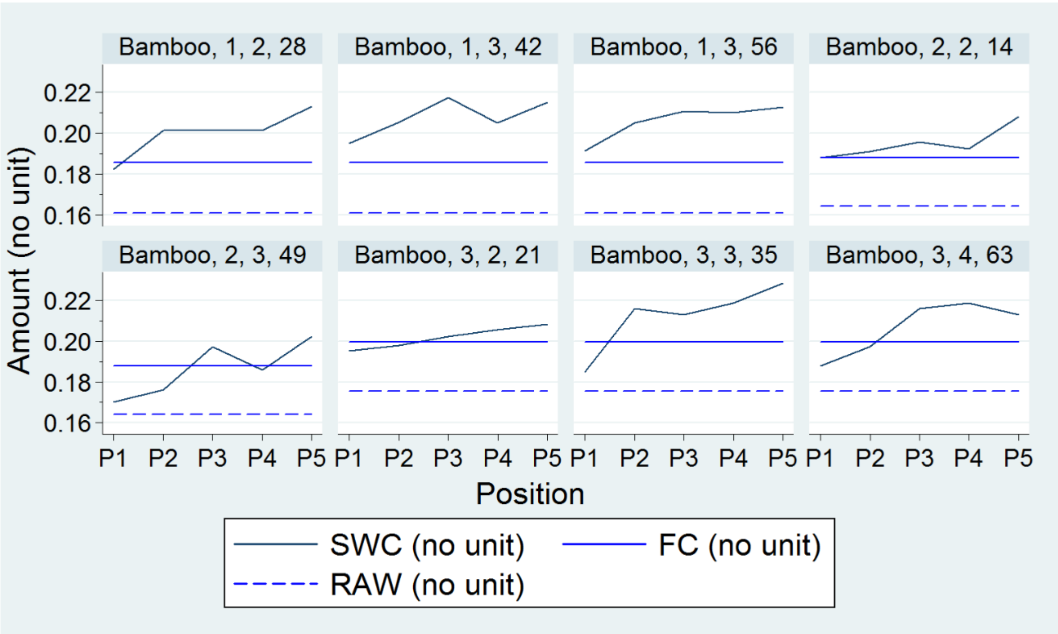

Figure 4.4 *Soil-water content (SWC), field capacity (FC) and readily available water (RAW) in the bamboo-drip system - season 1*

Note: First, second and third numbers are respectively for block, growth phase and days after transplanting. Growth phase 2 = development phase, 3 = mid-season phase, 4 = late season phase. P = position (Figure 4.1).

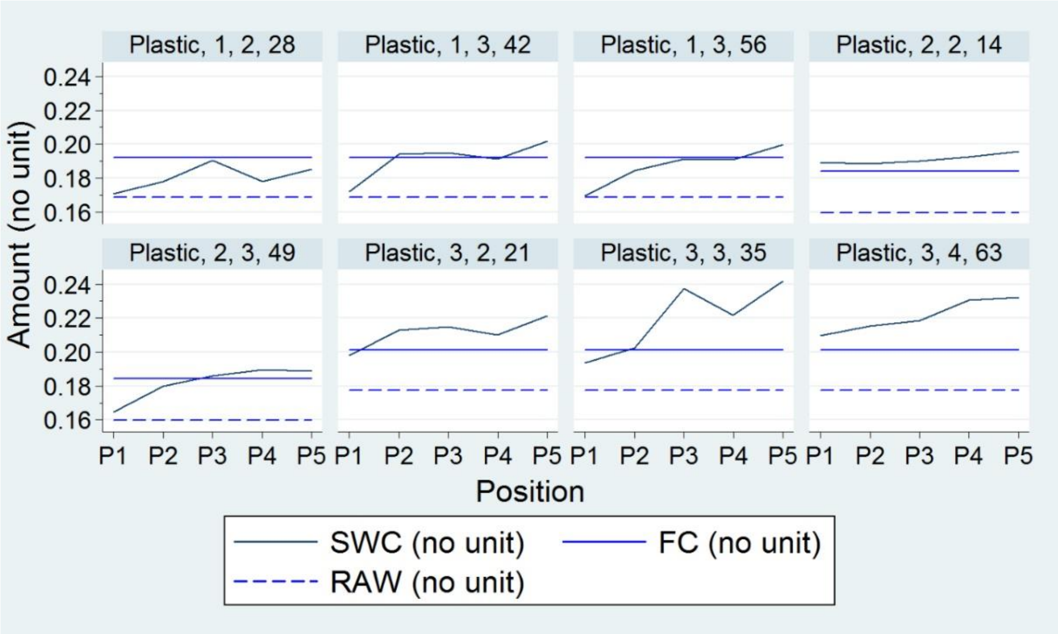

Figure 4.5 *Soil-water content (SWC), field capacity (FC) and readily available water (RAW) in the plastic-drip system - season 1*

Note*:* First, second and third numbers are respectively for block, growth phase and days after transplanting. Growth phase 2 = development phase, 3 = mid-season phase, 4 = late season phase. P = position (Figure 4.1).

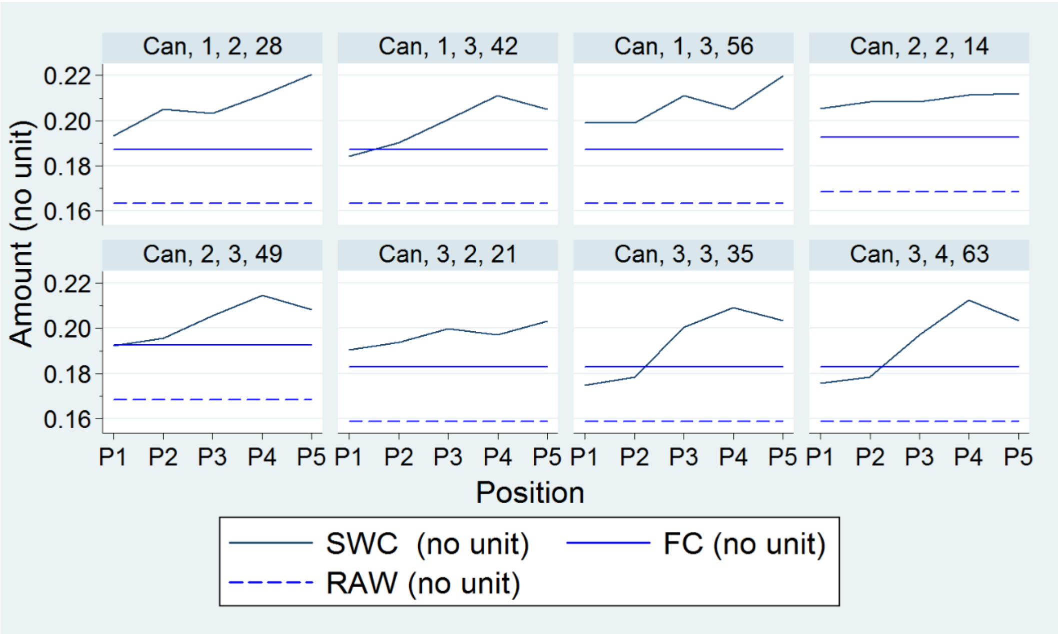

Figure 4.6 *Soil-water content (SWC), field capacity (FC) and readily available water (RAW) in the watering-can system - season 1*

Note: First, second and third numbers are respectively for block, growth phase and days after transplanting. Growth phase 2 = development phase, 3 = mid-season phase, 4 = late season phase. P = position (Figure 4.1).

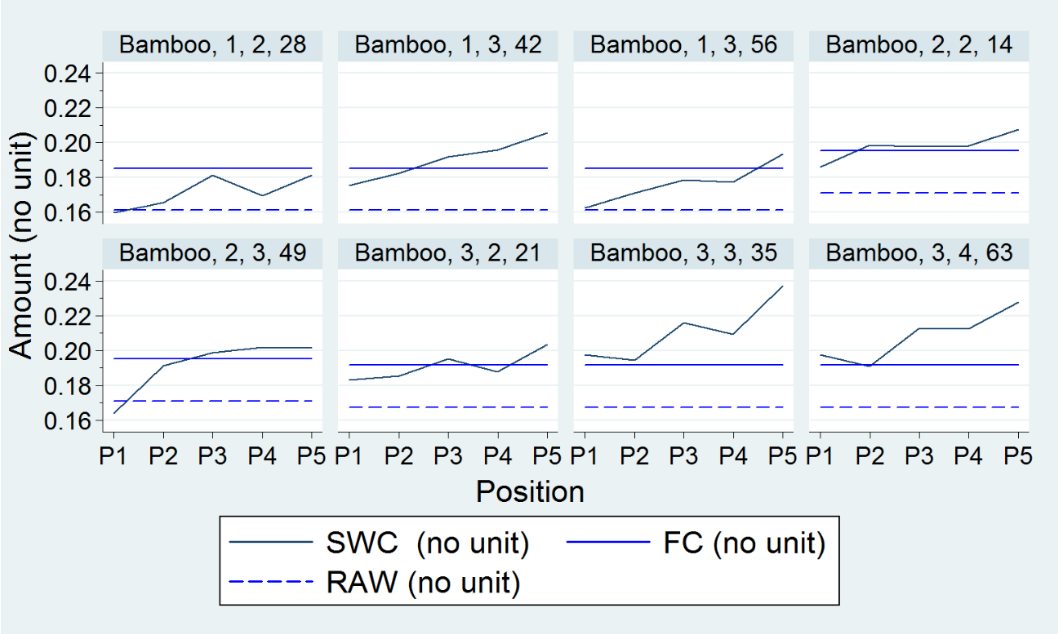

Figure 4.7 *Soil-water content (SWC), field capacity (FC) and readily available water (RAW) in the bamboo-drip system - season 2*

Note: First, second and third numbers are respectively for block, growth phase and days after transplanting. Growth phase 2 = development phase, 3 = mid-season phase, 4 = late season phase. P = position (Figure 4.1).

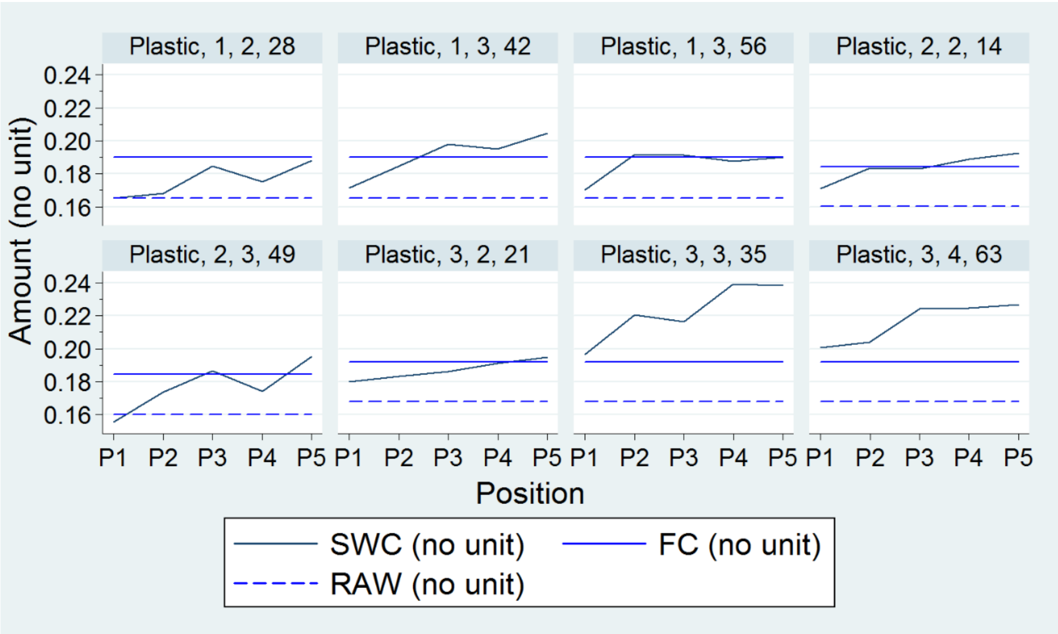

Figure 4.8 *Soil-water content (SWC), field capacity (FC) and readily available water (RAW) in the plastic-drip system - season 2*

Note: First, second and third numbers are respectively for block, growth phase and days after transplanting. Growth phase 2 = development phase, 3 = mid-season phase, 4 = late season phase. P = position (Figure 4.1).

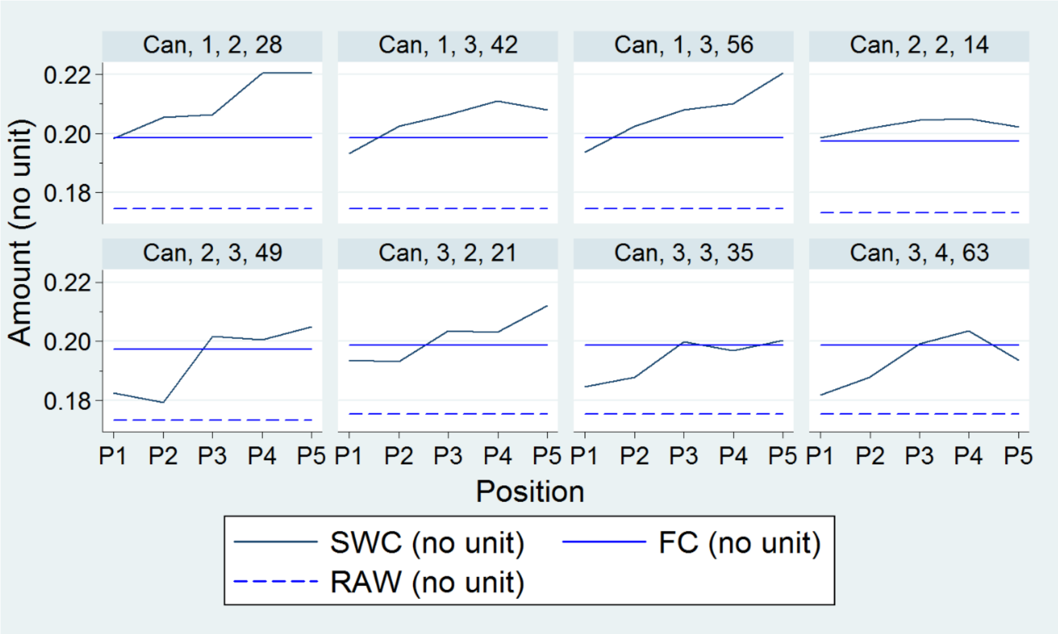

Figure 4.9 *Soil-water content (SWC), field capacity (FC) and readily available water (RAW) in the watering-can system - season 2*

Note: First, second and third numbers are respectively for block, growth phase and days after transplanting. Growth phase 2 = development phase, 3 = mid-season phase, 4 = late season phase. P = position (Figure 4.1).

Table 4.5 *Comparison of measured soil-water content (SWC) to saturation (Sat), field capacity (FC), readily available water (RAW) and permanent wilting point (PWP) (both seasons combined)*

			P-value							
Position	**Phase**	**Irrigation system**	**< Sat**	**> Sat**	**< FC**	**> FC**	**< RAW**	**> RAW**	**< PWP**	**> PWP**
P1	Dev	Bamboo-drip	0**	1	0.0732*	0.9268	0.9916	0.0084**	1	0**
		Watering-can	0**	1	0.8447	0.1553	1	0**	1	0**
		Plastic-drip	0**	1	0.0355**	0.9645	0.9716	0.0284**	1	0**
	Mid	Bamboo-drip	0**	1	0.0484**	0.9516	0.9924	0.0076**	1	0**
		Watering-can	0**	1	0.0975*	0.9025	0.9999	0.0001**	1	0**
		Plastic-drip	0**	1	0.0035**	0.9965	0.9085	0.0915*	1	0**
	Late	Bamboo-drip	0.0019**	0.9981	0.3389	0.6611	0.9609	0.0391**	0.9965	0.0035**
		Watering-can	0.0008**	0.9992	0.1442	0.8558	0.8417	0.1583	0.9892	0.0108**
		Plastic-drip	0.0044**	0.9956	0.8425	0.1575	0.9817	0.0183**	0.9974	0.0026**
P2	Dev	Bamboo-drip	0**	1	0.441	0.559	0.9986	0.0014**	1	0**
		Watering-can	0**	1	0.9753	0.0247**	1	0**	1	0**
		Plastic-drip	0**	1	0.2371	0.7629	0.9916	0.0084**	1	0**
	Mid	Bamboo-drip	0**	1	0.7042	0.2958	0.9998	0.0002**	1	0**
		Watering-can	0**	1	0.4086	0.5914	1	0**	1	0**
		Plastic-drip	0**	1	0.5511	0.4489	0.9997	0.0003**	1	0**
	Late	Bamboo-drip	0.0018**	0.9982	0.3848	0.6152	0.9764	0.0236**	0.9977	0.0023**
		Watering-can	0.0009**	0.9991	0.2425	0.7575	0.8828	0.1172	0.9893	0.0107**
		Plastic-drip	0.0047**	0.9953	0.893	0.107	0.9816	0.0184**	0.9969	0.0031**
P3	Dev	Bamboo-drip	0**	1	0.8749	0.1251	1	0**	1	0**
		Watering-can	0**	1	0.9986	0.0014**	1	0**	1	0**
		Plastic-drip	0**	1	0.5623	0.4377	0.9995	0.0005**	1	0**
	Mid	Bamboo-drip	0**	1	0.9889	0.0111**	1	0**	1	0**
		Watering-can	0**	1	0.9996	0.0004**	1	0**	1	0**
		Plastic-drip	0**	1	0.9137	0.0863*	0.9999	0.0001**	1	0**

	Late	Bamboo-drip	0.0021**	0.9979	0.9771	0.0229**	0.9951	0.0049**	0.9989	0.0011**
		Watering-can	0.0009**	0.9991	0.7738	0.2262	0.9672	0.0328**	0.994	0.006**
		Plastic-drip	0.0049**	0.9951	0.9774	0.0226**	0.9938	0.0062**	0.9986	0.0014**
P4	Dev	Bamboo-drip	0**	1	0.6029	0.3971	0.9994	0.0006**	1	0**
		Watering-can	0**	1	0.9975	0.0025**	1	0**	1	0**
		Plastic-drip	0**	1	0.4068	0.5932	0.9987	0.0013**	1	0**
	Mid	Bamboo-drip	0**	1	0.9736	0.0264**	1	0**	1	0**
		Watering-can	0**	1	0.9998	0.0002**	1	0**	1	0**
		Plastic-drip	0**	1	0.8391	0.1609	0.9995	0.0005**	1	0**
	Late	Bamboo-drip	0.0022**	0.9978	0.9716	0.0284**	0.9935	0.0065**	0.9986	0.0014**
		Watering-can	0.0011**	0.9989	0.9011	0.0989*	0.9753	0.0247**	0.9941	0.0059**
		Plastic-drip	0.0052**	0.9948	0.9853	0.0147**	0.9952	0.0048**	0.9988	0.0012**
P5	Dev	Bamboo-drip	0**	1	0.9828	0.0172**	1	0**	1	0**
		Watering-can	0**	1	0.9994	0.0006**	1	0**	1	0**
		Plastic-drip	0**	1	0.8167	0.1833	0.9997	0.0003**	1	0**
	Mid	Bamboo-drip	0**	1	0.9994	0.0006**	1	0**	1	0**
		Watering-can	0**	1	0.9998	0.0002**	1	0**	1	0**
		Plastic-drip	0**	1	0.9775	0.0225**	0.9999	0.0001**	1	0**
	Late	Bamboo-drip	0.0027**	0.9973	0.9506	0.0494**	0.9856	0.0144**	0.9967	0.0033**
		Watering-can	0.0011**	0.9989	0.7545	0.2455	0.9588	0.0412**	0.9926	0.0074**
		Plastic-drip	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 4.1); ** highly significant; * significant; P-value = probability of being wrong when saying there is a difference between the groups compared.

Within-season spatial and between-season temporal variations of soil-water content per irrigation system are shown in Tables 4.6 and 4.7, respectively.

Table 4.6 *Spatial variation of soil-water content per irrigation system*

Season	Compared	Irrigation system	Position	F-value	P-value
Season 1	Block1 vs Block 2	Bamboo-drip	P1	-0.0104	0.606
			P2	-0.0203	0.135
			P3	-0.0133	0.26
			P4	-0.0163	0.084*
			P5	-0.0086	0.713
		Watering-can	P1	0.0067	1
			P2	0.0038	1
			P3	0.0019	1
			P4	0.004	1
			P5	-0.005	1
		Plastic-drip	P1	0.0063	1
			P2	-0.0014	1
			P3	-0.0042	1
			P4	0.0043	1
			P5	-0.0031	1
	Block1 vs Block3	Bamboo-drip	P1	-0.0001	1
			P2	-0.0002	1
			P3	0.0007	1
			P4	0.0089	0.358
			P5	0.0029	1
		Watering-can	P1	-0.0118	0.437
			P2	-0.0146	0.252
			P3	-0.0058	0.346
			P4	-0.0029	1
			P5	-0.0118	0.152
		Plastic-drip	P1	0.0296	0.035**
			P2	0.0246	0.026**
			P3	0.0314	0.014**
			P4	0.0341	0.011**
			P5	0.0364	0.013**
	Block2 vs Block3	Bamboo-drip	P1	0.0103	0.62
			P2	0.0202	0.138
			P3	0.0139	0.228
			P4	0.0252	0.015**
			P5	0.0114	0.399
		Watering-can	P1	-0.0185	0.181
			P2	-0.0184	0.178
			P3	-0.0077	0.22
			P4	-0.0068	0.729
			P5	-0.0068	0.737
		Plastic-drip	P1	0.0233	0.123
			P2	0.026	0.033**
			P3	0.0356	0.014**
			P4	0.0298	0.031**
			P5	0.0394	0.014**
Season 2		Bamboo-drip	P1	0.0091	1

Block1 vs Block2		P2	0.0221	0.044**
		P3	0.0143	0.364
		P4	0.0191	0.433
		P5	0.011	1
	Watering-can	P1	-0.0045	1
		P2	-0.013	0.342
		P3	-0.0038	0.216
		P4	-0.0111	0.132
		P5	-0.0127	0.363
	Plastic-drip	P1	-0.0057	1
		P2	-0.0029	1
		P3	-0.0065	1
		P4	-0.0044	1
		P5	-0.0002	1
Block1 vs Block3	Bamboo-drip	P1	0.0269	0.071*
		P2	0.0174	0.07*
		P3	0.0242	0.05*
		P4	0.0225	0.217
		P5	0.0294	0.136
	Watering-can	P1	-0.0082	0.56
		P2	-0.0139	0.213
		P3	-0.0061	0.028**
		P4	-0.0127	0.056*
		P5	-0.0143	0.197
	Plastic-drip	P1	0.0234	0.065*
		P2	0.0212	0.396
		P3	0.0177	0.499
		P4	0.0325	0.211
		P5	0.0258	0.287
Block2 vs Block3	Bamboo-drip	P1	0.0177	0.351
		P2	-0.0047	1
		P3	0.0099	0.754
		P4	0.0034	1
		P5	0.0184	0.596
	Watering-can	P1	-0.0038	1
		P2	-0.0009	1
		P3	-0.0023	0.667
		P4	-0.0016	1
		P5	-0.0016	1
	Plastic-drip	P1	0.0291	0.044**
		P2	0.0241	0.38
		P3	0.0242	0.315
		P4	0.0369	0.202
		P5	0.0261	0.37

P = position (Figure 4.1); ** highly significant; * significant; F-value is the ratio of the variance between the groups compared and the variance within those groups. P-value is the probability of being wrong when saying there is a difference between the groups compared.

Table 4.7 *Temporal variation of soil-water content per irrigation system*

Compared	Block	Irrigation system	Position	F-value	P-value
Season1 vs Season2	Block 1	Bamboo-drip	P1	-0.0237	0.018**
			P2	-0.031	0.004**
			P3	-0.026	0.013**
			P4	-0.0246	0.04**
			P5	-0.0203	0.044**
		Plastic-drip	P1	-0.0018	0.409
			P2	-0.0041	0.649
			P3	-0.001	0.826
			P4	-0.0008	0.914
			P5	-0.0013	0.871
		Watering-can	P1	0.0028	0.574
			P2	0.0054	0.29
			P3	0.002	0.565
			P4	0.0047	0.297
			P5	0.0012	0.868
	Block 2	Bamboo-drip	P1	-0.0041	0.798
			P2	0.0114	0.301
			P3	0.0016	0.201
			P4	0.0108	0.096*
			P5	-0.0007	0.891
		Plastic-drip	P1	-0.0138	0.442
			P2	-0.0056	0.477
			P3	-0.0032	0.336
			P4	-0.0095	0.331
			P5	0.0015	0.727
		Watering-can	P1	-0.0084	0.501
			P2	-0.0114	0.468
			P3	-0.0037	0.204
			P4	-0.0104	0.065*
			P5	-0.0065	0.108
	Block 3	Bamboo-drip	P1	0.0033	0.595
			P2	-0.0134	0.116
			P3	-0.0024	0.77
			P4	-0.0111	0.28
			P5	0.0063	0.624
		Plastic-drip	P1	-0.008	0.368
			P2	-0.0075	0.549
			P3	-0.0147	0.34
			P4	-0.0024	0.882
			P5	-0.0118	0.457
		Watering-can	P1	0.0064	0.36
			P2	0.0061	0.319
			P3	0.0017	0.378
			P4	-0.0052	0.366
			P5	-0.0013	0.814

P = position (Figure 4.1); ** highly significant; * significant; F-value is the ratio of the variance between the groups compared and the variance within those groups. P-value is the probability of being wrong when saying there is a difference between the groups compared.

Seasonal averages of evapotranspiration and irrigation amounts per irrigation system are shown in Figure 4.10.

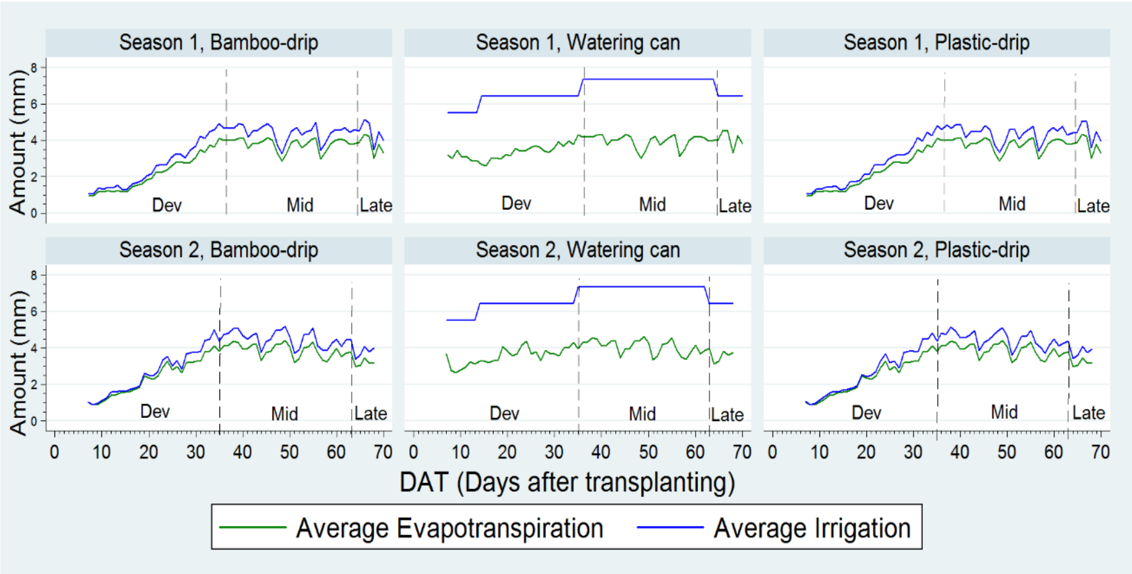

Figure 4.10 *Seasonal averages of evapotranspiration and irrigation amounts per irrigation system*

Note: Dev = development phase; Mid = mid-season phase; Late = late season phase

At all five positions monitored, soil-water content was above *PWP* (Figures 4.4, 4.5, 4.6, 4.7, 4.8 and 4.9 and Table 4.5) and below *Sat* (Table 4.5). Overall, soil-water content was in the acceptable range for plants (i.e. between *RAW* and *FC*) in all systems, but rose above *FC* at particular positions and growth phases (Table 4.8). Hence, irrigation scheduling could be improved by lowering irrigation input or introducing longer times 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.

Soil-water content above *FC* was observed at P3 and P4 located in the maximum rooting front, and at P5, which is completely below the root zone, albeit 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[18] or internal drainage. This occurs after infiltration has ceased and brings water from the wetting pattern to the drier part of the soil ahead of the wetting front (from P2 to P3) or from moist to drier parts of the soil profile through deep percolation (from P4 to P5). In the case of the frequent non-deficit irrigation practiced in this study, the redistribution process was likely to have been dominated by the deep percolation (Camp, 1998) observed during mid and late seasons.

Table 4.8 *Positions and growth phases where soil-water content exceeded field capacity*

Position	Bamboo-drip system	Plastic-drip system	Watering-can system
P3			Development phase
	Mid-season phase	Mid-season phase	Mid-season phase
	Late season phase	Late season phase	
P4			Development phase
	Mid-season 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 4.1).

At P4 in both drip systems, *SWC* above *FC* was more obvious during the late season due to the combined effect of excessive irrigation (Figure 4.10) and a lower water absorption by the roots as compared to the mid-season, where 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 (P4 during mid-season), and lower in areas with medium and high soil-water content ranges (P4 during late season).

[18] Mechanism by which, soil-water after an irrigation or precipitation event is redistributed by vascular plants that have roots in both wet and extremely dry soil.

At P3 and P5 in the watering-can system, *SWC* was above *FC* during mid-season (like in the two drip systems), but also during the development phase where water content was below *FC* in the drip systems. Excessive water content at P3 and P5 as early as during the development phase could be explained by excessive irrigation and one-dimensional water movement downward from the soil surface in watering-can irrigation as opposed to the 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 the late season (like in the two drip systems), but also during development and mid-season phases (like at P3 and P5 in the same system). As mentioned before, this is due to infiltration of the excessive irrigation water, and root gradient-related redistribution to P4, which is closer to the roots' maximum intensity zone than P3 and P5.

Overall, no spatial difference can be observed between the monitored positions both within the irrigation treatments and during each cropping season. But during season 1, there is a slight spatial difference in 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.

Overall, no temporal difference can be observed between the monitored positions both within the irrigation systems and from one season to the other. However, in the bamboo-drip system, there is a slight temporal difference in the first block, due not to a different irrigation performance, but to minor particularities in soil characteristics (see above).

4.2.1.2. Soil-water matric potential

For each irrigation system, measured soil-water matric potentials are presented per growth phase and per cropping season (Figures 4.11 to 4.28). Average, minimum and maximum values are also presented per monitored position, irrigation system and growth phase (Table 4.9).

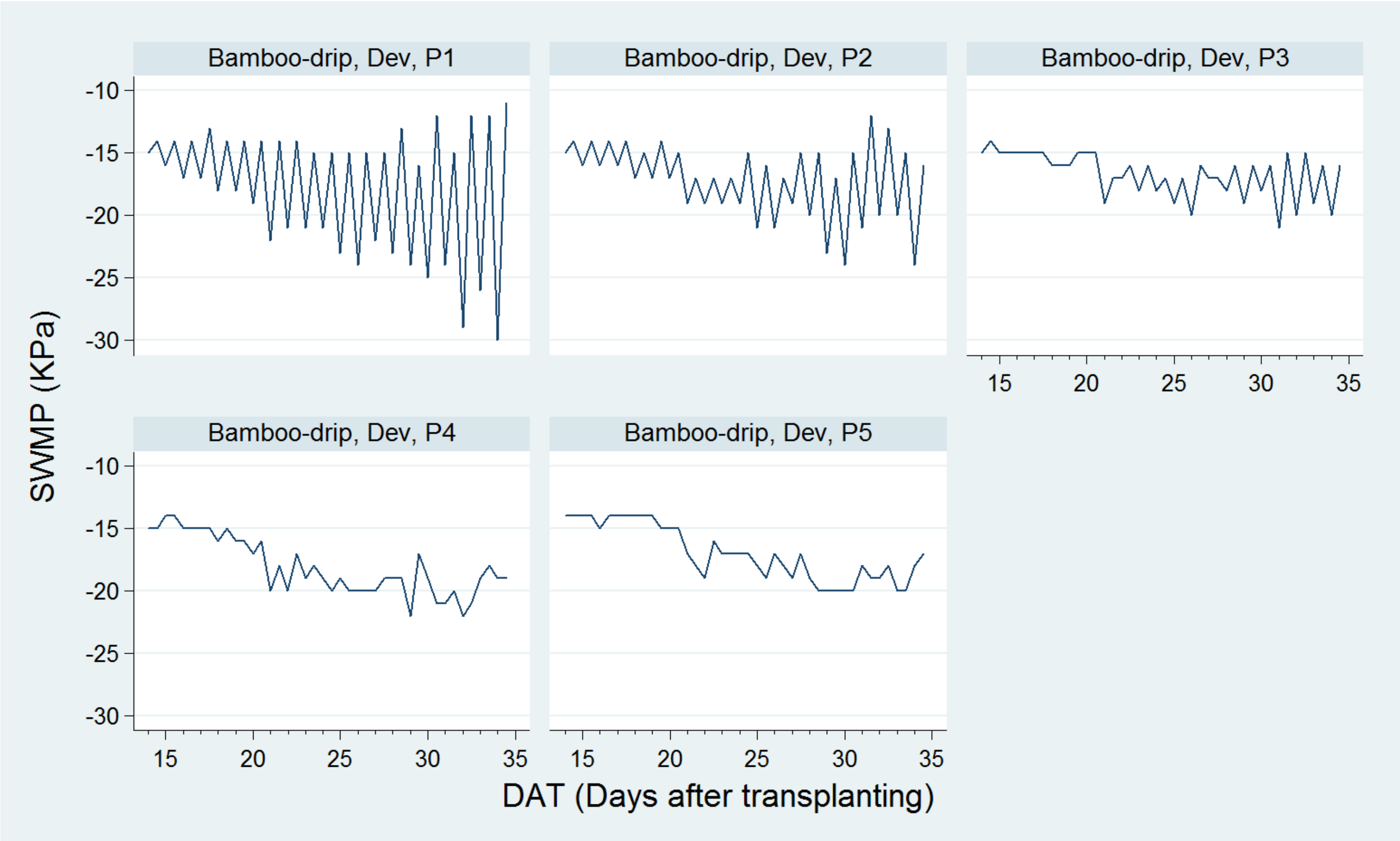

Figure 4.11 *Measured matric potential - bamboo-drip system - development phase - Season 1*
Note: SWMP = soil-water matric potential; Dev = development phase; P = position (Figure 4.1)

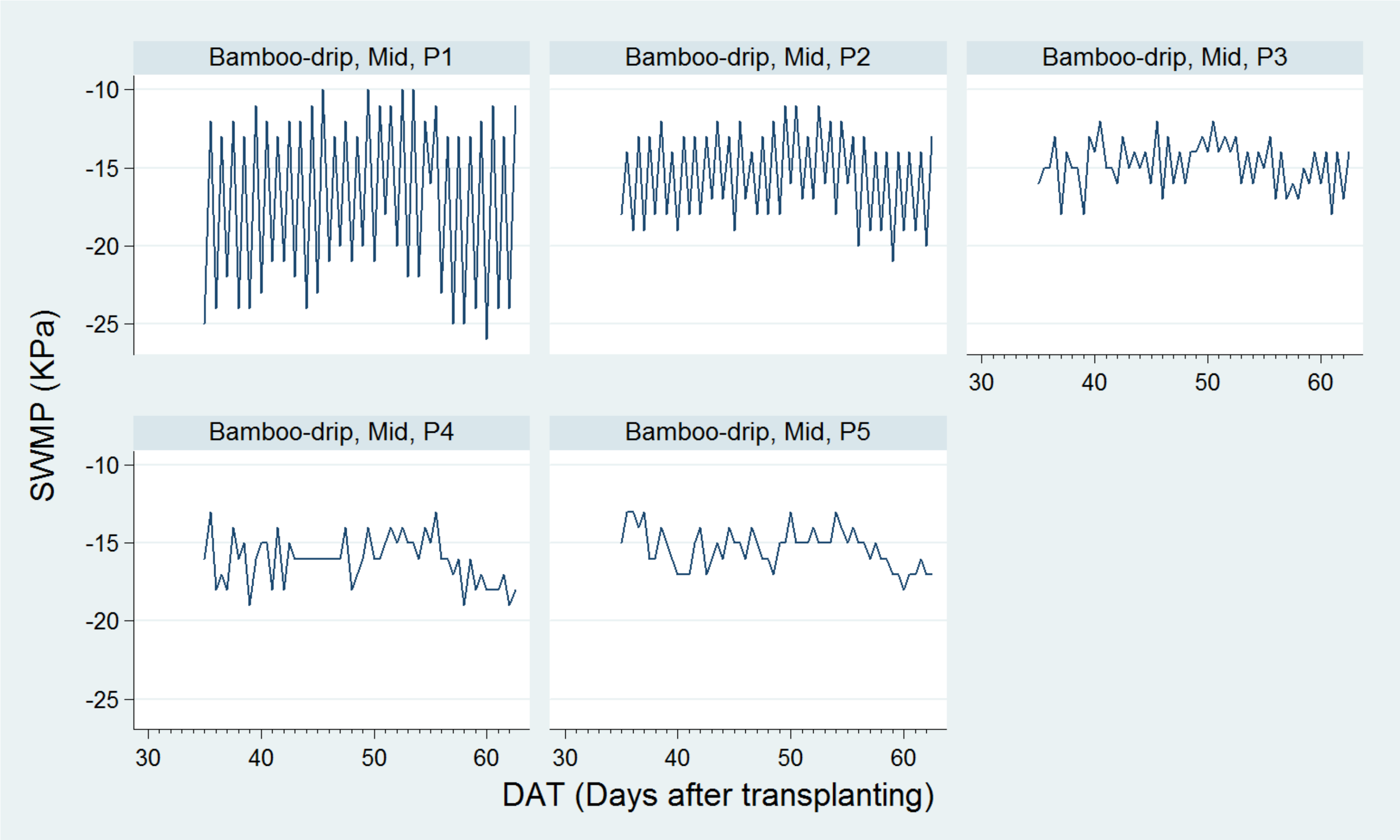

Figure 4.12 *Measured matric potential - bamboo-drip system – mid-season phase - Season 1*
Note: SWMP = soil-water matric potential; Mid = mid-season phase; P = position (Figure 4.1)

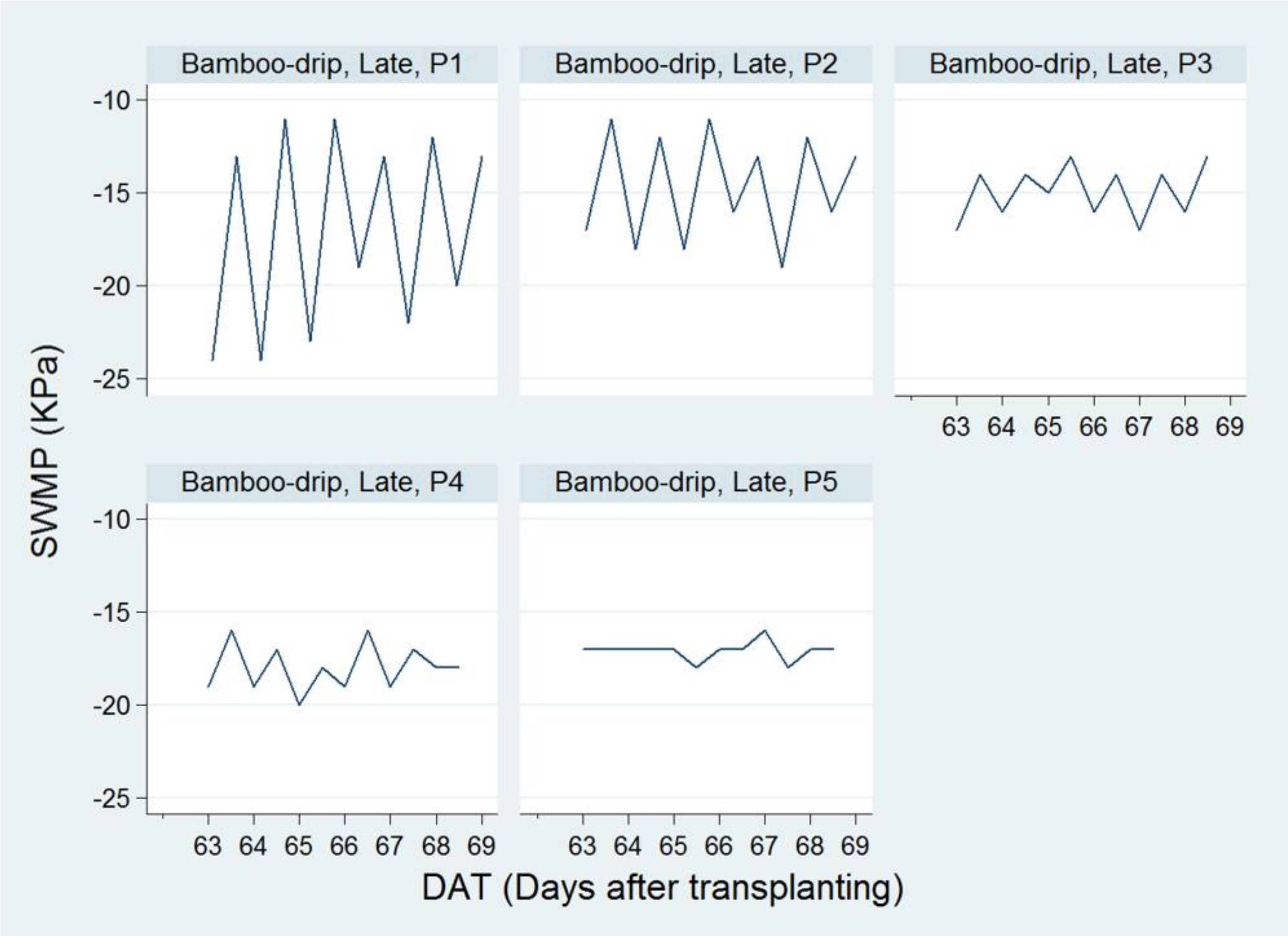

Figure 4.13 *Measured matric potential - bamboo-drip system – late season phase - Season 1*
Note: SWMP = soil-water matric potential; Late = late-season phase; P = position (Figure 4.1)

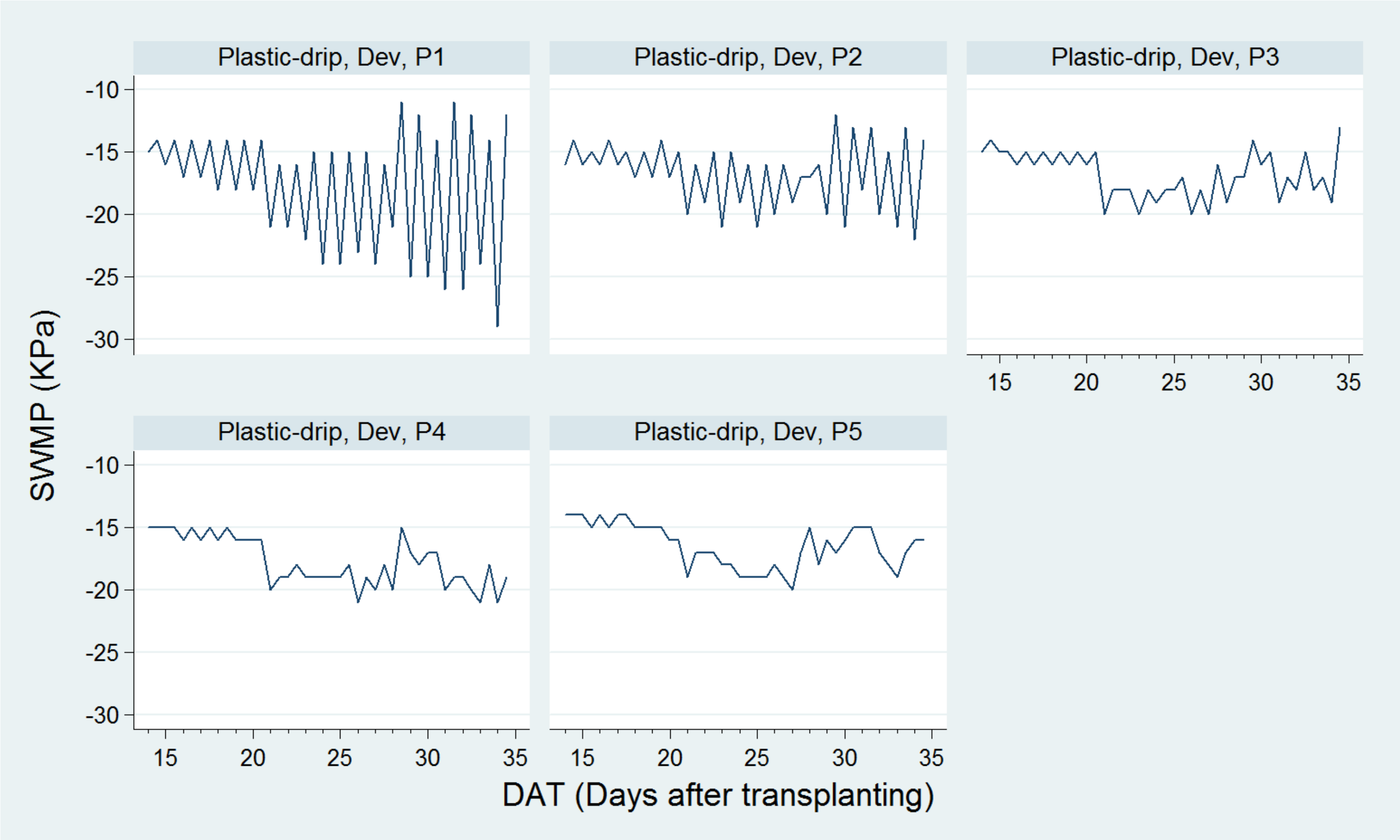

Figure 4.14 *Measured matric potential – plastic-drip system - development phase - Season 1*
Note: SWMP = soil-water matric potential; Dev = development phase; P = position (Figure 4.1)

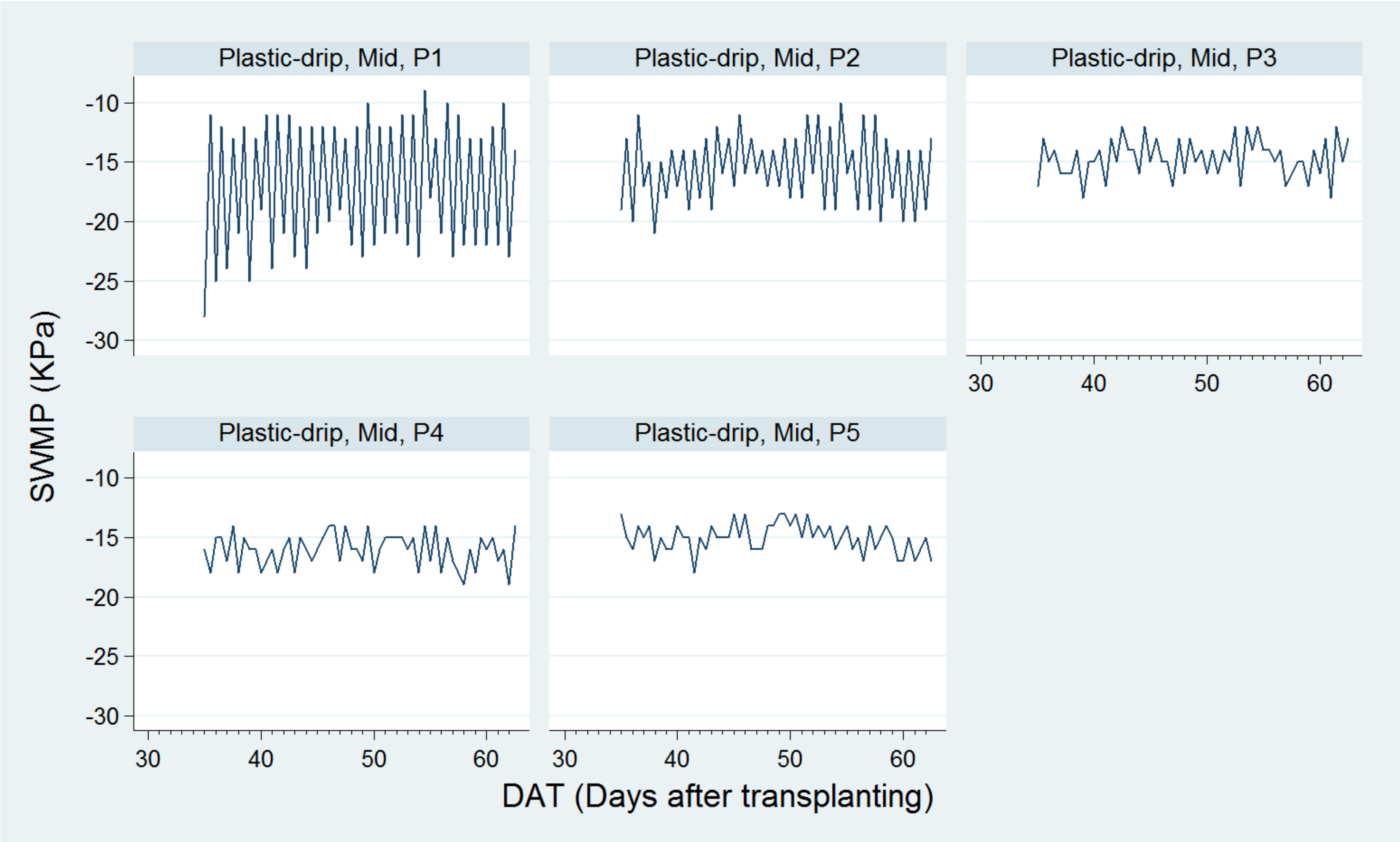

Figure 4.15 *Measured matric potential – plastic-drip system – mid-season phase - Season 1*
Note: SWMP = soil-water matric potential; Mid = mid-season phase; P = position (Figure 4.1)

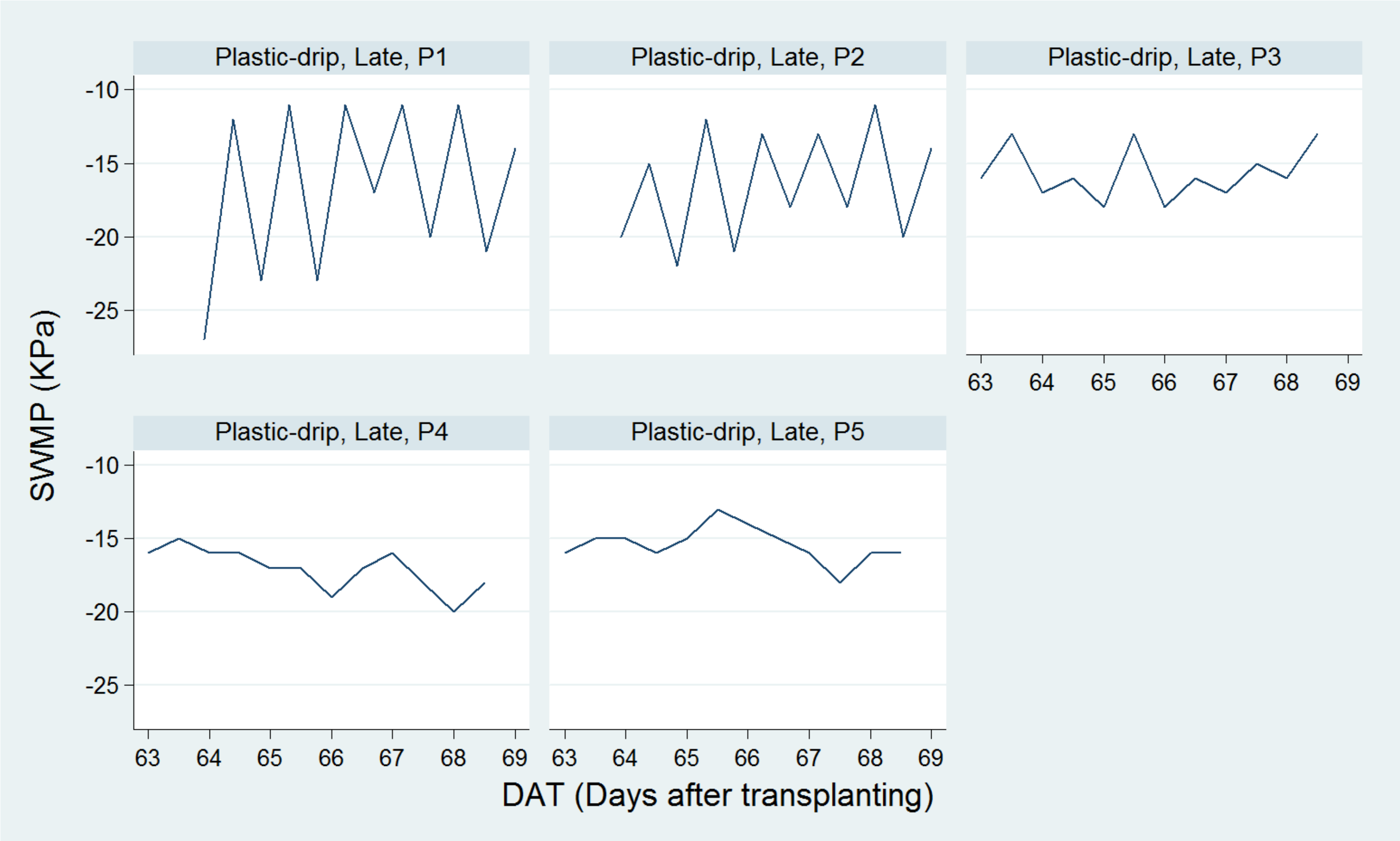

Figure 4.16 *Measured matric potential – plastic-drip system – phase - Season 1*
Note: SWMP = soil-water matric potential; Late = late season phase; P = position (Figure 4.1)

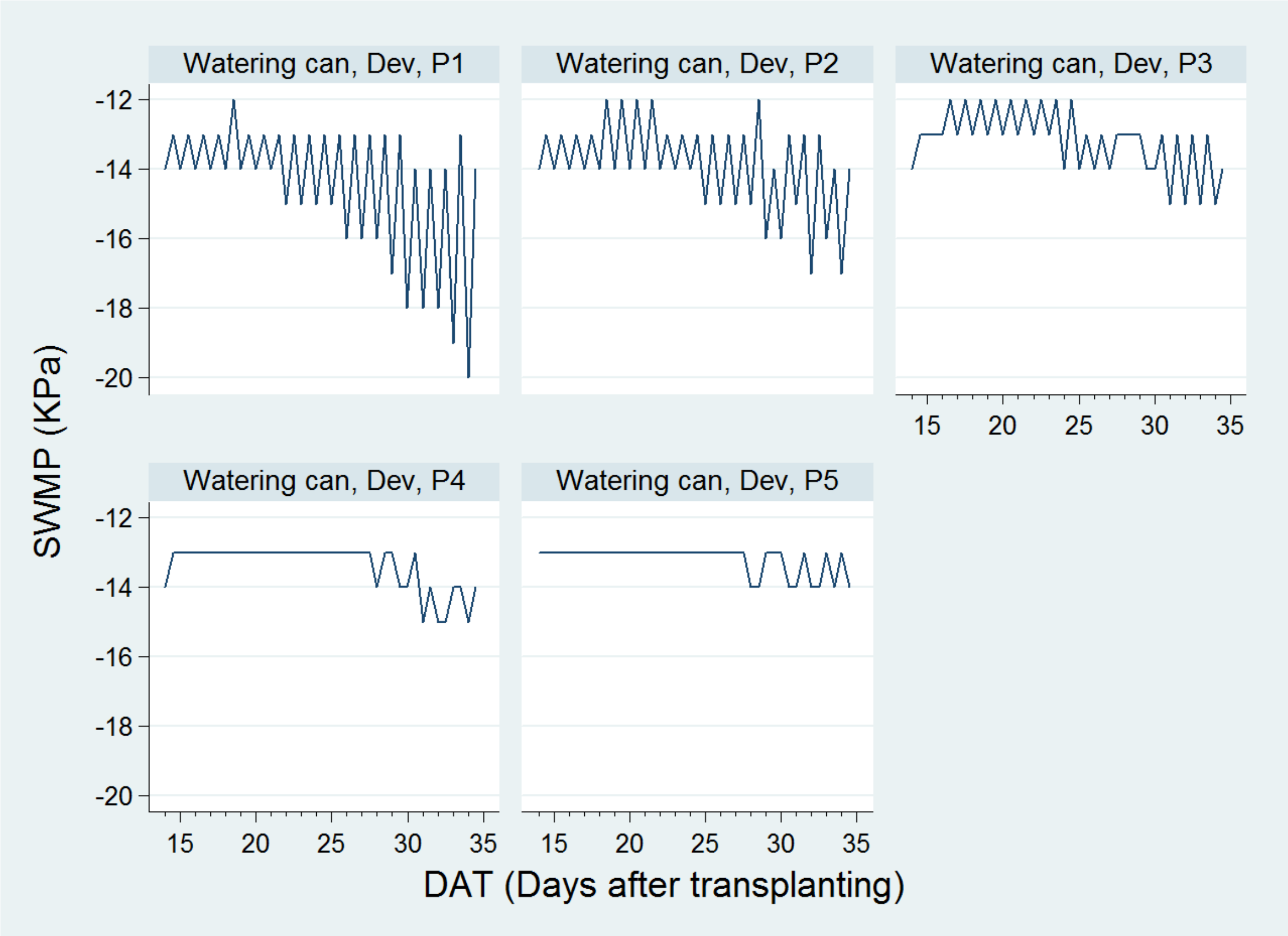

***Figure 4.17** Measured matric potential – watering-can system – development phase - Season 1*
Note: SWMP = soil-water matric potential; Dev = development phase; P = position (Figure 4.1)

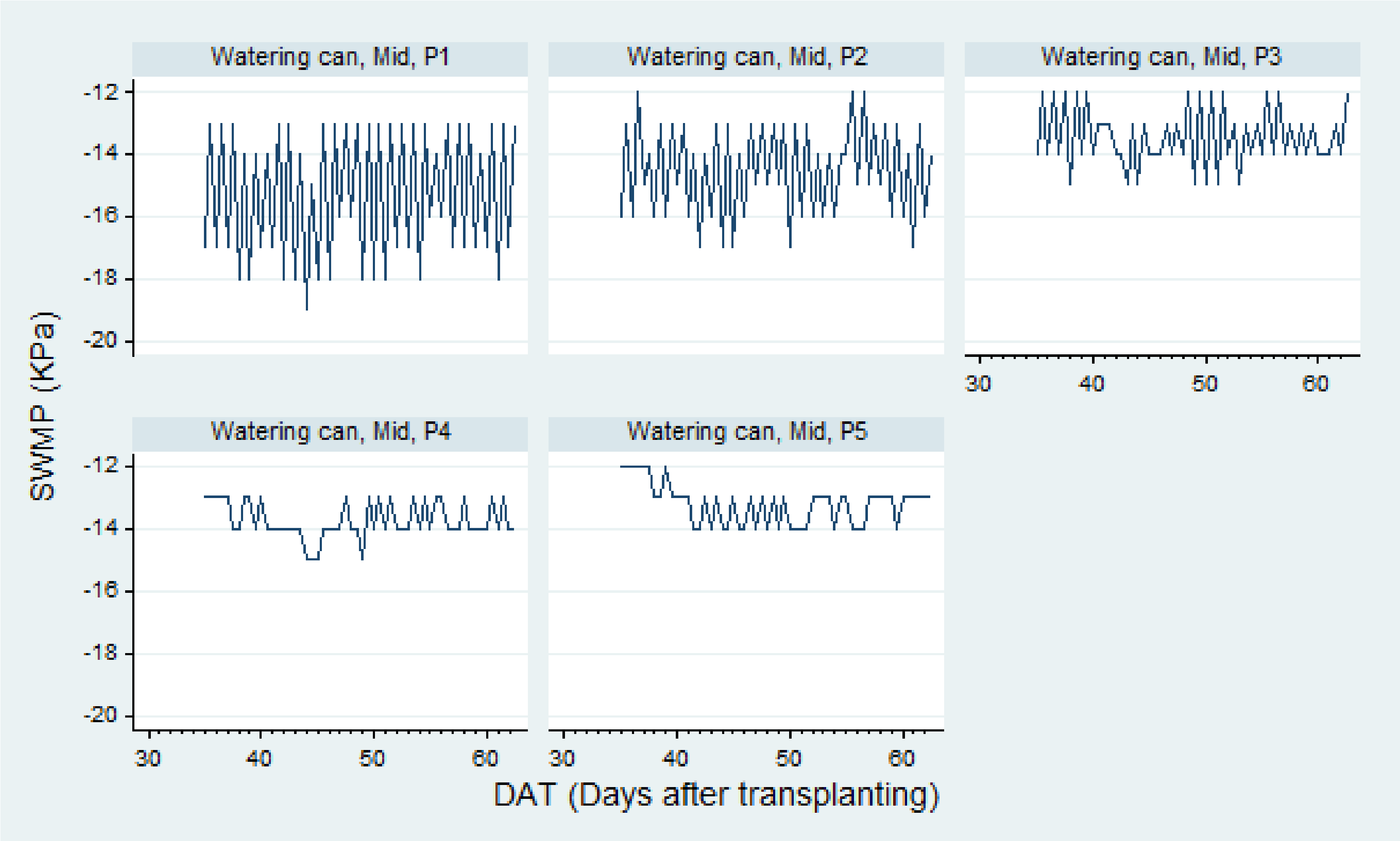

Figure 4.18 *Measured matric potential – watering-can system – mid-season phase - Season 1*
Note: SWMP = soil-water matric potential; Mid = mid-season phase; P = position (Figure 4.1)

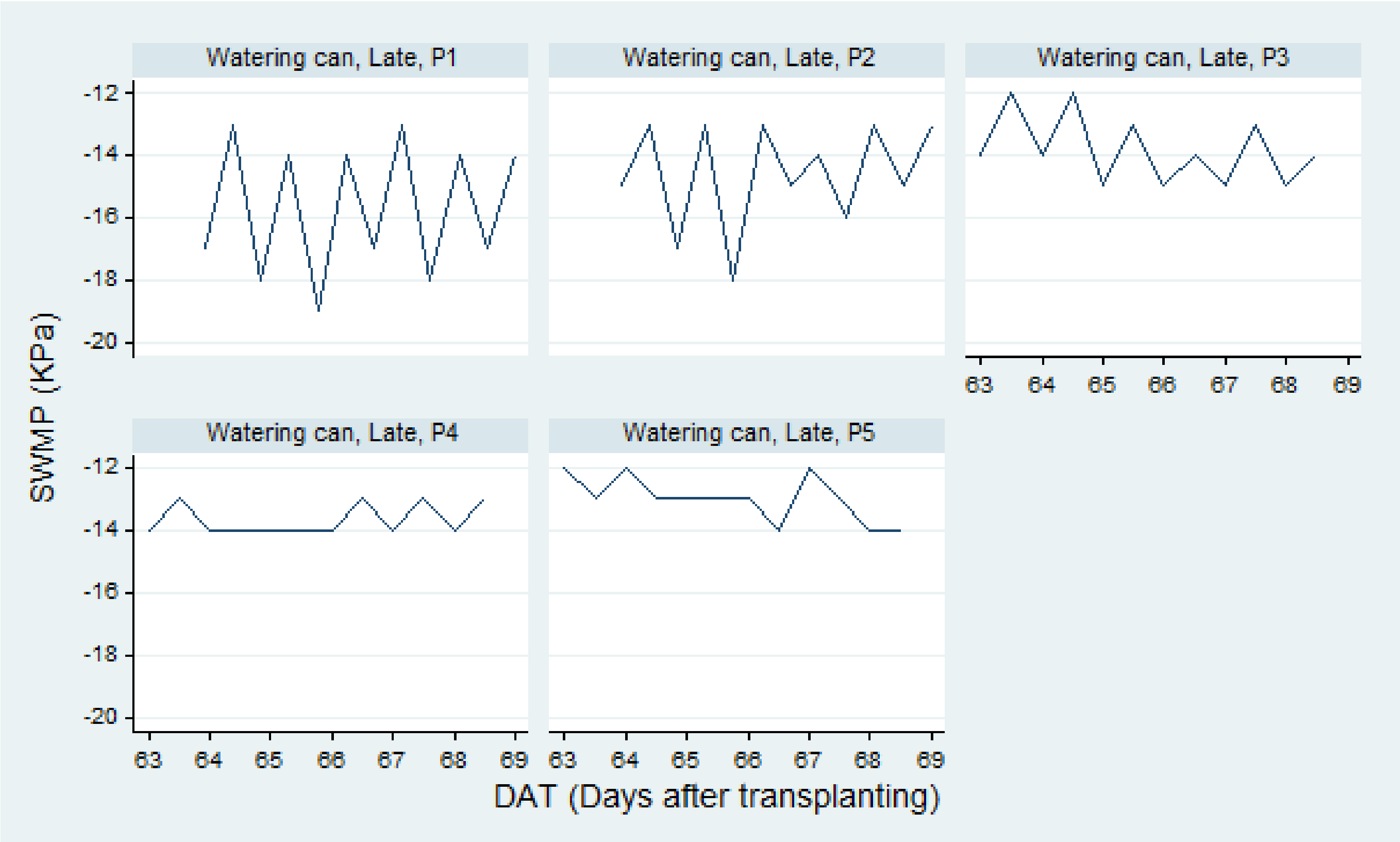

Figure 4.19 *Measured matric potential – watering-can system – late season phase - Season 1*
Note: SWMP = soil-water matric potential; Late = late season phase; P = position (Figure 4.1)

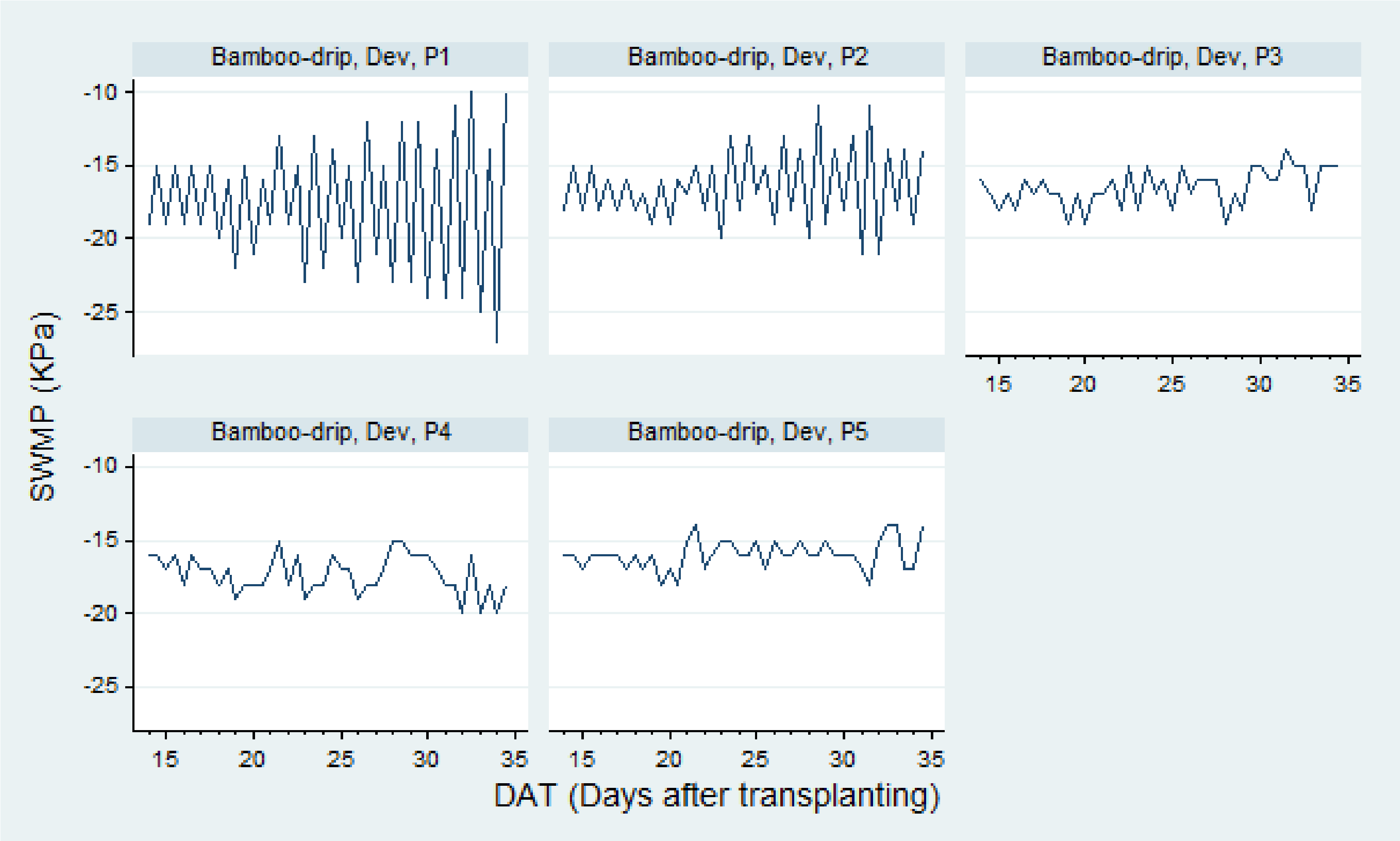

Figure 4.20 *Measured matric potential – bamboo-drip system – development phase - Season 2*
Note: SWMP = soil-water matric potential; Dev = development phase; P = position (Figure 4.1)

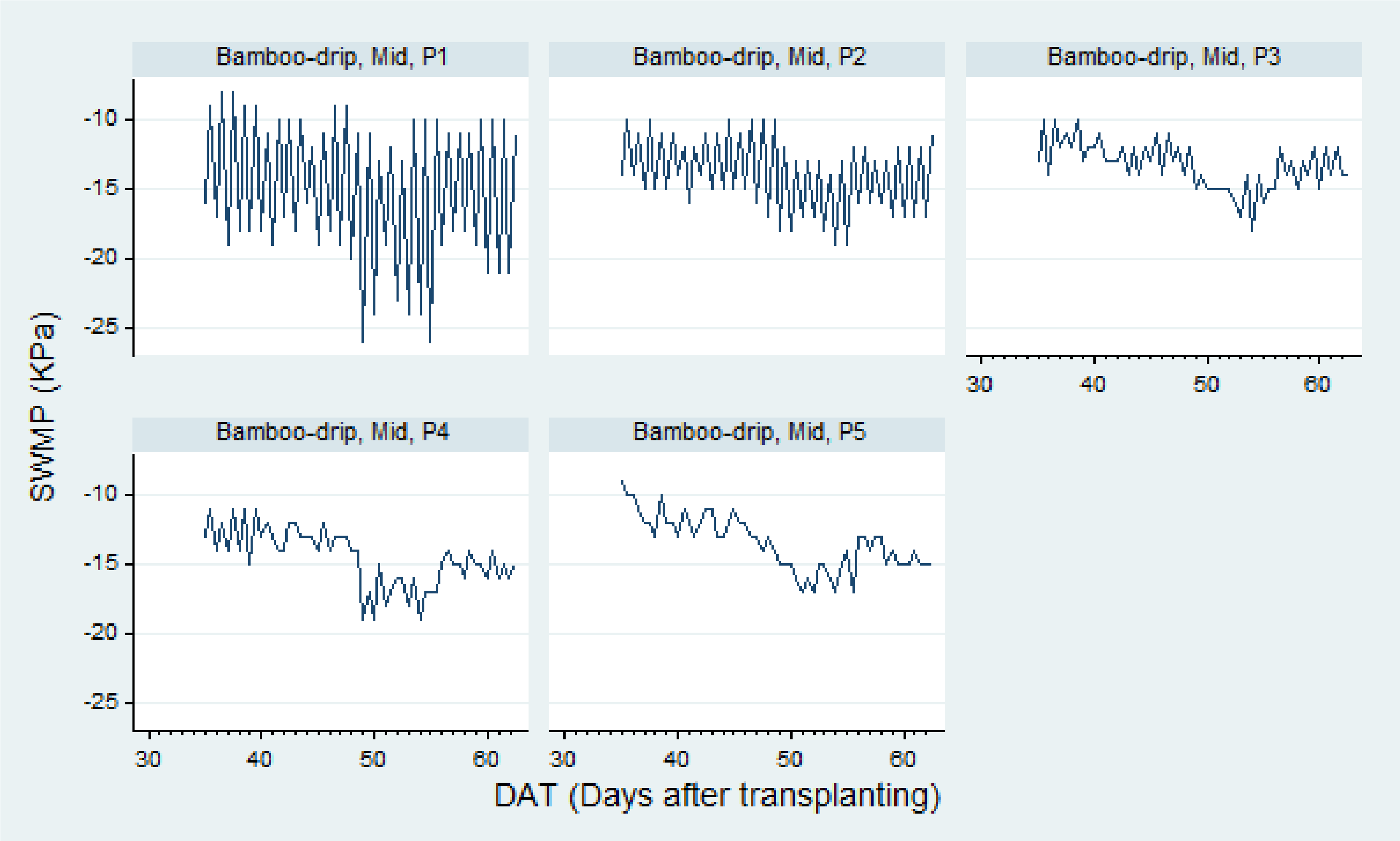

***Figure 4.21** Measured matric potential – bamboo-drip system – mid-season phase - Season 2*
Note: SWMP = soil-water matric potential; Mid = mid-season phase; P = position (Figure 4.1)

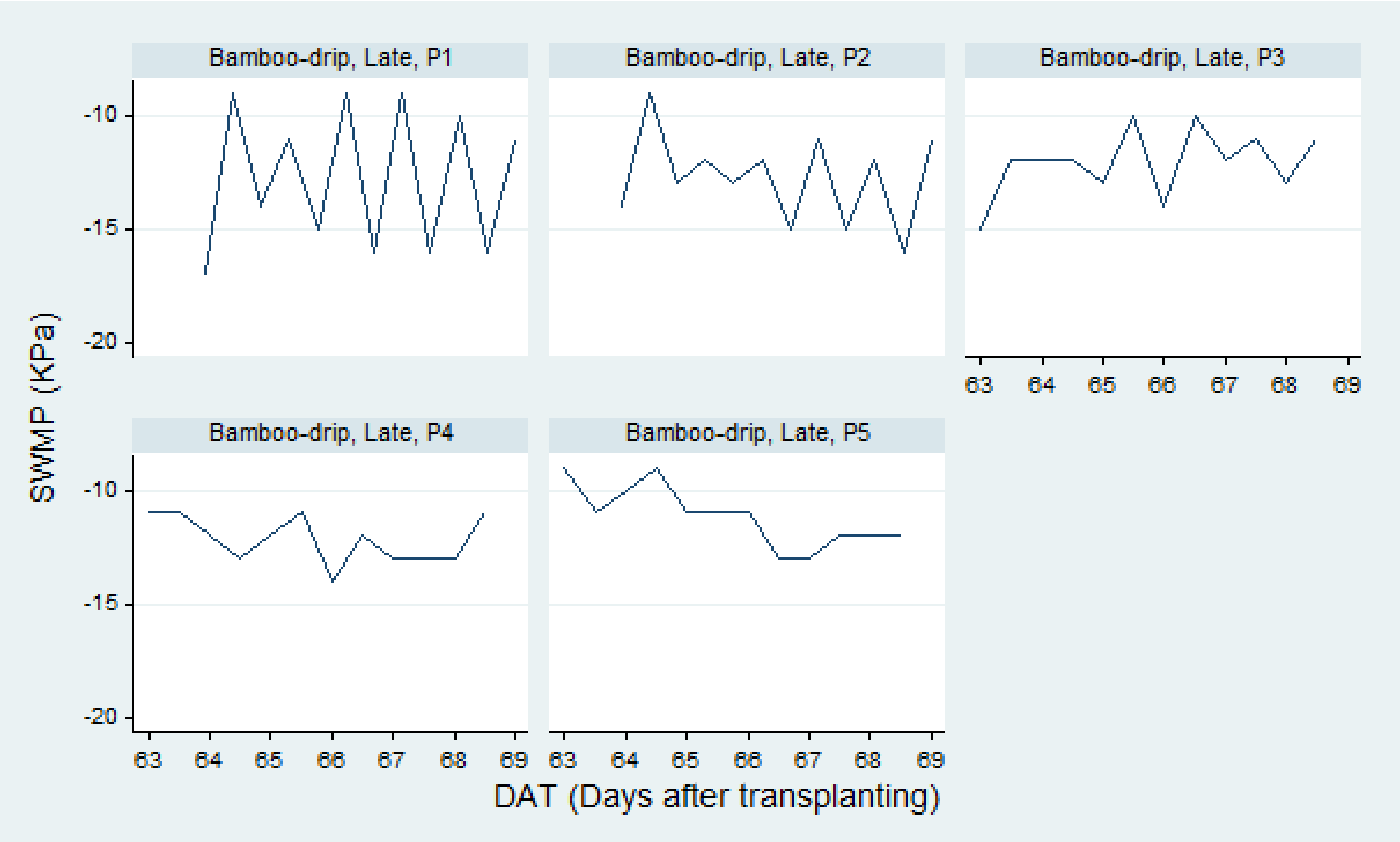

Figure 4.22 *Measured matric potential – bamboo-drip system – late season phase - Season 2*
Note: SWMP = soil-water matric potential; Late = late season phase; P = position (Figure 4.1)

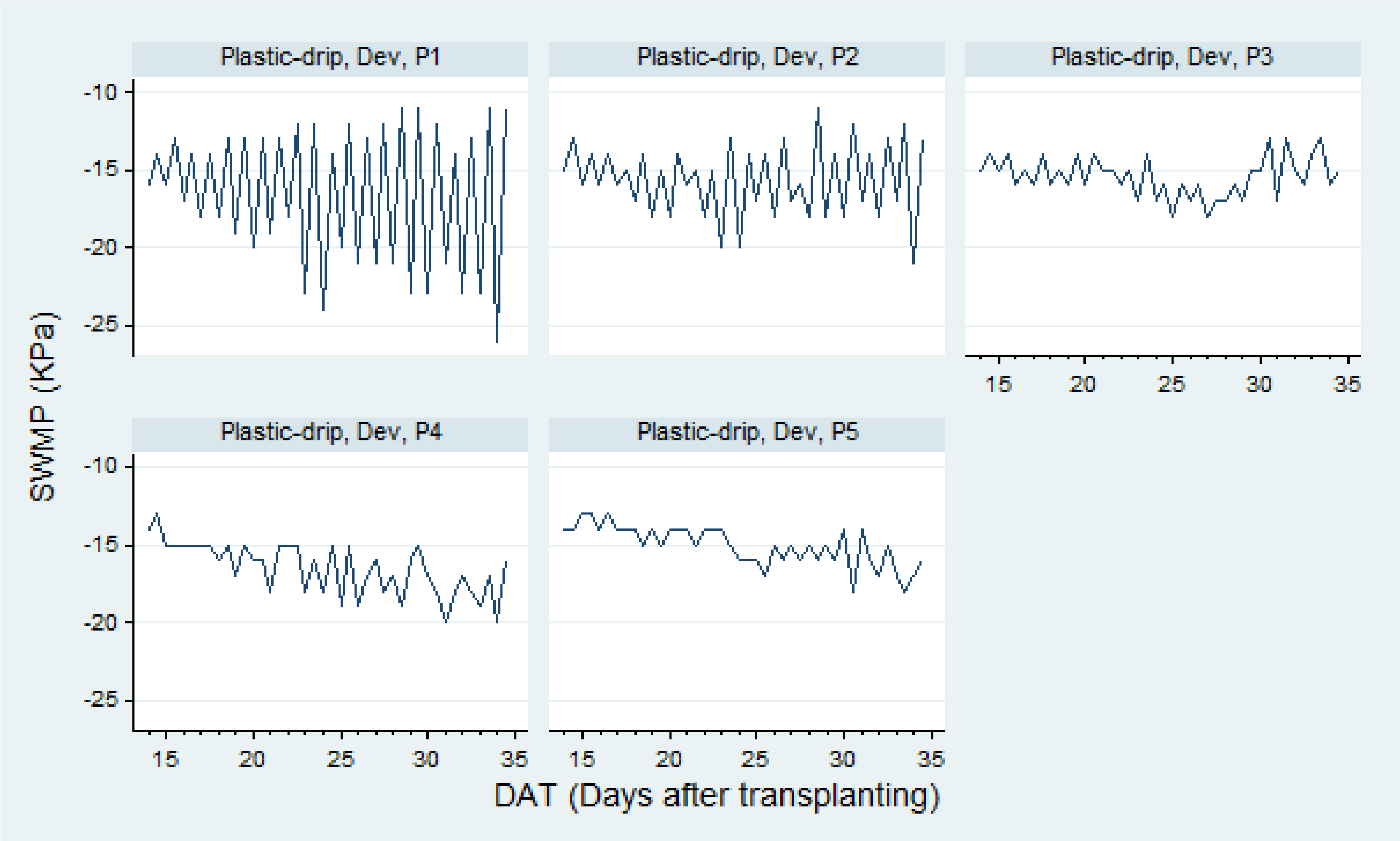

Figure 4.23 *Measured matric potential – plastic-drip system – development phase - Season 2*
Note: SWMP = soil-water matric potential; Dev = development phase; P = position (Figure 4.1)

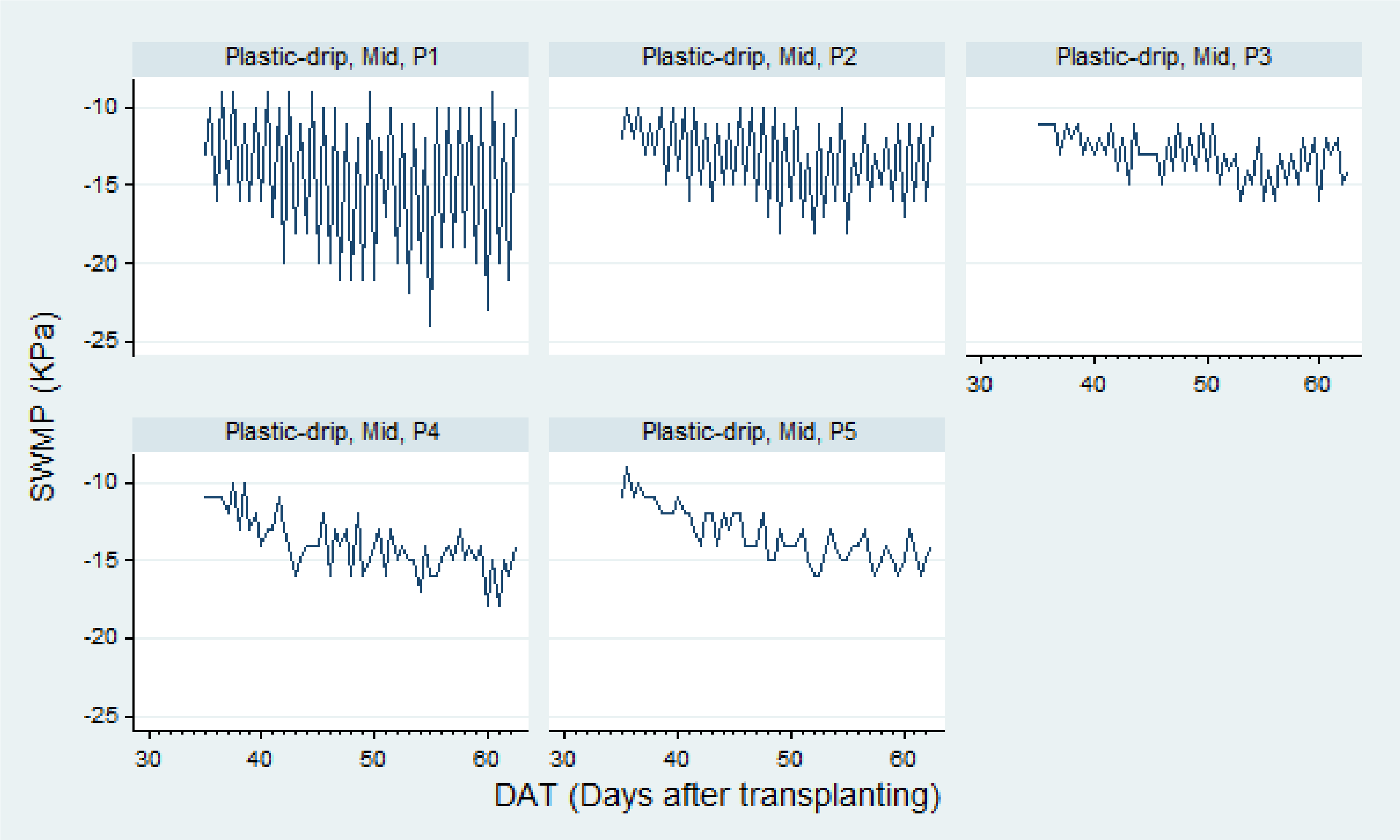

Figure 4.24 *Measured matric potential – plastic-drip system – mid-season phase - Season 2*
Note: SWMP = soil-water matric potential; Mid = mid-season phase; P = position (Figure 4.1)

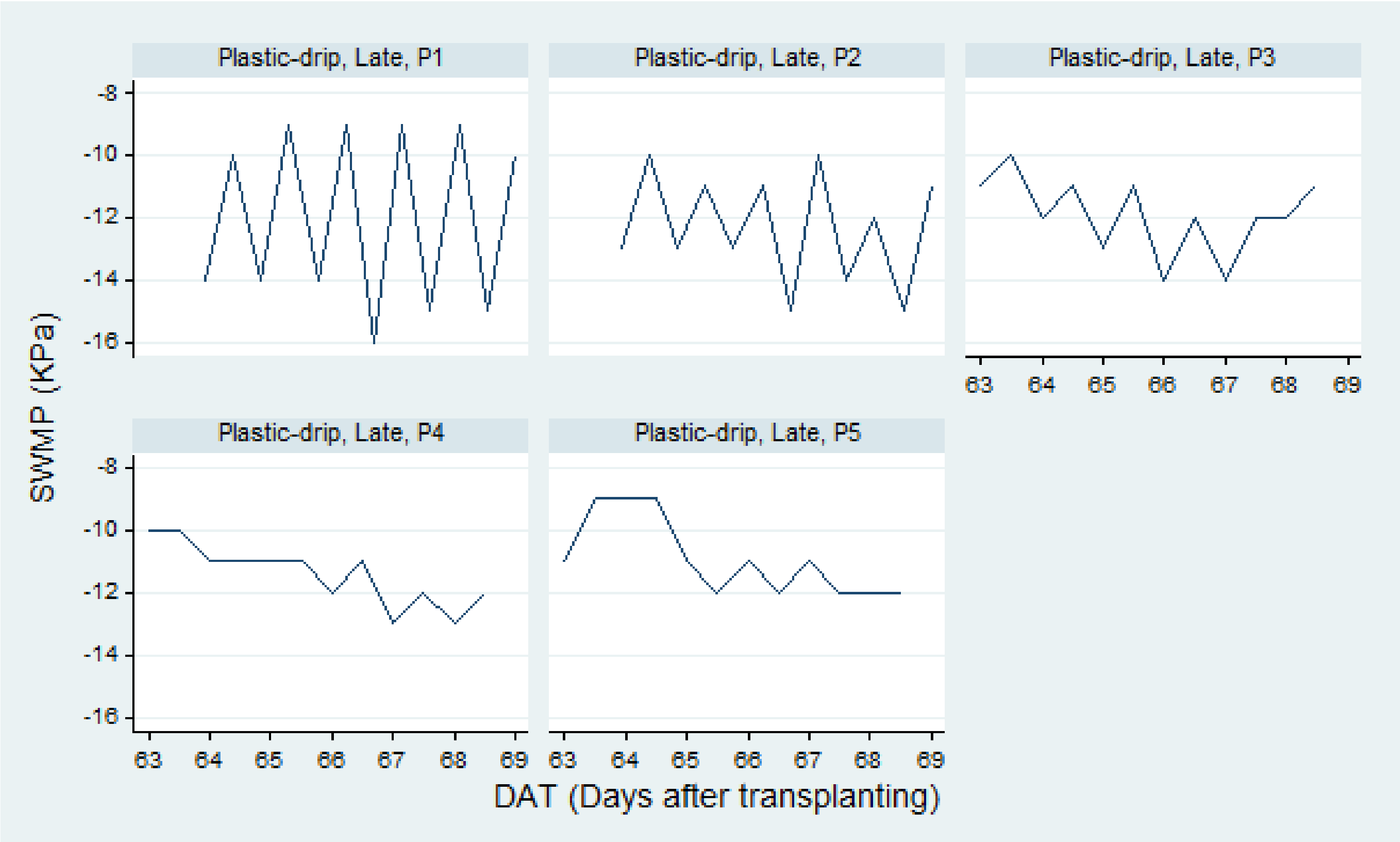

Figure 4.25 *Measured matric potential – plastic-drip system – late season phase - Season 2*
Note: SWMP = soil-water matric potential; Late = late season phase; P = position (Figure 4.1)

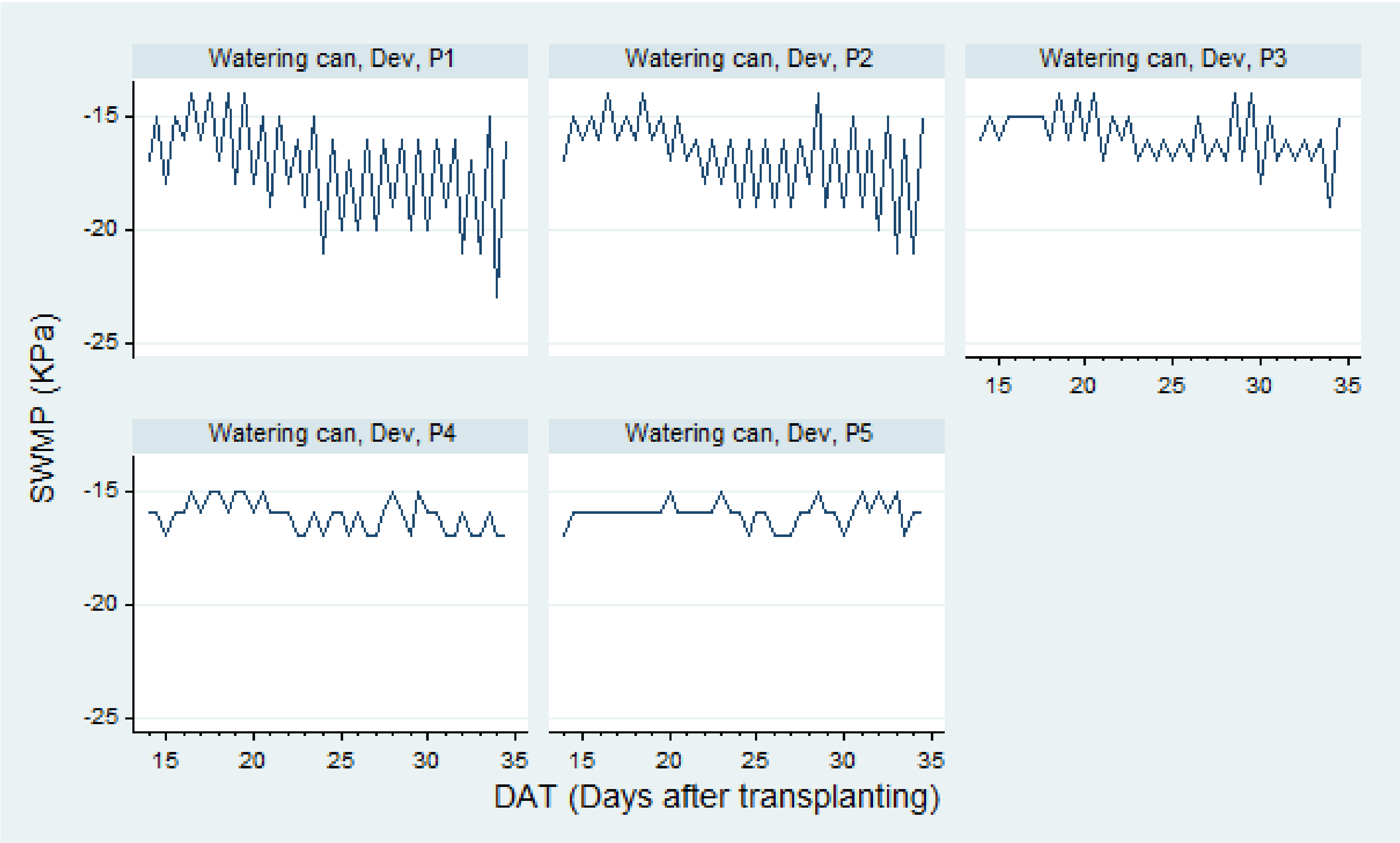

Figure 4.26 *Measured matric potential – watering-can system – development phase - Season 2*
Note: SWMP = soil-water matric potential; Dev = development phase; P = position (Figure 4.1)

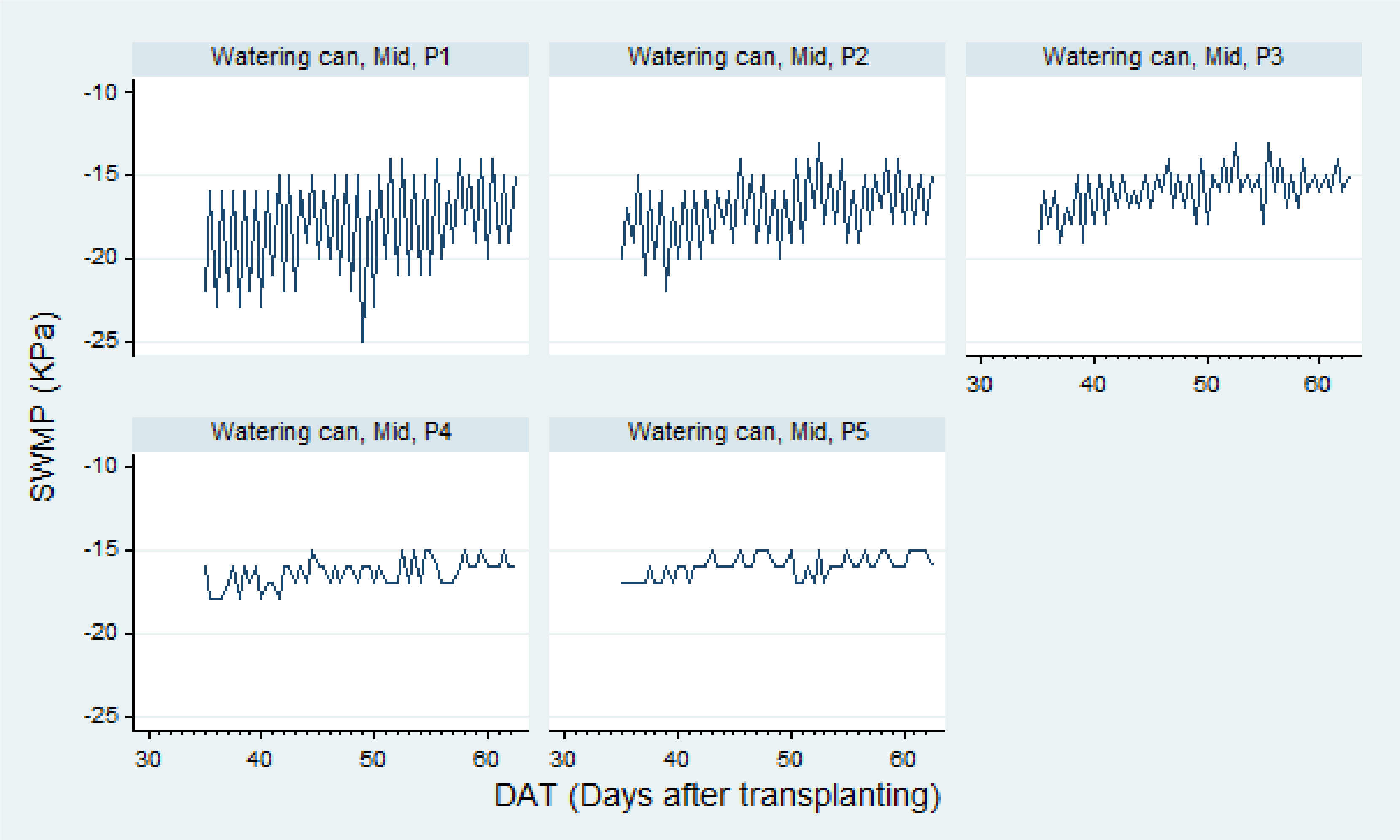

Figure 4.27 *Measured matric potential – watering-can system – mid-season phase - Season 2*
Note: SWMP = soil-water matric potential; Mid = mid-season phase; P = position (Figure 4.1)

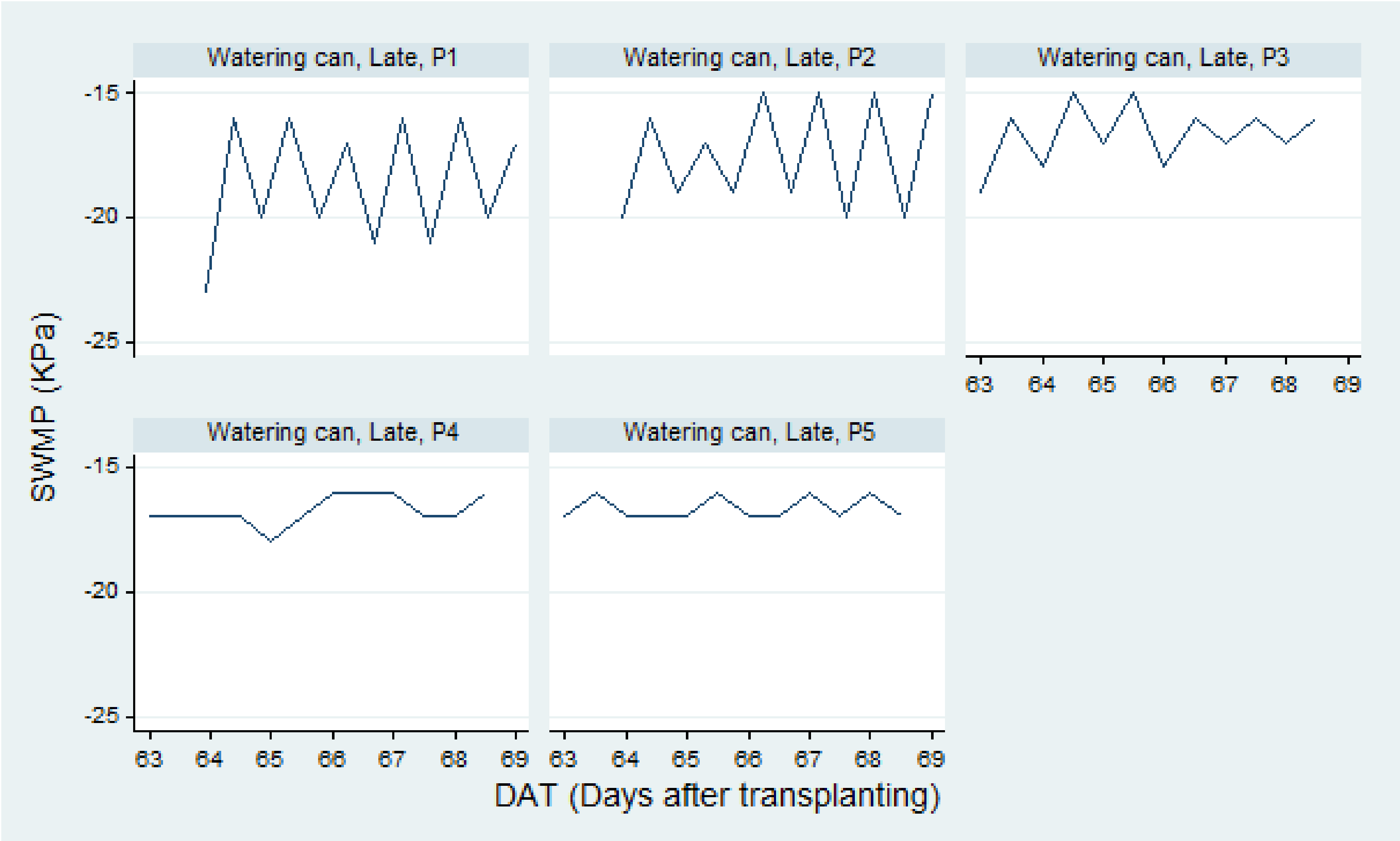

Figure 4.28 *Measured matric potential – watering-can system – late season phase - Season 2*
Note: SWMP = soil-water matric potential; Mid = mid-season phase; P = position (Figure 4.1)

Table 4.9 *Average, minimum and maximum soil-water matric potential per monitored position, irrigation system and growth phase*

			Soil-water matric potential (KPa)			
Position	**Irrigation system**	**Growth Phase**	**Avg**	**Min**	**Max**	**Total interval** (for the three growth phases)
P1	Bamboo-drip	Development	-18	-30	-10	
		Mid-season	-16	-26	-8	[-30;-8]
		Late season	-15	-24	-9	
	Watering-can	Development	-16	-23	-12	
		Mid-season	-17	-25	-13	[-25;-12]
		Late season	-17	-23	-13	
	Plastic-drip	Development	-17	-29	-11	
		Mid-season	-16	-28	-9	[-29;-9]
		Late season	-14	-27	-9	
P2	Bamboo-drip	Development	-17	-24	-11	
		Mid-season	-15	-21	-10	[-24;-9]
		Late season	-14	-19	-9	
	Watering-can	Development	-15	-21	-12	
		Mid-season	-16	-22	-12	[-22;-12]
		Late season	-16	-20	-13	
	Plastic-drip	Development	-16	-22	-11	
		Mid-season	-14	-21	-10	[-22;-10]
		Late season	-14	-22	-10	
P3	Bamboo-drip	Development	-17	-21	-14	
		Mid-season	-14	-18	-10	[-21;-10]
		Late season	-14	-17	-10	
	Watering-can	Development	-15	-19	-12	
		Mid-season	-15	-19	-12	[-19;-12]
		Late season	-15	-19	-12	
	Plastic-drip	Development	-16	-20	-13	
		Mid-season	-14	-18	-11	[-20;-10]
		Late season	-14	-18	-10	
P4	Bamboo-drip	Development	-18	-22	-14	
		Mid-season	-15	-19	-11	[-22;-11]
		Late season	-15	-20	-11	
	Watering-can	Development	-15	-17	-13	
		Mid-season	-15	-18	-13	[-18;-13]
		Late season	-15	-18	-13	
	Plastic-drip	Development	-17	-21	-13	
		Mid-season	-15	-19	-10	[-21;-10]
		Late season	-14	-20	-10	
P5	Bamboo-drip	Development	-16	-20	-14	
		Mid-season	-14	-18	-9	[-20;-9]
		Late season	-14	-18	-9	
	Watering-can	Development	-15	-17	-13	
		Mid-season	-15	-17	-12	[-17;-12]
		Late season	-15	-17	-12	
	Plastic-drip	Development	-16	-20	-13	
		Mid-season	-14	-18	-9	[-20;-9]
		Late season	-13	-18	-9	

Avg = average; Min = minimum; Max = maximum; P = position (Figure 4.1)

Overall, soil-water matric potential fluctuated around a constant value and in a narrow intervall at each monitored position (Table 4.10).

Table 4.10 *Soil-water matric potential interval and range per monitored position and irrigation system*

		Soil-water matric potential (KPa)	
Position	**Irrigation system**	**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 4.1)

Between the two drip-irrigation systems (bamboo-drip and plastic-drip), fluctuation intervalls and ranges of soil-water matric potential 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 in areas 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 is also not surprising, 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 (Cheng *et al.*, 2009).

Positions P3 and P4 show nearly similar fluctuation intervalls and ranges, i.e. nearly similar wetting levels and root activity.

In the watering-can system, fluctuation intervals and ranges of soil-water matric potential 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 remain nearly constant from P4 to P5. This shows again that roots are denser and more active closer to where the plant sits, and where evapotranspiration fluxes are more important. The nearly similar fluctuation intervall and range between P4 and P5 suggest that roots did not reach P4 where water movements are due solely to soil matric gradients.

Research on drip irrigation indicated that good soil moisture conditions can be maintained in the root zone throughout the crop growing season when the soil-water matric potential (SWMP) at 20 cm depth immediately under the emitters is kept higher than -20 KPa (Kang *et al*., 2010). As far as tomato plants are concerned, Wang *et al*. (2007) found that fruit yield is not negatively influenced when the *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 yields. Under the bamboo system, *SWMP* was in the above-mentioned ranges, making this system very conducive to good plant growth and yield, with respect to water management. Hence, when operated appropriately, the bamboo system can achieve good soil-water management.

4.2.2. Layout optimization

For soil-water content (SWC) and soil-water matric head (SWMH), statistic estimators R^2, *NRMSE* and *NSE* before calibration, after calibration and at validation are shown in Tables 4.11 and 4.12. These indicators were further summed per irrigation system (Table 4.13). The visual fit of observed and simulated soil-water content, and the residual plots of the soil-water matric head are also shown in Figures 4.29 to 4.36.

Table 4.11 *Statistic estimators for soil-water content before calibration, after calibration and at validation*

		B1		**B2**		**B3**			**P1**		**P2**		**P3**			**C1**		**C2**		**C3**		
	Qr	0.059		0.062		0.066			0.063		0.06		0.068			0.062		0.062		0.06		
	Qs	0.41		0.417		0.429			0.398		0.422		0.448			0.44		0.404		0.42		
	Alpha	0.03		0.028		0.026			0.027		0.029		0.027			0.028		0.027		0.029		
	n	1.5		1.678		1.583			1.635		1.668		1.574			1.676		1.606		1.682		
	K_{sat}	86.26		96.4		82.18			73.47		102.8		98.29			122.4		71.58		104.2		
	l	0.5		0.5		0.5			0.5		0.5		0.5			0.5		0.5		0.5		
	DAT	**28**	**42, 56**	**14**	**49**	**21**	**35**	**63**	**28**	**35, 56**	**14**	**49**	**21**	**35**	**63**	**28**	**35, 56**	**14**	**49**	**21**	**35**	**63**
R^2 (no unit)	Cb	0.9	0.9	0.8	0.9	0.9	0.8	0.7	0.8	0.9	0.9	0.9	0.9	0.8	0.9	0.8	0.6	0.9	0.9	0.8	0.8	0.8
	Ca	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.9	0.9	0.8	0.9	0.9	0.9	0.8	0.8	0.8	0.9	0.8	0.9	0.8	0.8
	V	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.9	0.8	0.9	0.9	0.9	0.8	0.9	0.8	0.9	0.8	0.9	0.9	0.9
NRMSE (%)	Cb	3.3	1.7	3.4	4.7	1.4	3.3	4.3	2.4	2.5	2.1	3.4	2.8	4.6	2.9	7	5.7	1.5	2.4	2.4	3.8	4.1
	Ca	2.8	1.5	2.4	2.5	1.6	3.5	4.2	1.6	1.9	0.8	2.2	1.9	4.1	4.4	2.6	2.4	0.6	1.9	1	3.6	3.8
	V	2.4	2.5	1.8	3	1.8	3.9	4.7	2.2	1.8	2.3	2.6	1.4	4.4	2.5	2.4	1.6	0.5	2.6	2.2	1.8	1.9
NSE (no unit)	Cb	0.6	0.8	0.2	0.6	0.7	0.8	0.6	0.7	0.8	-0.4	0.6	0.6	0.8	0.6	-1	-0.2	0.1	0.7	0.1	0.8	0.7
	Ca	0.8	0.9	0.7	0.9	0.6	0.8	0.6	0.9	0.9	0.7	0.8	0.8	0.8	0.1	0.7	0.8	0.8	0.8	0.8	0.8	0.8
	V	0.8	0.9	0.8	0.9	0.8	0.7	0.5	0.8	0.9	0.7	0.9	0.8	0.7	0.8	0.7	0.8	0.8	0.8	0.7	0.7	0.8

Qr = residual soil-water content (no unit), Qs = saturated soil-water content (no unit); Alpha = parameter α in the soil-water retention function (cm^{-1}); n = parameter n in soil-water retention function (no unit); K_{sat} = saturated hydraulic conductivity ($cm.day^{-1}$); l = tortuosity parameter in conductivity function (no unit); DAT = days after transplanting; Cb = before calibration; Ca = after calibration; V = at validation; R^2 = pearson coefficient of determination; NRMSE = normalized root mean square error; NSE = ash-Sutcliffe efficiency; Shading highlights negative NSE values.

Table 4.12 *Statistic estimators for soil-water matric head before calibration, after calibration and at validation*

		B1		**B2**		**B3**			**P1**		**P2**		**P3**			**C1**		**C2**		**C3**		
	Qr	0.059		0.062		0.066			0.063		0.06		0.068			0.062		0.062		0.06		
	Qs	0.41		0.417		0.429			0.398		0.422		0.448			0.44		0.404		0.42		
	Alpha	0.03		0.028		0.026			0.027		0.029		0.027			0.028		0.027		0.029		
	n	1.5		1.678		1.583			1.635		1.668		1.574			1.676		1.606		1.682		
	K_{sat}	86.26		96.4		82.18			73.47		102.8		98.29			122.4		71.58		104.2		
	l	0.5		0.5		0.5			0.5		0.5		0.5			0.5		0.5		0.5		
	DAT	**28**	**42, 56**	**14**	**49**	**21**	**35**	**63**	**28**	**35, 56**	**14**	**49**	**21**	**35**	**63**	**28**	**35, 56**	**14**	**49**	**21**	**35**	**63**
R^2 (no unit)	Cb	0.9	0.9	0.9	0.9	0.8	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.9	0.8	0.7	0.9	0.9	0.9	0.9
	Ca	0.9	0.9	0.9	0.9	0.8	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.7	0.9	0.9	0.9	0.9
	V	0.9	0.9	0.9	0.9	0.8	0.9	0.8	0.9	0.9	0.9	0.9	0.8	0.9	0.8	0.9	0.9	0.8	0.9	0.9	0.9	0.9
NRMSE (%)	Cb	7.3	5.6	5.8	11.2	6.5	7.7	10.2	8.7	7.4	3.9	8.1	8	9.2	9.1	11.3	10.5	3	4.3	3.2	3.8	4.3
	Ca	7.4	5.3	3.4	5.6	4.8	7.6	10.4	7.9	7.7	2.9	7.2	4.8	8.1	8.7	4.6	3.6	2.6	4.4	3.2	3.9	4.4
	V	9.3	5.1	3.7	6.5	6.1	7.5	7.3	7.7	6.8	4.2	6.9	6.6	6.6	7	4.4	3.5	3.3	5.1	3.2	4.1	3.8
NSE (no unit)	Cb	0.9	0.9	0.5	0.6	0.7	0.9	0.7	0.8	0.8	0.7	0.8	0.5	0.8	0.8	0	0	0.6	0.8	0.8	0.9	0.9
	Ca	0.9	0.9	0.8	0.9	0.8	0.9	0.7	0.9	0.8	0.8	0.9	0.8	0.9	0.8	0.8	0.9	0.7	0.8	0.8	0.9	0.9
	V	0.8	0.9	0.8	0.9	0.8	0.9	0.8	0.9	0.9	0.8	0.9	0.8	0.8	0.8	0.9	0.9	0.7	0.9	0.9	0.9	0.9

Qr = residual soil-water content (no unit), Qs = saturated soil-water content (no unit); Alpha = parameter α in the soil-water retention function (cm^{-1}); n = parameter n in the soil-water retention function (no unit); K_{sat} = saturated hydraulic conductivity ($cm.day^{-1}$); l = tortuosity parameter in the conductivity function (no unit); DAT = days after transplanting; 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; Shading shows the values of NRMSE above 10%.

Table 4.13 *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 (SWC)	Bamboo-drip system	0.8	0.9	0.9	3.2	2.6	2.9	0.6	0.7	0.8
	Plastic-drip system	0.9	0.9	0.9	2.9	2.4	2.5	0.5	0.7	0.8
	Watering-can system	0.8	0.8	0.9	3.8	2.3	1.8	0.2	0.8	0.8
Soil-water matric head (SWMH)	Bamboo-drip system	0.9	0.9	0.9	7.8	6.4	6.5	0.7	0.8	0.9
	Plastic-drip system	0.9	0.9	0.9	7.8	6.7	6.5	0.8	0.8	0.9
	Watering-can system	0.9	0.9	0.9	5.8	3.8	3.9	0.6	0.8	0.9

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.

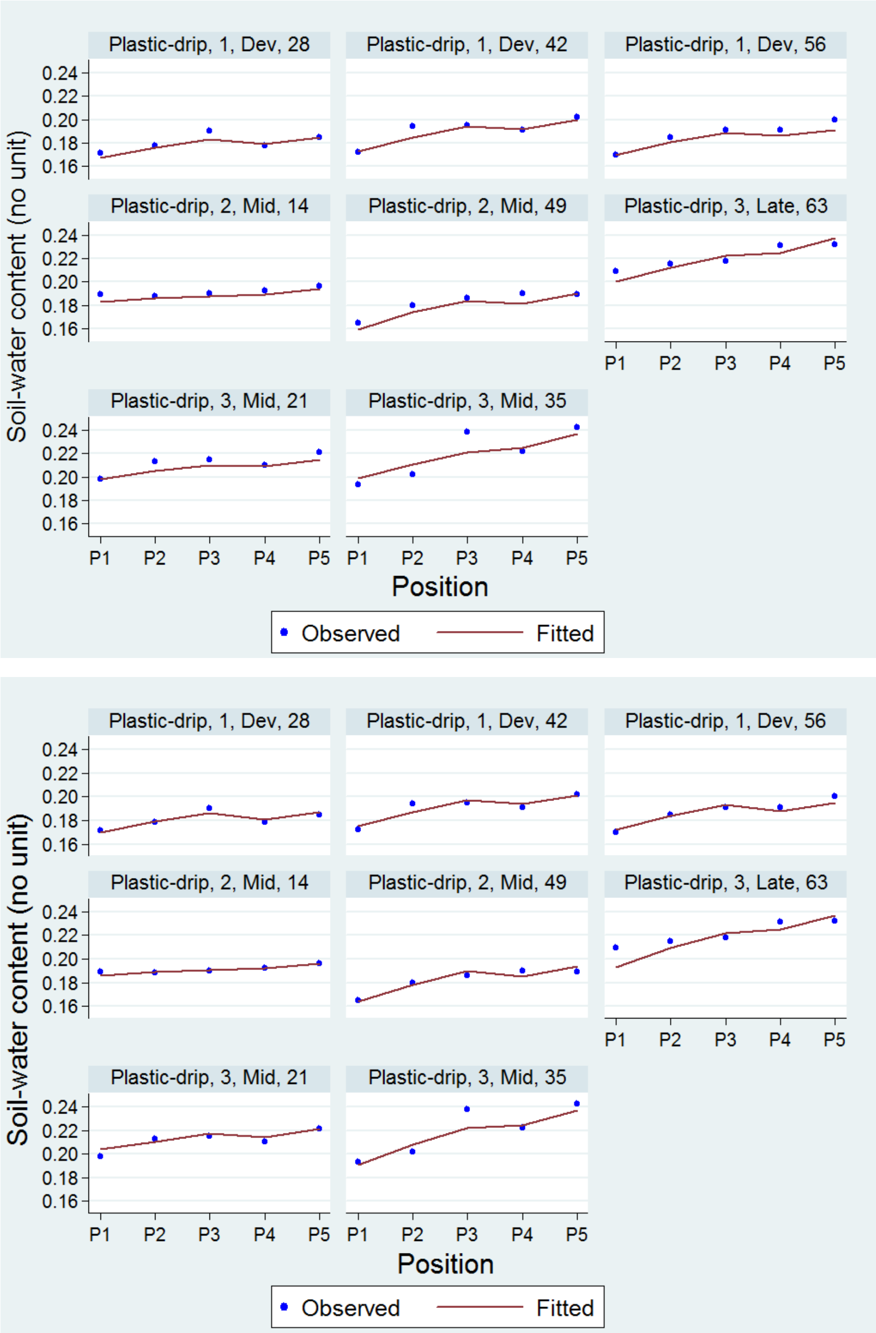

***Figure 4.29** Observed and fitted soil-water content in the plastic-drip system before calibration (up) and after calibration (down)*
Note: Dev = development phase; Mid = mid-season phase; Late = late-season phase; First number = replicate (block), second number = days after transplanting; P = position (Figure 4.1).

The fact that the observed soil-water contents values are mostly at one side of the fitted curve before calibration constitutes a bad visual fit and indicates that ROSETTA-estimates of K_{sat} for each plot are slightly higher than the actual values. The visual fit improved after calibration (observed values distributed more or less homoscedastically around the fitted curve), which consisted of adjusting the ROSETTA-estimated K_{sat} values at each growth (Table 4.4)

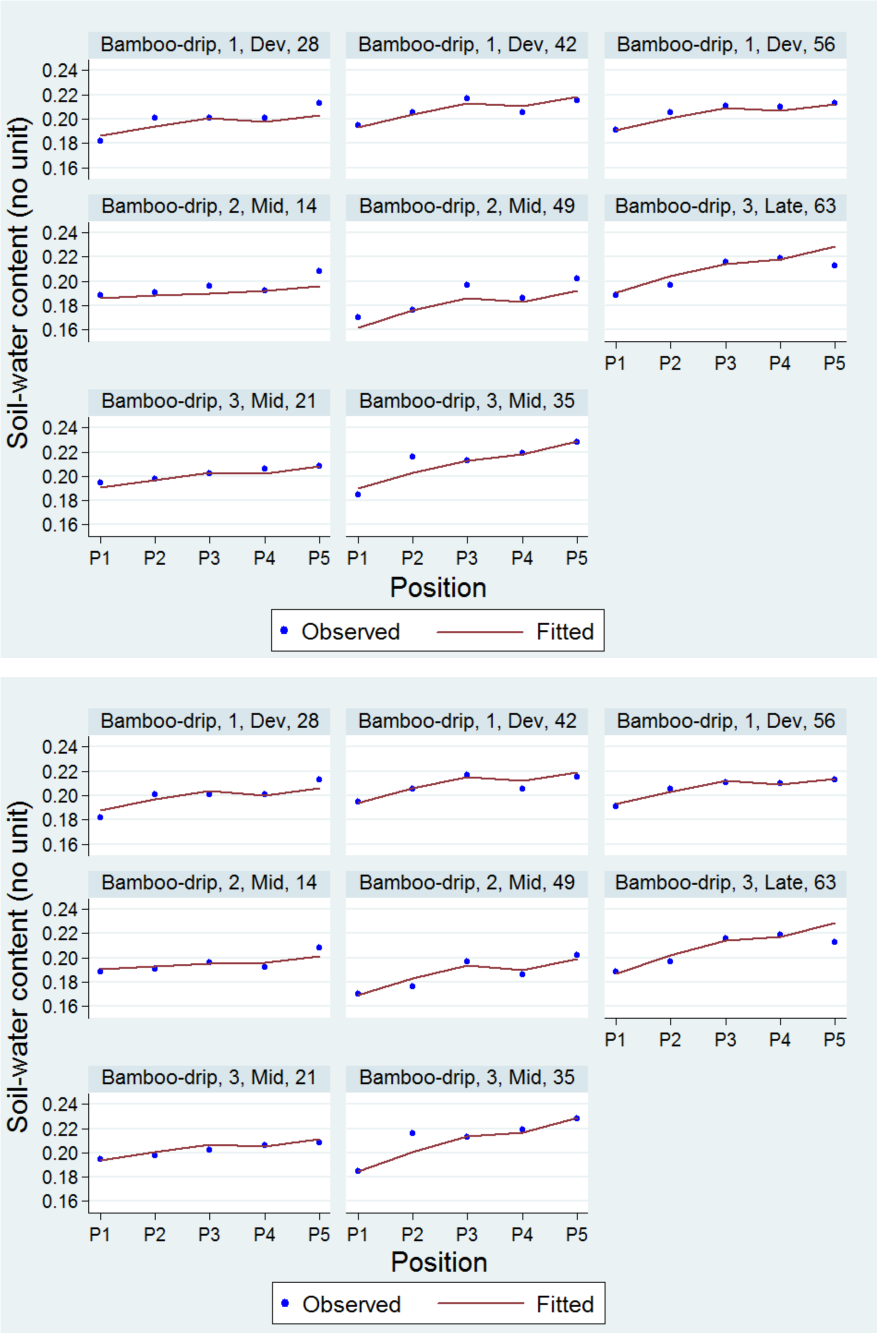

***Figure 4.30** Observed and fitted soil-water content in the bamboo-drip system before calibration (up) and after calibration (down)*

Note: Dev = development phase; Mid = mid-season phase; Late = late season phase; First number is for replicate (block) and second for time of monitoring (days after transplanting); P = position (Figure 4.1).

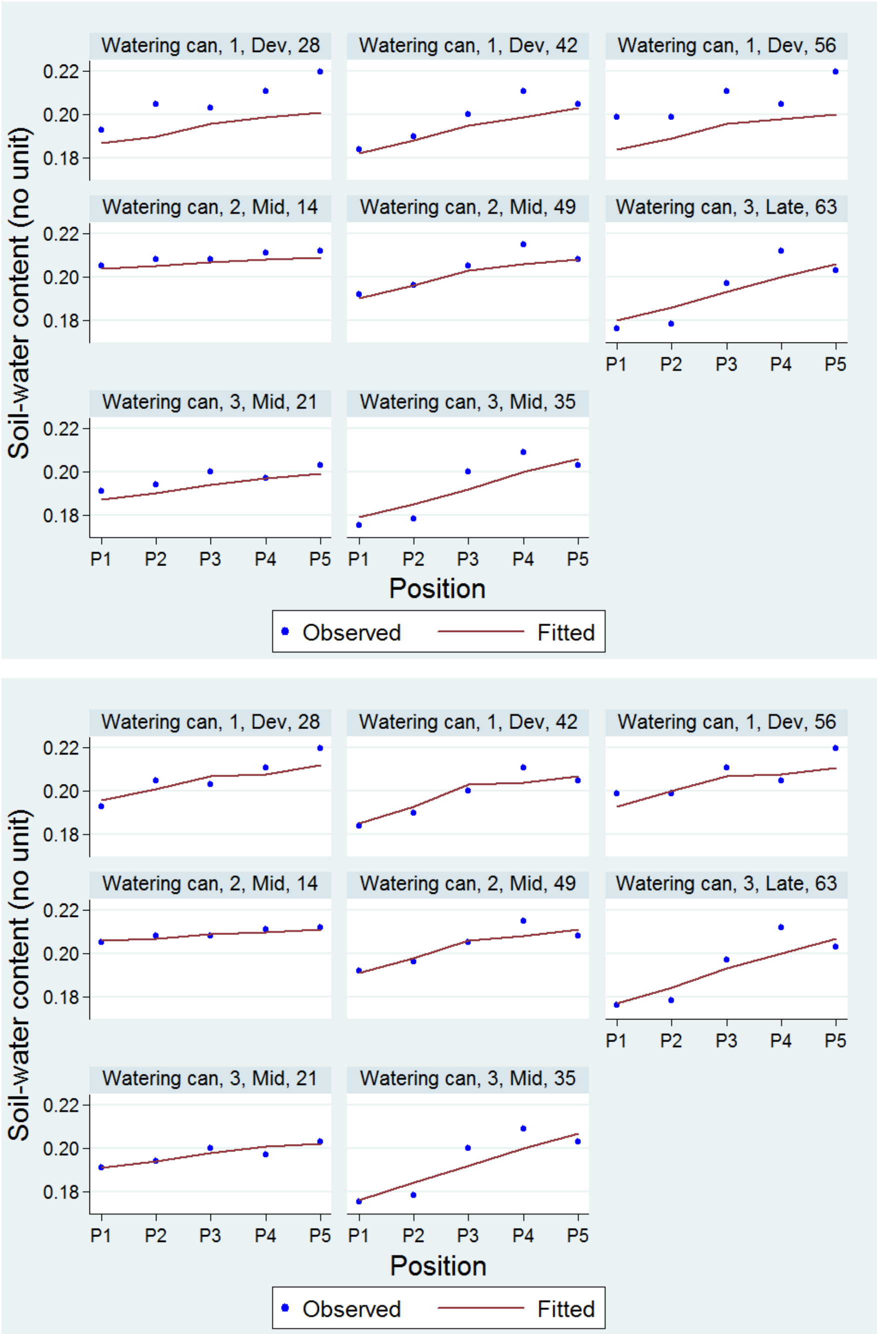

***Figure 4.31** Observed and fitted soil-water content in the watering-can system before calibration (up) and after calibration (down)*

Note: Dev = development phase; Mid = mid-season phase; Late = late season phase; First number is for replicate (block) and second for time of monitoring (days after transplanting); P = position (Figure 4.1).

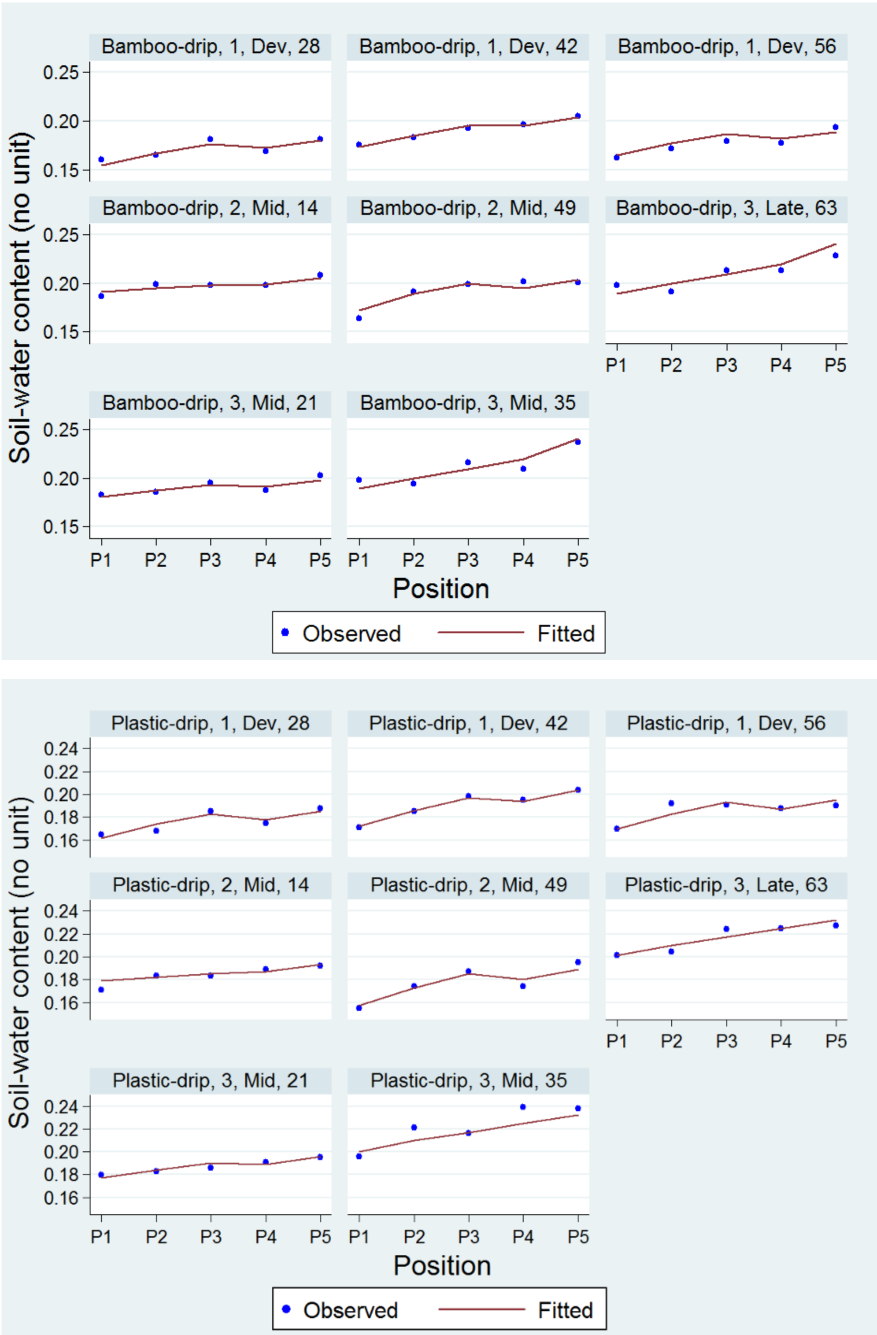

Figure 4.32 *Observed and fitted soil-water content at validation in the bamboo-drip (up) and the plastic-drip (down) systems*

Note: Dev = development phase; Mid = mid-season phase; Late = late season phase; First number is for replicate (block) and second for time of monitoring (days after transplanting); P = position (Figure 4.1).

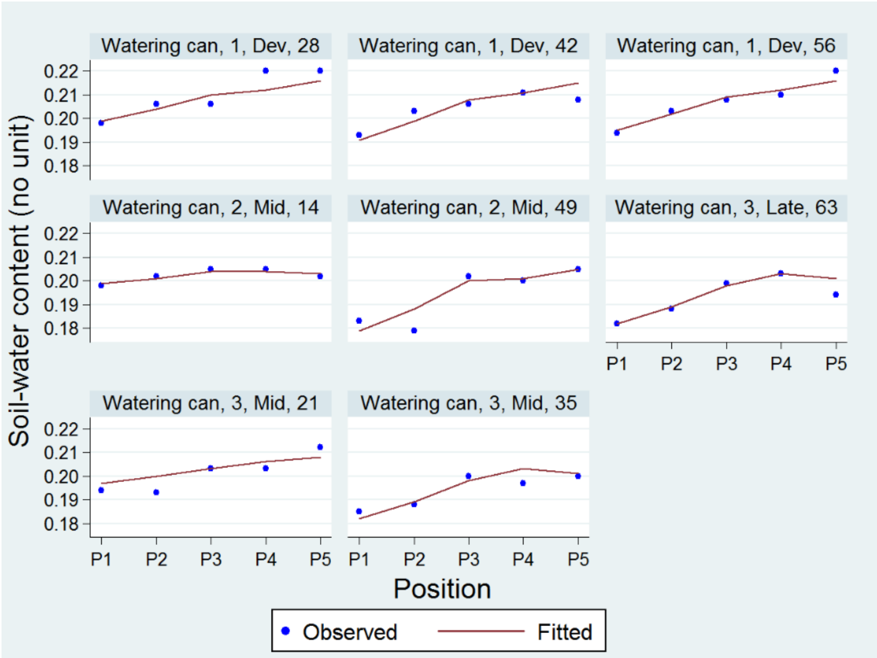

Figure 4.33 *Observed and fitted soil-water content at validation in the watering-can system*

Note: Dev = development phase; Mid = mid-season phase; Late = late season phase; First number is for replicate (block) and second for time of monitoring (days after transplanting); P = position (Figure 4.1).

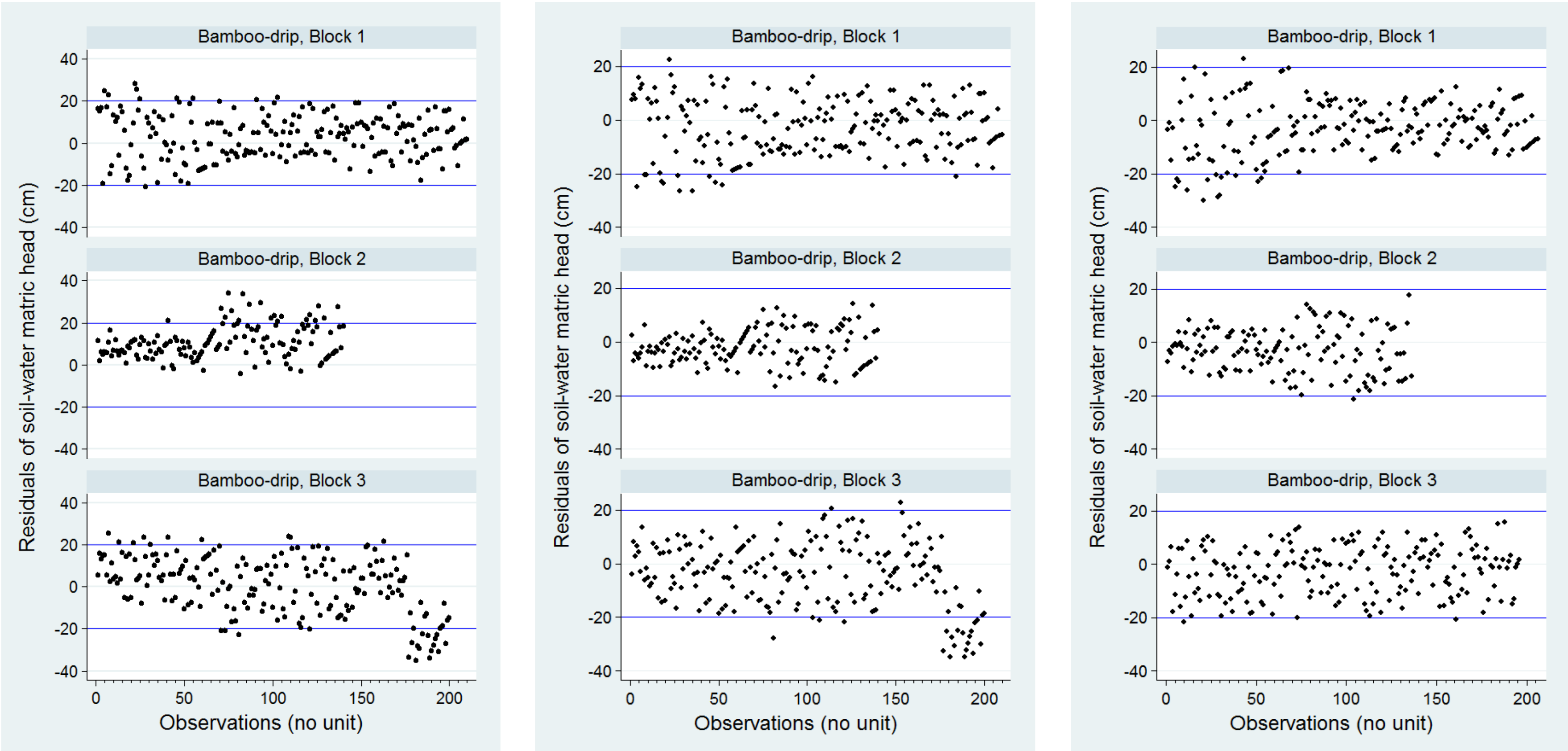

***Figure 4.34** Residuals of soil-water matric head in the bamboo-drip system - before calibration (left column), after calibration (middle column) and at validation (right column)*
Note: The interval where the spread of the residuals lies (after calibration and at validation) is highlighted by two lines.

It can be seen overall that the spread of residuals is more scattered before calibration than after calibration and at validation. This shows that calibration brought the simulated values of the soil-water matric head closer to the observed values.

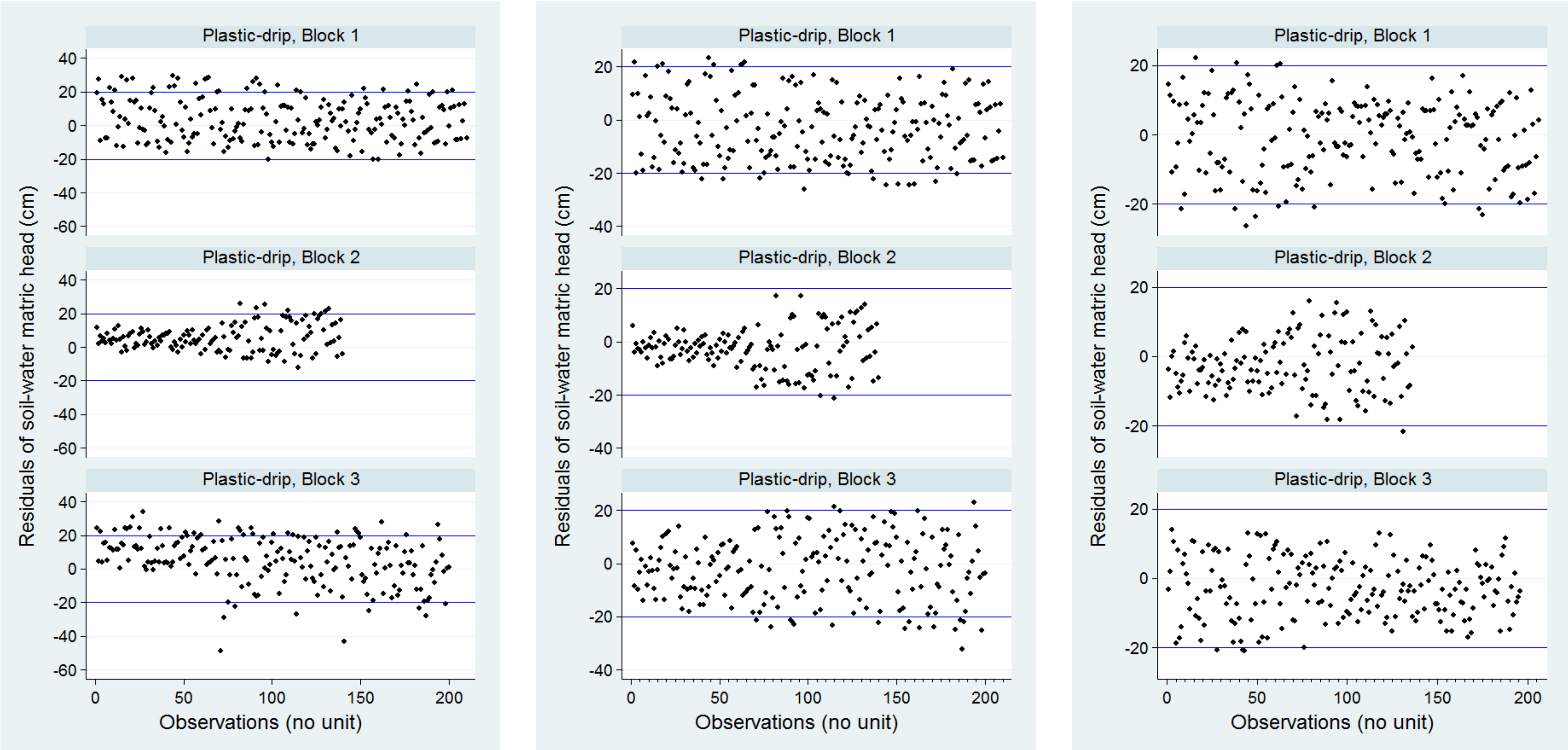

Figure 4.35 *Residuals of soil-water matric head in the plastic-drip system – before calibration (left column), after calibration (middle column) and at validation (right column)*
Note: The interval where the spread of the residuals lies (after calibration and at validation) is highlighted by two lines.

It can be seen overall that the spread of residuals is more scattered before calibration than after calibration and at validation. This shows that calibration brought the simulated values of the soil-water matric head closer to the observed values.

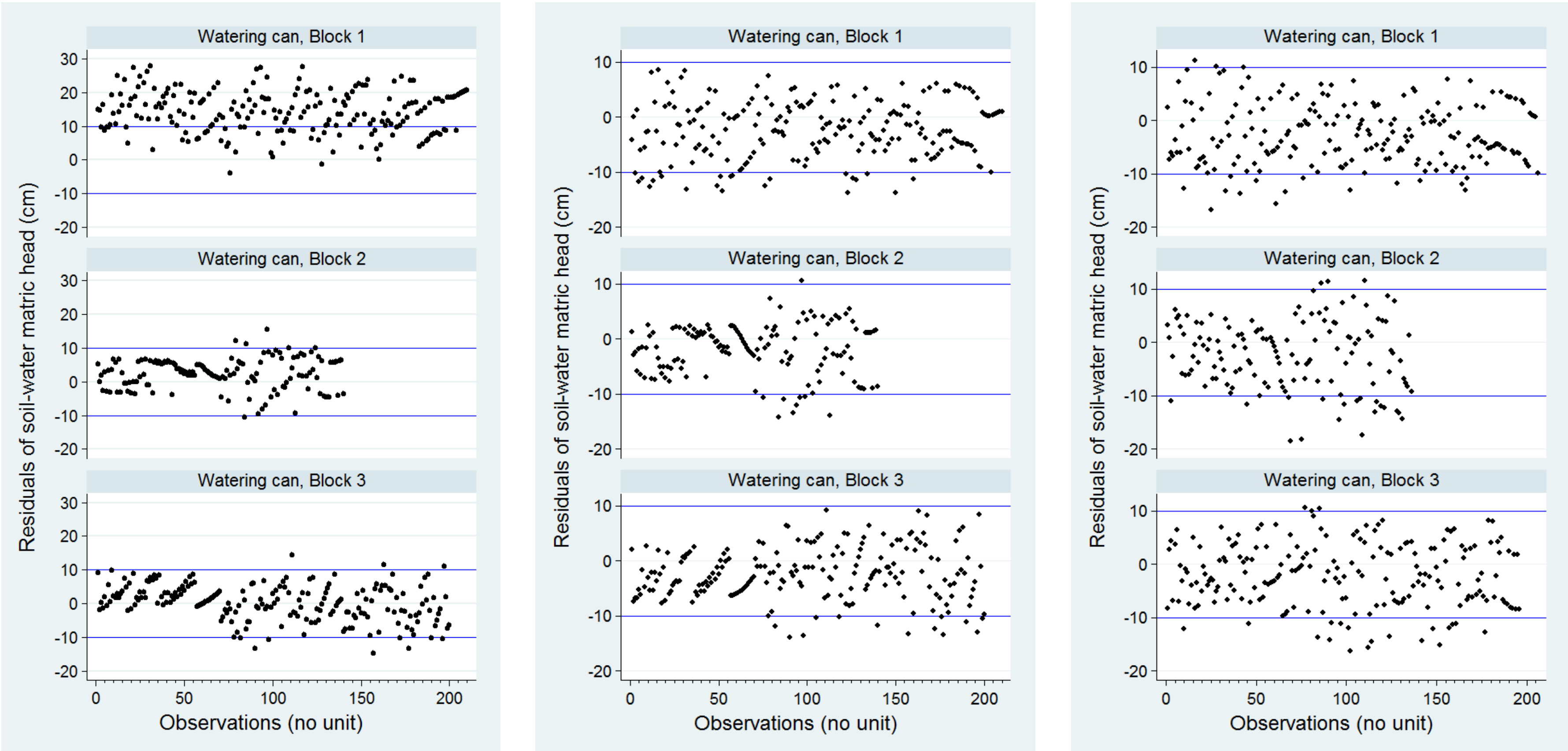

Figure 4.36 *Residuals of soil-water matric head in the watering-can system – before calibration (left column), after calibration (middle column) and at validation (right column)*

Note: The interval where the spread of the residuals lies (after calibration and at validation) is highlighted by two lines.

It can be seen overall that the spread of residuals is more scattered before calibration than after calibration and at validation. This shows that calibration brought the simulated values of the soil-water matric head closer to the observed values.

For soil-water content (SWC) and soil-water matric head (SWMH), statistic estimators (R^2, *NRMSE* and *NSE* before calibration, after calibration and at validation, show that *NRMSE* values were at least good (≤ 20%) at calibration and at validation (Table 4.13). This indicates low mean deviation between observed and simulated *SWC* and *SWMH* values. The *NSE* values were also overall above 0.5, indicating a good agreement between observed and simulated values, and that HYDRUS 2D model shows an acceptable modeling performance. Values of the Pearson coefficient of variation (R^2) were overall above 75 %, indicating a good correlation between observed and predicted values.

As observed and predicted *SWC* values before calibration were already fairly well correlated (high R^2 values), calibration aimed essentially to reduce deviation (NRMSE) and improve agreement (NSE) and visual fit (Figures 4.29 to 4.33 for soil-water content and Figure 4.34, 4.35 and 4.36 for soil-water matric head). HYDRUS 2D was then able to predict soil-water content and matric head throughout both cropping seasons for the three irrigation systems with only a small bias of estimation. Hence, it can be used to simulate soil-water dynamics and deep percolation with non-significant errors.

- **Calibration and validation of AquaCrop**

Observed and simulated yields for calibration and validation and *NRMSE* are given in Table 4.14. Residuals between simulated and observed yields are presented in Figure 4.37. The satisfactory performance of the simulations led to a reasonable fit of yields in the three irrigation systems. The *NRMSE* values are excellent (below 10%). Additionally, residuals distribution is homoscedastic, i.e. the spread of the residuals is generally about the same, and no systematic patterns can be observed. AquaCrop was thus well calibrated and validated, and can be used to simulate yields in the experimental conditions of this study, with high reliability.

Table 4.14 *Dry yields (observed and simulated) and NRMSE (after calibration and at validation)*

		After calibration			At validation		
Irrigation system	**Plot**	**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** (%)
Bamboo-drip	1	0.7	0.6	3.9	0.6	0.6	8.7
	2	0.7	0.6	2.9	0.6	0.6	1
	3	0.6	0.6	11.1	0.7	0.6	1.9
Plastic-drip	1	0.7	0.6	7.4	0.6	0.6	7.6
	2	0.6	0.6	12.4	0.6	0.6	4.2
	3	0.6	0.6	4.2	0.7	0.6	0.9
Watering-can	1	0.6	0.6	1.1	0.7	0.6	1.9
	2	0.6	0.6	6.4	0.7	0.6	5.6
	3	0.7	0.6	1	0.7	0.6	3.8

NRMSE = normalized root mean square error

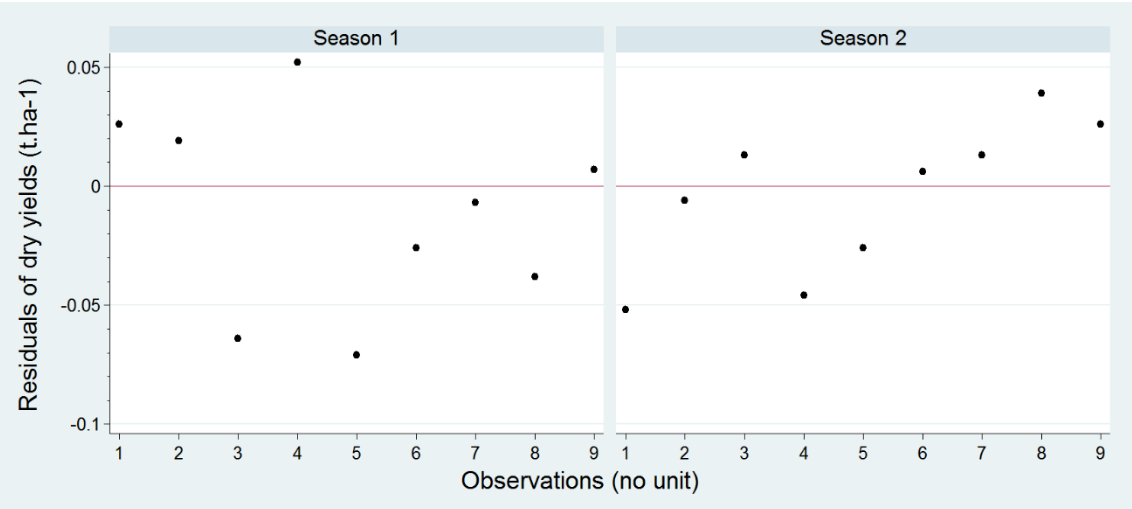

Figure 4.37 *Residuals of dry yields after calibration (left) and at validation (right)*

- **Optimization (identification of best spacing)**

As spacing was progressively reduced (with 1 cm steps from 60 cm down to 30 cm), plant density and evapotranspiration increased, while gross irrigation remained the same. As a result, fresh yields also increased, while deep percolation decreased. However, the increase in fresh yields can be assumed to reach a limit where competition between plants for resources is maximum, and further spacing reduction would result in lower yields. Table 4.15 shows values of deep percolation and fresh yield for each spacing, along with the respective variation from the reference value (value at 60 cm spacing).

Table 4.15 *Deep percolation and fresh yield per spacing, and variations from the reference spacing (60 cm)*

Spacing (cm)	**Laterals per plot**	**Emitters per lateral**	**Emitters/Plants per plot**	**Deep percolation** (mm)	**Δ_Deep percolation** (%)	**Fresh Yield** (kg. plot-1)	**Δ_Fresh Yield** (%)
60	4	8	32	40.9	-	5.2	-
59	4	8	32	40.9	0	5.2	0
58	4	8	32	40.9	0	5.2	0
57	4	8	32	40.9	0	5.2	0
56	4	8	32	40.9	0	5.2	0
55	4	9	36	23.1	-43.6	6.1	18.8
54	4	9	36	23.1	-43.6	6.1	18.8
53	4	9	36	23.1	-43.6	6.1	18.8
52	4	9	36	23.1	-43.6	6.1	18.8
51	4	9	36	23.1	-43.6	6.1	18.8
50	4	10	40	10.2	-75.1	7.2	39.7
49	4	10	40	12	-70.6	7.2	39.7
48	5	10	50	8.1	-80.3	7.9	52.4
47	5	10	50	8.1	-80.3	7.9	52.4
46	5	10	50	8.1	-80.3	7.9	52.4
45	5	11	55	7.6	-81.5	8.7	69.1
44	5	11	55	6.5	-84.2	8.7	69.1
43	5	11	55	6.5	-84.2	8.7	69.1
42	5	11	55	6.5	-84.2	8.7	69.1
41	5	12	60	6.1	-85.1	10.1	95.6
40	6	12	72	5.5	-86.6	9.8	89.1
39	6	12	72	4.7	-88.5	9.8	89.1
38	6	13	78	4.5	-89	9.9	92.3
37	6	13	78	3.6	-91.3	9.9	92.3
36	6	13	78	3.6	-91.3	9.9	92.3
35	6	14	84	3.4	-91.7	10.1	96.1
34	7	14	98	3	-92.7	9.3	79.1
33	7	15	105	2.9	-92.9	8.8	70.5
32	7	15	105	2.9	-92.9	8.8	70.5
31	7	16	112	2.8	-93.1	8.4	61.9
30	8	16	128	2.5	-94	7.3	41.1

Δ_Deep percolation = variation of deep percolation from that of 60 cm spacing; Δ_Fresh yield = variation of fresh yield from that of 60 cm spacing

Deep percolation (DP) and fresh yield (Y) were line-charted at log-scale and a polynomial trendline fit to their curve (Figure 4.38).

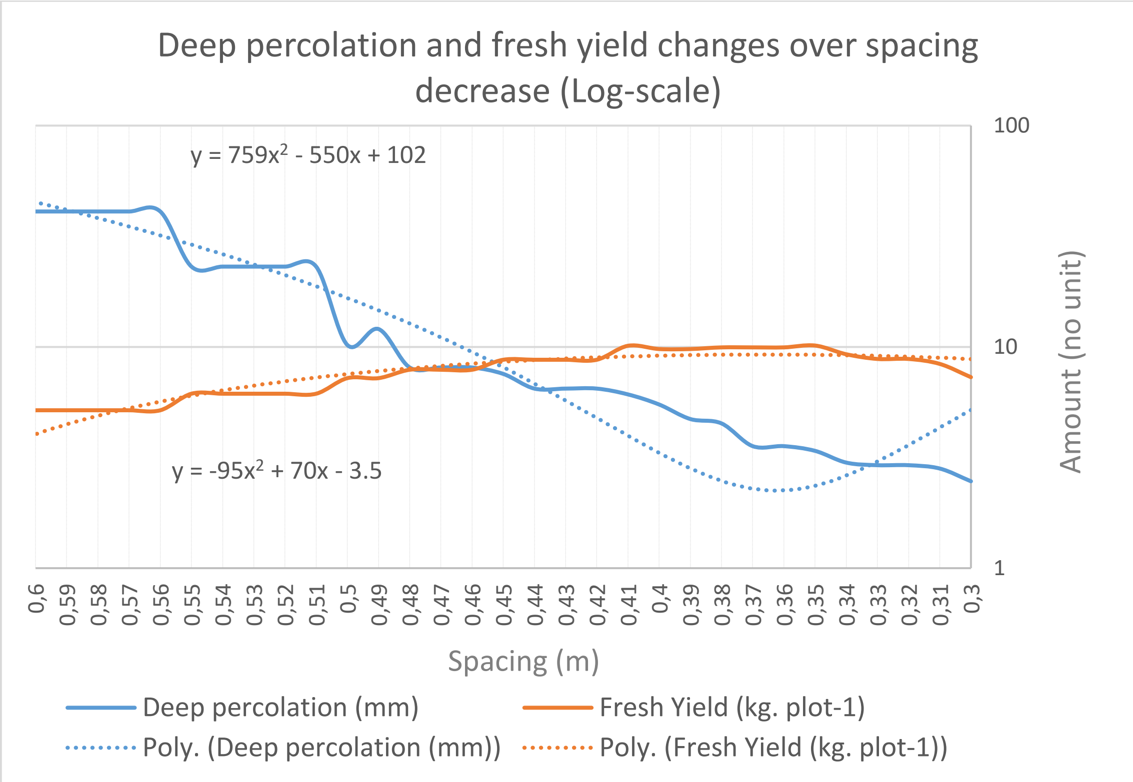

Figure 4.38 *Deep percolation and fresh yield changes over spacing decrease*

The chart equations were used as objective functions in GAMS:

$$\textbf{OF}_1 \textit{ (For DP): min } DP = 759x^2 - 550x + 102 \qquad (4.12)$$

$$\textbf{OF}_2 \textit{ (For Y): max } Y = -95x^2 + 70x - 3.5$$

where x is the spacing of emitters and laterals ranging from 30 cm to 60 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 deep percolation is reduced by 93.5% from the value at 60 cm spacing. For fresh yield, the feasible solution lies between 8.82 kg.plot^{-1} (fresh yield at 32 and 33 cm spacing) 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 the spacing where the best compromise between fresh yield and deep percolation was observed under the bamboo system, and for sandy loam soil.

5. CHAPTER 5 : CONCLUSIONS AND OUTLOOK

The bamboo-drip system is workable, but still can be improved. Its laterals and emitters have excellent hydraulic properties, and emitter flow variation is essentially due to emitter plugging. Emitter plugging can be reduced by improving the uniformity of the bamboo segments used to construct the pipes, or by running the system at higher pressure heads. This would also improve flow uniformity in the bamboo-drip system as a whole, but could increase system cost on a large scale.

The bamboo-drip system showed good yield and water productivity performance overall. Its yield performance was similar to that of the conventional plastic-drip and watering-can systems after the first cropping season, which was confirmed by the second season. Water productivity performance was similar to that of the plastic-drip system within and between seasons, but 99% and 85% higher than that of the watering-can system due to a lower gross irrigation amount. However, the system could not unfold its full potential due to the absence of mineral fertilization, the low planting density applied, the pruning performed and the heat stress the plants were subject to during harvest index development. Better yields and water productivity could be obtained under this system by optimizing its layout, i.e. by identifying the spacing of emitters and laterals which would maximize fresh yields while minimizing water losses through deep percolation. Deficit irrigation and partial root drying technique are two techniques which could be combined with the bamboo-drip system to increase yield and water productivity. Furthermore, the economic (net-benefit) advantages of this system should be investigated and compared to the conventional plastic-drip system by considering different scenarios, e.g. cost of water, thus utilizing its cost-benefit advantage as far as possible.

Overall, soil-water management under the bamboo system was 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 the two cropping seasons. Soil-water content increased 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 the 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. These values 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 the liquid and gas phases of the soil.

Integration of hydrologic and agronomic behaviors of the bamboo-drip system on sandy loam soil revealed 34 cm as the best spacing, where the best compromise of deep percolation and fresh yield was observed.

Higher performance of the bamboo-drip system could be obtained by using one lateral per two cropping rows, and integrating water and nutrient management through fertigation[19] and deficit irrigation. The difference in cost savings between the bamboo-drip and plastic-drip systems should be investigated through longer time-series studies, as the labor intensity of watering-can irrigation may be offset by cheap labor costs with the use of the bamboo system, but investment costs of the bamboo system may also be determinant. Another potential way of using the bamboo-drip system is to bury the lines (main and laterals). Studies have shown that with buried drip lines, crop yields are equal to or better than those of surface lines. In addition, buried systems require less or equal amounts of water and fertilizer compared to surface irrigation. A buried bamboo-drip system would, on the one hand, lower the likeliness of the lines being damaged or tampered with by fieldworkers and rodents. Furthermore, the soil surface would remain dry, thus reducing weed growth. However, the bamboo segments would have to be treated accordingly for protection against termites. Waste water could also be applied through the buried lines, resulting in the deeper placement of phosphorus in the soil profile, and an easier plant uptake. Easing the manufacture of the hand-made emitters is also a way to improve accessibility to the bamboo system. Last but not least, several social, technical, and institutional challenges will have to be overcome for the bamboo-drip system to revolutionize drip irrigation in rural and peri-

[19] Process combining fertilization and irrigation by injecting soil amendments, fertilizers, and other water-soluble products into an irrigation system (https://www.maximumyield.com/definition/1773/fertigation).

urban West Africa. Nevertheless, this system holds the promise to enable a more productive use of water for smallholder farmers, to allow the poorest to produce vegetables under dry spells and changing climate, and to improve food security at household level and in water-scarce areas of West Africa.

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