Experimental Agriculture (2021), **57**, 338–351
doi:10.1017/S0014479722000011

RESEARCH ARTICLE

Effects of spatial and temporal regulation of drip emitters and tube configurations on water productivity of juvenile macadamia trees in the tropics

Surya P. Bhattarai[1], Lance Pendergast[2], Li Shuyan[3] and David J. Midmore[1,*]

[1]Central Queensland University, Institute for Future Farming Systems, School of Health, Medical and Applied Science, Rockhampton, QLD 4702, Australia, [2]Department of Agriculture and Fisheries Queensland, PO Box 1085, Townsville, QLD 4810, Australia and [3]Department of Fruit Crop Research, Dalian, Liaoning Province, People Republic of China
*Corresponding author. Email: d.midmore@cqu.edu.au

(Received 25 September 2021; revised 17 November 2021; accepted 01 January 2022)

Summary

Macadamia in Australia is traditionally grown in semi-arid climates with hot and humid summers and cool winters supporting rainfed cultivation. Recent industry expansion into more northern, drier production areas of Queensland, Australia, requires supplementary irrigation for successful macadamia production. However, ever-increasing demand for irrigation water in these areas is both competitive and regulated. Limited information is available to optimize water use efficiency for field-grown macadamia trees. We trialled a technique that employs specially designed drip tubes with push-in emitter plugs to close emitters so that transplanting can start with emitters closed distant from tree bases and open next to the trunks of each tree. Additional emitters are then gradually opened (i.e., plugs are removed) as tree canopy size increases over subsequent years. This technique was tested on single and double in-line irrigation tube configurations per row of macadamia. Temporal regulation of emitter closure significantly reduced irrigation input by 75, 50 and 25% in the first, second and third year of treatment. Hence, irrigation over the three-year establishment period was reduced to one-half that of the non-regulated crop. These early reductions of irrigation in juvenile trees had no significant negative effects on plant growth (height, canopy spread, leaf chlorophyll and leaf photosynthetic rates), nor on nut counts. Control of emitter discharge between the plants along the row in the earlier stage (i.e., before complete within-row canopy cover) also reduced weed growth between the trees in the row. Notable growth advantages of the single in-line over the double in-line tube configuration were evident, with a non-significant but sizeable benefit on nut counts too. Effects of the temporal regulation of emitters and of in-line tube configurations must be validated on cultivars with differing water requirements and for the longer-term reproductive performance and nut quality.

Keywords: Deficit irrigation; Drip irrigation; Emitter control; Variable flow; Root length density; Growth; Nut count; Single in-line tube; Double in-line tube

Introduction

Macadamia (*Macadamia integrifolia*) is native to the coastal rainfall regions of southern Queensland and northern New South Wales of Australia (Turner, 1893). However, it has morphological adaptations to cope with dry sub-tropical environments. These traits include sclerophyllous leaves and root systems with ability to extract, transport and conserve water under low soil moisture conditions (Lloyd *et al.*, 1991). Macadamia performs well in fertile, well-drained soils, at temperatures above 10 °C (optimum temperature is 25 °C), and where annual rainfall ranges between 1,000 and 2,000 mm. Macadamia roots are often shallow and surface feeders (Firth *et al.*, 2003) and are susceptible to *Phytophthora* root rot disease, often pronounced in wetter soil conditions.

Australia is one of the world's largest macadamia producers (averaging 49 000 tonnes in shell production over the past five years (2015–2019) compared to that of the *c.* 160 000 tonnes produced globally), and macadamia constitutes the fourth largest Australian horticultural export crop in value. The Australian macadamia industry, valued at the farm gate at $293 million in 2020, contributes significantly to regional employment and rural economies (AMS, 2020). Australia has an estimated 10.2 million trees varying in age from newly planted to over 40 years old, covering an area of 33 000 ha with 25 000 ha currently bearing (AMS, 2020).

Macadamia in the traditional production zones of northern NSW and SE Queensland in Australia was predominantly grown as a rainfed crop but has recently expanded to central Queensland with some irrigation (Trochoulias and Johns, 1992), because macadamia trees appeared to respond positively to irrigation in these drier zones. The industry is expanding rapidly into the more-drier northerly production areas of Queensland particularly in Gympie, Bundaberg, Rockhampton, Emerald and the Atherton Tablelands where supplementary irrigation is essential for sustainable yield and quality production (Searle and Lu, 2003). Nowadays, on average over the country, more macadamia crops are produced with than without supplementary irrigation. Improving the water use efficiency of macadamia production is crucial to sustain and expand growth of irrigated macadamia production in these northern locations.

In the southern production areas of Australia, irrigation has been shown to have little effect on yield and kernel quality (Trochoulias and Johns, 1992). Indeed, in wet years, supplementary irrigation decreased nut size in the well-watered treatments relative to the rainfed controls (Trochoulias and Johns, 1992). However, despite the sclerophyllous traits, macadamia is susceptible to periods of drought, as evidenced by studies conducted by Stephenson *et al.* (1995) and Stephenson *et al.* (2002) under controlled conditions in the south of Queensland and by Searle and Lu (2003) for field-grown macadamia in Bundaberg, near central Queensland. Growth in general is diminished by drought, and drought stress around floral development and during nut maturation reduces both yield (especially nut number) and quality. As a rule of thumb, water use by reasonably mature trees in lysimeter studies ranges from 52 L/tree/day for winter to 80 L/tree/day for summer seasons (Stephenson *et al.*, 2003) and up to 110 L/tree/day (Stephenson *et al.*, 1995) although Searle and Lu (2003), albeit for different varieties and in a different location, reported lower values of 20–30 and 40–55 L/tree/day, for winter and summer, respectively. Zapp (2019) further suggested that mature macadamia trees can be successfully converted from sprinkler to drip irrigation (the latter more water use efficient) without difficulty in harvest, although according to Smith (2016) sprinklers are preferred over drip for their greater ground coverage.

Variation between macadamia cultivars for water use (Searle and Lu, 2003) has implications for new plantings of macadamia in water-limiting environments. The differing water requirements of cultivars (Hardner *et al.*, 2009), and the efficiency with which crops use water to produce commercially viable nut yield, should guide the irrigation management for different macadamia varieties. Furthermore, Smith (2016) highlights the tree water use dependency on the crop N status and supply.

Plant spacing and root distribution can be the determinant of drip irrigation design with respect to selection of emitter placement geometry. Commercial plantations of macadamia generally follow a wide row spacing (row to row 4–10 m and within row 3–5 m configurations) as narrow row configurations can compromise the operation of machinery. New plantations in northern warmer regions in Australia are supported with water delivered via either mini sprinkler or drip irrigation. Single or double in-line drip tubes with pressure compensated drip emitters are configured to irrigate long rows. Emitter spacing within drip lines varies between 40–75 cm. Root density of mature macadamia trees is reported to be higher close to the trunk, and only one-half at 1.0 m from the trunk compared to that at 0.5 m from the trunk at 0–10 cm soil depth

https://doi.org/10.1017/S0014479722000011 Published online by Cambridge University Press

(Firth *et al.*, 2003). This pattern is consistent with other fruit trees, in that the highest root density is generally within 1 m of the trunk (Reid *et al.*, 1993). Hence, emitters distant from the trees are less likely to contribute to plant water requirements, particularly in the early growth phase.

Trees in new plantings, with their limited root spread, will predominantly rely on water supply from the one to two emitters proximal to the trunk. A large volume of any water delivered further between trees is beyond the reach of the effective young tree root zones and hence is wasted and supports weed growth. Therefore, a dynamic drip irrigation design that allows the temporal closure of individual drip emitters further from the tree trunk may be useful to enhance water use efficiency.

Herein, we examined the effectiveness of having in-line emitters distant from the tree trunks plugged, and later unplugged successively away from the trunk, in a juvenile plantation of macadamia variety HAES 741 which is reasonably susceptible to moisture stress and requires regular watering, especially when the nuts are forming (Searle and Lu, 2003). The hypothesis was that one could save irrigation water use by juvenile trees by progressively unplugging emitters over time, without compromising growth, potential yield determination and overall tree health. This was done in single and double in-line drip irrigation tube configurations per macadamia row in the Central Highland region of Queensland, Australia.

Materials and Methods

Site description

The trial was conducted at Nogoa Valley Orchard, Emerald, Central Highlands in Queensland, Australia (23°33’15.4"S; 148°05’39.9"E). The site represents a humid subtropical climate with warm to hot summers and mild, dry winters. Historically, monthly maximum temperatures ranged from 34 °C in January to 22 °C in July, while minimum ranged from 22 °C to 7 °C. The average annual rainfall is 551 mm with wetter summer months (October to March) and drier (rainfall <30 mm per month) winter months (April – Sept). Weather data for the site were sourced from a nearby weather station located at Emerald airport (~3 km aerial distance).

The soil type is a self-mulching black cracking clay (vertisol). The site, previously a grazing pasture, was levelled and formed into 25 cm high beds in February 2009 and transplanted with two-year-old grafted macadamia seedlings, at tree spacings of 8 m between and 4 m within rows.

Crop description

The trial, initiated on 23 June 2010, superimposed treatments on the existing transplants of the variety HAES 741. First fruit generally occurs within four years of transplanting in this variety. The variety is self-pollinating, prefers full sun and requires water in both winter and summer. The grafted plants used the rootstock variety H2 Hinde of *M. integrifolia* because of its ease of propagation and ability to produce vigorous and uniform seedlings (O’Hare *et al.*, 2004).

Irrigation configuration, treatments and design

The property sourced year-round irrigation water from the Fairbairn Dam of Lake Maraboon, located 6 km from the farm. Irrigation water for the 6.57 ha trial site was pumped directly from an on-farm dam using a single pump station. The pump was equipped with a controller that enabled scheduling separate irrigation cycles to each block and treatment.

For the year before treatments were installed, a single line per row of Netafim drip tubes with 50 cm emitter spacing and 3.5 L/h emitter delivery rate was installed on all rows flush with the trunks. Subsequently, as the trial began (Figure S1), on one-half of the plots the single in-line was removed and a double in-line drip irrigation configuration per row of crop was superimposed offset 25 cm perpendicularly from the trunks and delivering, with emitters spaced at 50 cm apart, the same amount of water as the single in-line configuration (3.5 L/h emitters in the single and 1.75 L/h in the double in-line tube configurations). Treatments, therefore, comprised single and double in-line irrigation tapes with (closed, also referred to as emitter regulation) and without (open) spatial closure of the emitters using push-in ring plugs. Each treatment was replicated in three blocks. Spatial control of drip emitters in the closed treatment was achieved by progressive opening of emitters further away from the trunk as trees aged. In the closed treatment, the trial started with 2 or 4 emitters open (in single and double in-line tube treatments, respectively), and 6 or 12 emitters closed per tree (Figure S1). Further emitters (1 or 2, per single or double in-line tube configuration, respectively) were gradually opened at the rate of one additional emitter position per year. Therefore, the number of emitters open were 2, 4, 6, 8 per tree for the single in-line tube configuration and 4, 8, 12, 16 for the double in-line tube configuration in year 1, 2, 3 and 4, respectively. Netafim Techline Drip Emitter Plug Rings were used to plug emitters. The open treatment had 8 or 16 emitters open per tree, from commencement of the trial in the single and double in-line treatments, respectively.

The irrigation set-up for the trial was installed and tested on 23 June 2010 on custom-designed drip tube manufactured by John Deere Water. The drip-tube layout consisted of 32 rows, spaced at 8 m, with individual row length of ~250 m. The trial was completed in the middle of the fourth year, in November 2013, after the second season nut harvest.

Irrigation monitoring

An in-line water meter model ARAD IRT (Convergent Water Controls, Australia) recorded irrigation water inputs for individual blocks/treatment for each irrigation event. Soil moisture in each plot was monitored by calibrated in-ground Micro-gopher capacitance sensors (Dataflow Systems Ltd, New Zealand installed to 1.2 m depth at 25 cm perpendicular to the closest emitter to a plant). Irrigation scheduling was based on soil moisture distribution (irrigated when soil moisture reached refill point, 22 mm/100 mm, in the open treatment) in the soil profile depth of 10–20 cm. In part of the second and third year of the trial, the grower reduced irrigation as is industry practice to encourage growth of deeper and lateral roots.

Plant data collection

Five randomly selected trees for each treatment within each block were marked and used for plant data collection; data collection followed the same sample trees over the 3.5 years.

Plant data collected comprised plant height, leaf chlorophyll concentration, canopy size, stem girth, leaf photosynthesis, stomatal conductance, leaf water potential, fruit counts and root distribution. Distribution uniformity of emitters was evaluated, using 100 catch cans following the method by Prince (2016), on 21 September 2010 with irri-GATEWAY (CSIRO, Australia) software according to Veeranna *et al.* (2017).

Plant height was measured with a Levelling Staff (Stanley Australia) from the ground to the highest apical meristem of the main stem of the plant. A surrogate of leaf chlorophyll concentration was estimated from five randomly selected fully matured green leaves per plant using a Minolta SPAD 502 leaf chlorophyll meter (Konica, Minolta, USA). Canopy size was measured on four occasions as canopy spread (l x b) at the mid-height of the plant and also estimated based on the light interception by the canopy using a Ceptometer – Accupar LP-80 (Decagon, USA). Stem girth was measured using an open reel fibreglass measuring tape (Stanley, Australia) at a position 25 cm above the ground which was above the grafting union. Leaf gas exchange was measured between 0090 and 1200 h using an infrared gas analyser (ADC BioScience, UK) at six-monthly intervals. Mid-day leaf water potential was measured on five fully mature topmost leaves per plot, using a Scholander pressure chamber following the method by Blum *et al.* (1973).

Nut counts per plant were quantified visually in the third and fourth year of the trial approximately 2 to 4 weeks before harvest (fourth and fifth year of the tree age).

At trial end, soil cores were collected, one per plot, at 25 cm offset positions from the tube line to 30 cm depth. Roots were washed, scanned to derive root length estimates (using Delta-T Scan, Root Analysis System UK), dried and weighed to enable evaluation of treatment effects on root distribution.

Slashing of weeds between rows was conducted twice-yearly, but to avoid damage to the surface drip tubes within-row weeding was not undertaken. Weed cover within the exposed space in crop rows was assessed visually at the end of the trial using a wire grid 1 m by 1 m (1 = 10% or less, 9 = 90% or more) at five random locations per plot.

Data analysis

All crop data collected throughout the trial were subjected to a factorial analysis of variance (ANOVA) using the *VSNL* GenStat version 19 (VSN International, 2019).

Results

Weather

Annual rainfall (Table 1) in the first year of the trial was almost double (1042 mm) compared to the long-term annual average rainfall (551 mm year^{-1} for the past 30 years). Annual rainfall for the second year (2011/12) was also considerably greater than the long-term average and in the third (2012/13) year was slightly lower than the long-term average (Table 1).

The long-term annual average maximum and minimum temperatures are 29.9 and 16.3 °C, respectively, and annual average maximum and minimum temperatures during the trial period varied only by 1 °C compared to the long-term average. Daily global solar exposure (MJ m^{-2}) ranged from 4 to 30 MJ m^{-2}. Seasonal variation of the daily global solar exposure was evident with daily global solar radiation on clear days increasing gradually from 17 MJ m^{-2} in June to 28 to 30 MJ m^{-2} in January and decreasing thereafter (Figure S2).

Irrigation inputs

Irrigation input over the 3.5 years in single or double in-line tube configurations with all emitters open treatment was 10.328 ML/ha (Table 1). Cumulative irrigation over the trial period was reduced by 75, 50, 25% and nil in the first, second, third and fourth years in the emitter regulation treatment (drip lines with some emitter ring plugs closed) compared to the control (Table 1). A total irrigation water saving of 4.418 ML/ha was achieved over the trial period in the emitter regulation treatment.

Uniformity of irrigation

A distribution uniformity (DU) of 88% was achieved for the entire irrigation system (data not presented). Some low flow positions in the trial area were identified and repaired, particularly in double in-line tube configurations where some drip-line leaks induced pressure drops and associated lower emitter flow rates.

Plant growth

There was no effect of emitter regulation treatment on plant height at any stage during the trial (Figure 1a). However, there was a tendency for plant height to be greater in the single compared to the double in-line configuration, and in the early growth stage (174 days) irrespective of the

https://doi.org/10.1017/S0014479722000011 Published online by Cambridge University Press

Table 1. Precipitation (P), irrigation (I) and reference evapotranspiration (ET_O) with and without emitters open during the trial expressed as mm

Treatments	Year 1 (23/6/10–22/6/11)			Year 2 (23/6/11–22/6/12)			Year 3 (23/6/12–22/6/13)			Year 4 (23/6/13–27/10/13)			Total			
	P	I	ETo	P	I	ETo	P	I	ETo	P	I	ETo	P	I	P + I	ETo
Emitters open	1041.8	343.3	1775	753.7	213.9	2112	444.4	410.7	2172	89.4	64.9	751	2329.3	1032.8	3362.1	6810
Emitters closed	1041.8	111.4	1775	753.7	107	2112	444.4	307.7	2172	89.4	64.9	751	2329.3	591	2920.3	6810

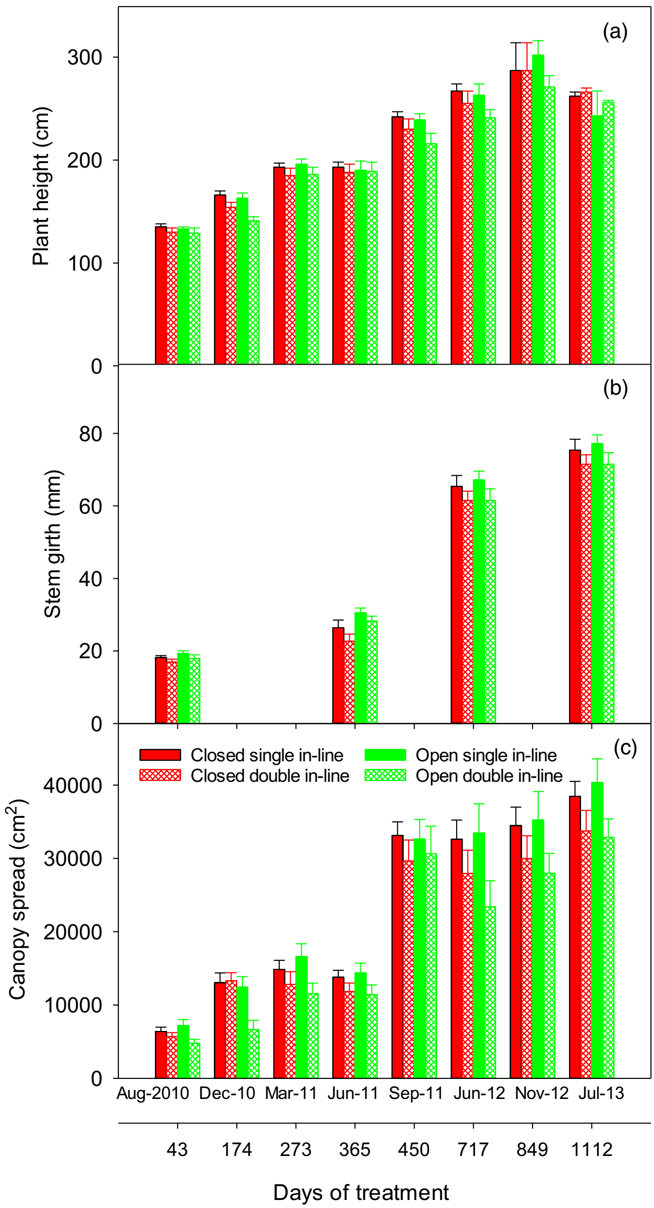

Figure 1. Effect of irrigation treatments on macadamia a) plant height, b) stem girth and c) canopy spread over the period of three years (bars represent mean ± SE). (Closed emitters single in-line: red bar, closed emitters double in-line: red hatching, open emitters single in-line: green bar, open emitters double in-line: green hatching).

emitter regulation treatment, the difference was significant (161.3 vs 142.5 cm, SED = 4.50). By the end of the trial, plant height reached between 2.5 and 3.0 m. The decrease in plant height noted in the final sampling (Figure 1a), for all treatments, was associated with the standard practice of mechanical trimming for control of plant height.

While there were no effects of treatments on stem girth (which ranged from *c.* 18 to *c.* 70 mm from 43 to 1112 days after treatments began – Figure 1b), as for plant height, stem girth tended to be greater for the single than double in-line configuration. Canopy spread of the macadamia trees

https://doi.org/10.1017/S0014479722000011 Published online by Cambridge University Press

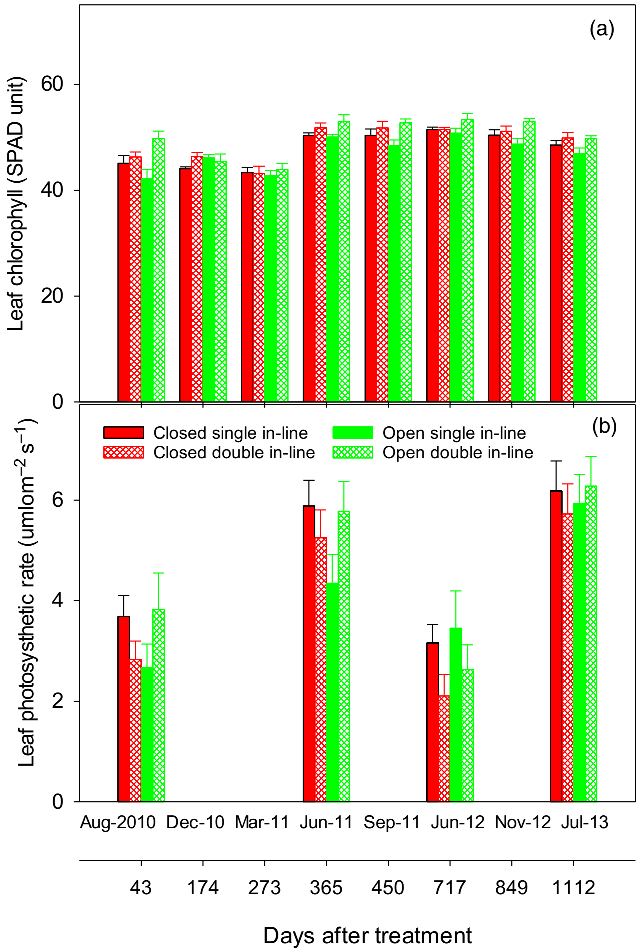

Figure 2. Effect of irrigation treatments on macadamia a) a surrogate for leaf chlorophyll content (SPAD units) and b) leaf photosynthetic rate over the period of three years (bars represent mean ± SE). (Closed emitters single in-line: red bar, closed emitters double in-line: red hatching, open emitters single in-line: green bar, open emitters double in-line: green hatching).

was always significantly greater (on average by 14%) in the single compared to the double in-line tube configuration (Figure 1c). There was however no effect of the emitter regulation treatment on canopy spread nor was the interaction between the emitter regulation and tube configuration significant.

Leaf parameters

The surrogate of leaf chlorophyll concentration ranged from 40 to 55 SPAD units with little change over the eight measurement events (Figure 2a). On six of the occasions, SPAD values in the double-line tube configuration treatment were significantly ($F \leq 0.05$) higher compared to the single in-line tube configuration and on average the SPAD readings in the double in-line configuration were 3–6% greater compared to the single in-line tube configuration (Figure 2a).

Leaf photosynthetic rate on the other hand, ranging from 2.5 to just over 6 μmol m^{-2} s^{-1}, did not differ between treatments (Figure 2b) and likewise leaf stomatal conductance, ranging from 0.0207 to 0.0287 mol m^{-2} s^{-1}, did not differ between treatments (data not presented).

https://doi.org/10.1017/S0014479722000011 Published online by Cambridge University Press

Table 2. Effect of emitter regulation treatments (emitters open or closed) and irrigation tube configuration (single or double in-line) on fruit counts per plant, root length density (RLD) at 0–30 cm depth recorded within 25 cm distance from the tree, weed density and soil moisture

Variables	Days after treatment	Emitters closed position		Emitters open position		*F* test (*p* value, LSD)
		Single in-line	Double in-line	Single in-line	Double in-line	
Fruit count per plant	820	36.9	31.9	35.0	21.0	Emitter plug= 0.301, (10.50) Rows=0.400, (10.18) Emitter x rows= 0.665, (14.67)
Fruit count per plant	1165	92.9	81	98	92.5	Emitter plug= 0.733, (9.7) Rows=0.322, (9.4) Emitter x rows= 0.743, (13.6)
RLD (cm cm^{-3})	1112	6.45	7.72	4.57	6.5	Emitter plug= <0.001, (0.139) Rows=<0.001, (0.135) Emitter x rows= 0.007, (0.194)
Weed density (Score, 0–9)	1112	3.6	4.5	7.2	8.5	Emitter plug= <0.001, (0.118) Rows=<0.001, (0.114) Emitter x rows= 0.063, (0.166)
Soil moisture (%)	43	33.14	39.14	55.70	73.50	Emitter plug= <0.001, (24.55) Rows=<0.419, (9.19) Emitter x rows= 0.013, (18.54)
	365	65.74	65.34	63.00	65.81	Emitter plug= <0.083, (26.73) Rows=<0.914, (10.01) Emitter x rows= 0.749, (20.19)
	717	17.33	17.07	14.40	21.42	Emitter plug= <0.652, (7.57) Rows=<0.071, (2.83) Emitter x rows= 0.009, (5.72)
	1112	36.31	33.25	35.50	50.37	Emitter plug= <0.053, (16.72) Rows=<0.293, (6.26) Emitter x rows= 0.006, (12.63)

NB: Weed score, 0 = no significant ground cover, 9 = 90–100% ground cover, and on 10% increment basis from 1–8).

For leaf water potential, there were no interactions between treatments and date of sampling, nor between tube line configuration and emitter regulation treatments; however, leaf water potential averaged over treatments increased from −1.17 MPa at 365 days to −1.08 MPa at 717 days and −0.98 MPa at 1129 days (LSD 5% = 0.017 MPa) and was greater for the single compared to double in-line configuration (−1.015 and −1.117 MPa, respectively, LSD 5% = 0.029 MPa) and for the open compared with the closed emitter treatment (-0.953 compared with −1.141 MPa, respectively, LSD 5% = 0.033 MPa).

Soil moisture

Soil moisture, as measured at 10–20 cm depth and 25 cm offset from the closest emitter to a plant, was less early than later in the trial (Table 2). On three of the four occasions for which data are presented, there was an interaction between emitter regulation and drip-line configurations. In general, soil moisture between single and double in-line configurations did not vary significantly

https://doi.org/10.1017/S0014479722000011 Published online by Cambridge University Press

under the open treatment, but the soil moisture was significantly greater for the double in-line irrigation treatment when all emitters were open (Table 2). Note that the high soil moisture at 365 days is associated with 119.8 mm of rainfall that occurred over the week from 355 days.

Root distribution

Root length density (RLD) measured 1112 days after the initiation of treatments ranged from 4.6 to 7.8 cm cm^{-3} (Table 2). In general, RLD was lower for the single compared to the double in-line tube configuration and was greater for the emitter regulation treatment compared to the open emitter treatment, especially for the single in-line configuration (Table 2).

Weed growth

Weed cover at the end of the trial was markedly less for the emitter regulation treatment compared to the open emitter treatment, and in the single compared to the double in-line configuration (Table 2), and the difference between the open and closed treatments was somewhat greater in the double than in the single in-line configuration.

Yield performance

Fruit count in the early part of the third year after treatments were applied ranged from 21 to 47 fruits per plant and increased to 81 to 98 in the same period in the fourth year (Table 2). Fruit count did not differ significantly between the treatments in either year during this early bearing stage, suggesting no yield penalty with the water saving in the early establishment of the crop.

Discussion

Rainfall during the first two years of the trial was well above the historic average (Table 1), especially during the first year, but still well below the reference evapotranspiration (ETo). Despite the implications of this regarding the absolute need for irrigation, there were a number of positive outcomes in our treatment comparisons relating to crop water management of interest for the macadamia industry. Of major importance, there were significant water savings with the regulation of emitters, that is in the treatment with fewer opened emitters, without loss in nut counts. Counts were also higher with the single than with the double in-line irrigation configuration.

The first year received total rainfall of 1014 mm, and a total of 3.43 ML ha^{-1} irrigation were applied to the open emitter treatment (irrigation comprised 25% of the total water received), whereas 1.11 ML ha^{-1} was applied to the closed treatment (irrigation comprised only 10% of the total water in that treatment). With a small canopy, occupying only 1.1 m of the 4 m linear space between trees, tree transpiration was low (although weeds would have been users of rainfall and applied irrigation water). In the subsequent second and third years, receiving 754 mm and 444 mm of rainfall, the emitters open treatment received 2.14 and 4.11 ML of irrigation, respectively, and the water applied was reduced to 1.07 and 3.08 ML ha^{-1} for the emitter regulated (closed) treatment, respectively. The closed treatments represented c. 25, 50 75 and 100% of total irrigation input for year 1, 2, 3 and part of 4, respectively, compared to that of the open emitter treatment. Trochoulias and Johns (1992) used a crop coefficient (Kc) of 0.88 for their eight-year plus macadamia crop with a canopy cover of less than 40%, whereas irrigation plus precipitation in the emitter regulation treatment in year one of the current trial was 78% of ETo, reducing to 46% in year two and 39% in year three as the grower customarily reduced water supply to the crop, during which canopy spread averaged less than 10% of the available plant area (calculations from Figure 1c).

https://doi.org/10.1017/S0014479722000011 Published online by Cambridge University Press

Converting the water inputs over the first three years of the current trial into litres per day per tree, for comparison with data presented by others (Stephenson *et al.*, 1995; 2003), the values of 96.6 L for the open emitter treatment and 83.6 L for the regulated irrigation treatment are somewhat higher than earlier reported data for trees twice the age of the trees in this trial. The greater water inputs in our field trial (compared to the previously reported lysimeter trials) could be due to 'wasted' irrigation in the space between trees, and to uncontrolled runoff, and deep drainage, particularly when associated with larger rainfall events.

Although there were no significant effects of either emitter regulation or irrigation tube configuration on nut count (Table 2), trees in the single in-line tube configuration showed greater canopy spread, notable from 272 days after commencement of treatment (Figure 1c), and reaching 3.92 m^2 vs. 3.35 m^2, (LSD = 0.5154) at trial end (1112 days), an effect evident also in stem girth (Figure 1b) and at times in plant height (Figure 1a), but not evident in leaf photosynthetic rate (Figure 2b). In contrast, the surrogate for leaf chlorophyll concentration from one year onwards was significantly greater in the double compared to the single in-line tube configuration (Figure 2a). The measured midday leaf water potential in this trial for the closed treatment (-1.141 MPa) was somewhat lower than those of unstressed macadamia plants (c. −0.8 MPa) and somewhat greater than those in a mildly stressed condition (c. −1.4 MPa) as reported by Stephenson *et al.* (2003) for lysimeter-grown trees. However, in the field the significant differences in midday leaf water potential between closed and open treatments did not result in the yield loss (nut counts over two years), even though there was a slightly lower soil moisture (particularly for year 2 and year 3) in the closed treatment, and in the open double in-line treatment leaves were less stressed at midday and photosynthesis was greater than for the closed treatment. This is contrary to the five-year results of Stephenson *et al.* (1995) who reported loss of nuts of c. 76% when mild water stress, albeit midday leaf water potential reaching −1.5 MPa, was imposed from flower initiation to nut drop. The more gradual nature of the stress which developed in the field compared to the relatively rapid onset of stress in the lysimeters of Stephenson *et al.* (1995) may be in part responsible for this difference between studies (Berliner and Oosterhuis, 1987), as may the difference in varieties trialled. This would suggest that macadamia can adapt and buffer for adverse conditions when the onset of water stress is gradual. Awada *et al.* (1967) found a similar result in Hawaii where nut counts (albeit with a different variety to that in our study) were maintained despite a continually low soil moisture causing mild water stress symptoms, and defoliation and dieback, in the leaf and shoot.

Smaller canopy size and greater concentration of leaf chlorophyll in the double in-line tube configuration suggest reduced soil moisture access by the trees compared to single in-line configuration, as the double in-line drip lines were 25 cm distant from either side of the tree trunk. However, a slightly low leaf photosynthetic rate recorded on three of the four measurement occasions in the single in-line tube treatment with all emitters open plots compared to the other treatments may suggest some temporal water logging in the rhizosphere causing stomatal closure and a rise in leaf temperature, and its associated suppressive effect on leaf photosynthesis in that treatment (Huett, 2004 – but a different variety to that used in the current trial), as macadamia is susceptible to water logging (Quinian and Wilk, 2005) and such a situation can prevail in a vertisol if irrigation inputs are in excess of crop daily evapotranspiration demand. Unfortunately, meter readings for irrigation were collected only on a one-to-two-month basis, so it is not possible to align actual water input with the dates upon which rates of photosynthesis were measured. Nevertheless, leaf photosynthetic rates were comparatively high on day 365, shortly after the *c.* 120 mm rainfall event, at a time when irrigation was most likely not needed.

With the wider spread of the canopy and its weed suppression property in the single compared to the double in-line tube configuration, there was as expected less weed cover. A narrower lateral spread of the irrigation with the single in-line tube would also be expected to induce less weed cover in that treatment. As hypothesized, the closed emitter treatment also had less weed cover than the open treatment (Table 2).

https://doi.org/10.1017/S0014479722000011 Published online by Cambridge University Press

Deficit and regulated deficit irrigation practices that offer water savings without loss in crop performance have been reported in a large number of tree crops (Goldhamer, 2007), including macadamia but because of frequent small rainfall events during summer rainy seasons, imposition of such a treatment for macadamia is difficult in Queensland (Stephenson and Searle, 2016). The ability of macadamia trees to collect and channel rainfall down the trunk under light to medium intensity rainfall, with the same variety as in our trial, has been reported (Searle and Lu, 2002). The resulting channelled water collects at the base of the trunk where it is rapidly absorbed by the soil and crop due to the dense and porous root mat close to the trunk, and the slightly better soil structure in this zone, and could be significant for a greater capture and utilization of rainfall, thus reducing the need for supplementary irrigation in the environment and soil type typical of the current trial. Light rainfall events for many other crops, unlike macadamia, turn out to be ineffective for those crops as such low amounts do not reach the root zone to supply water to the plant (Ali and Mubarak, 2017).

In our study, root length densities (4.5 to 7.7 cm cm^{-3}) were almost twice those reported by Firth *et al.* (2003) at a similar depth and distance from the trunk for rainfed trees of similar age planted at 7 m by 3 m and grafted onto *M. tetraphylla* at Clunes in northern New South Wales, a rootstock different to that used in the current study. Firth (1995) suggested root length density of 2 to 3 cm cm^{-3} soil is adequate for macadamia water uptake. Studies on macadamia have shown a higher RLD in the first 30 cm from the surface which decreased gradually through to the depth of 1.4 m (Smith, 2016), again albeit for a different variety to that studied herein. Given the high root length density close to the trunk, emitters at a distance might not contribute significantly to water uptake by the crop. The greater RLD in the closed treatment compared to the control might be a compensatory response to the reduced water availability mid-way between trees, and in the double compared to the single in-line tube configuration for sampling was made closer to the tree in the former. The amount of roots and the relative efficiency of roots of different cultivars and irrigation methods, particularly for the dynamic regulation of the emitters, should be investigated further as this may account for some of the reported differences in performance among cultivars, soil types and environmental conditions.

Reduced water allocation to trees in the closed treatment had no negative effects on tree growth and development. This suggests that there are opportunities for irrigation water savings with juvenile macadamia up to the early bearing stages. Future studies that regulate the emitter opening well beyond the juvenile stage are suggested to determine the effects of these treatments on subsequent crop growth, yield, quality and root diseases. Indeed, emitters at the mid-distance between trees, even trees spaced at 4 m apart, might not be necessary for effective growth and yields.

It is well known that root systems of macadamia trees can vary with grafting or not (Firth *et al.*, 2003), and the variety (Lloyd *et al.*, 1991), hence our results for variety HAES 741 on Hinde (H2) rootstocks need to be further validated for other varieties, and under drier conditions and over longer durations before adoption of this technology by the macadamia industries in Australia or overseas.

Given the development and adoption of drip irrigation technology in a number of plantation and fruit crops (Carr, 2014), use of temporarily closed-off emitters in early stages of plant establishment should have relevance for water savings not only to the macadamia industry.

Conclusions

The reduced irrigation of a juvenile macadamia plantation over its initial three plus years of establishment suggests that regulated emitter control (i.e., the closed treatment) can provide an opportunity for significant drip irrigation water savings. Trees irrigated with the progressive opening of emitters saved 50% irrigation water over three years compared to those irrigated without regulation. The reduction of irrigation showed no negative effects on tree growth, performance, nor on nut counts. Future studies extending the emitter regulation beyond the juvenile phase would enable evaluation of this irrigation strategy on matured bearing trees. There were notable differences between the single and double in-line tube configurations, with the single surpassing the performance of the double configuration in most attributes measured, including a non-significant but sizeable (a 36% increase in the first year of nut count and 10% in the second year) effect on nut count that merits further study. The outcome of this research informs the designing and manufacture of drip tube products that includes integrated emitter plugs enabling regulation of individual emitters. Such a new drip product could contain emitter plugs, allowing opening of individual drip emitters on demand by removing the emitter plugs.

Supplementary Material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0014479722000011

Acknowledgements. We acknowledge the assistance and support throughout the project by Mr Graham Fox, Deepak Sharma Paudel, Ms Kylie Hopkins and the property owners John and Cheny Walters and the Queensland Department of Agriculture and Fisheries for active contribution setting up the trial site and cooperation in data collection.

Financial Support. John Deere Water generously supplied 9000 m of custom made drip tube and 25 000 emitter rings. Financial support was provided by Woolworth Plc. and administered by Landcare Australia and is highly appreciated for without their support this work would have not been possible.

Conflicts of Interest. None.

References

Ali M.H. and Mubarak S. (2017). Effective rainfall calculation methods for field crops. An overview, analysis and new formulation. *Asian Research Journal of Agriculture* **7**, 1–12

Australian Macadamia Society Ltd. (2020). *Australian Macadamias Year Book 2020*. Lismore, NSW: Australian Macadamia Society Ltd. Available at https://trade.australian-macadamias.org/2020-australian-macadamias-yearbook/ (accessed 14 August 2021).

Awada M., Warmer R.M. and Watanabe Y. (1967). Effects of soil moisture stress on growth and yield of macadamia (*Macadamia integrifolia*). *Hawaii Agricultural Experiment Station Bulletin No* **69**, 1.

Berliner P.R. and Oosterhuis D.M. (1987). Effect of root and water distribution in lysimeters and in the field on the onset of crop water stress. *Irrigation Science* **8**, 245–255.

Blum A., Sullivan C.Y. and Eastin J.D. (1973). On the pressure chamber technique for estimating leaf water potential in sorghum. *Agronomy Journal* **65**, 337–338.

Carr M.K.V. (2014). *Advances in Irrigation Agronomy: Fruit Crops*. Cambridge: Cambridge University Press.

Firth D.J. (1995). *Root Development Studies in Macadamia. Final Report to the Horticultural Research and Development Corporation*. Alstonville: NSW Agriculture, Tropical Fruit Research Station.

Firth D.J., Whalley R.D.B. and Johns G.G. (2003). Distribution and density of the root system of macadamia on krasnozem soil and some effects of legume groundcovers on fibrous root density. *Australian Journal of Experimental Agriculture* **43**, 503–514.

Goldhamer D.A. (2007). Regulated deficit irrigation in trees and vines. In Holliday L. (ed), *Agricultural Water Management: Proceedings of a Workshop in Tunisia*. Washington, DC: The National Academies Press, pp. 70–80.

Hardner C.M., Peace C., Lowe A.J., Neal J., Pisanu P., Powell M., Schmidt A., Spain C. and Williams K. (2009). Genetic resources and domestication of macadamia. *Horticultural Reviews* **35**, 1–125.

Huett D.O. (2004). Macadamia physiology review: a canopy light response study and literature review. *Australian Journal of Agricultural Research* **55**, 609–624.

Lloyd J., Trochoulias T. and Ensbey R. (1991). Stomatal responses and whole-tree hydraulic conductivity of orchard *Macadamia integrifolia* under irrigated and non-irrigated conditions. *Australian Journal of Plant Physiology* **18**, 661–671.

O'Hare P.J., Stephenson R., Quinlan K. and Vock N. (2004). *Macadamia Grower's Handbook*. Nambour, QLD: Department of Primary Industries and Fisheries in collaboration with New South Wales Department of Primary Industries and the Australian Macadamia Society.

Prince R. (2016). *Measuring Delivery of Drip Irrigation Systems*. Department of Primary Industries and Regional Development, WA Agriculture and Food. Available at https://www.agric.wa.gov.au/strawberries/measuring-delivery-drip-irrigation-systems (accessed 16 January 2020).

Quinian K. and Wilk P. (2005). Macadamia Culture in NSW. Primefacts, 5 (January) 11 pp. Available at https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0005/75740/Macadamia-culture-in-NSW-Primefact-5—final.pdf (accessed 25 October 2019).
Reid J.B., Sorensen I. and Petrie R.A. (1993). Root demography of kiwifruit (*Actinidia deliciosa*). *Plant, Cell and Environment* **16**, 949–957.
Searle C. and Lu P. (2002). *Optimising Irrigation Scheduling for the Production of High Quality Macadamia Nuts. Final Report (Project MC98019).* Sydney, NSW: Horticulture Australia Ltd (HAL).
Searle C. and Lu P. (2003). Whole-tree water use and irrigation scheduling in macadamia. In: *Proceedings of the 2nd International Macadamia Symposium 2003.* Tweed Heads. Australian Macadamia Society, Lismore Australia, pp. 125–130.
Smith T. (2016). *Review of Macadamia Orchard Nutrition. Final Report (MC15012), Submitted to Horticulture Innovation Australia*. Australia: The Department of Agriculture and Fisheries (DAF), QLD Government. Available at https://era.daf.qld.gov.au/id/eprint/6543/ (accessed 23 November 2019).
Stephenson R.A., Gallagher E.C. and Doogan V.J. (2003). Macadamia response to mild water stress at different phenological stages. *Australian Journal of Agricultural Research* **54**, 67–75
Stephenson R.A., Gallagher E.C. and Gogel B.J. (2002). Macadamia nut size and maturity influenced by lime and nitrogen applications. *Australian Journal of Agricultural Research* **53**, 677–680. doi: 10.1071/ar01146.
Stephenson R.A. and Searle C. (2016). More from less? Efficient water use for macadamia. *Acta Horticulturae* **1109**, 67–73.
Stephenson R.A., Trochoulias T. and Baigent R.A. (1995). *Effect of Environment, Nutrition and Water on Production and Quality of Macadamia. Final Report to the Horticultural Research and Development Corporation*. Nambour: Queensland Department of Primary Industries, Maroochy Horticultural Research Station.
Trochoulias T. and Johns G.G. (1992). Poor response of macadamia (*Macadamia integrifolia* Maiden and Betche) to irrigation in a high rainfall area of subtropical Australia. *Australian Journal of Experimental Agriculture* **32**, 507–512.
Turner F. (1893). New commercial crops for New South Wales. The cultivation of the Australian nut (*Macadamia ternifolia* F.v.M.). *Agricultural Gazette of New South Wales* **4**, 3–5.
Veeranna J., Mishra A.K. and Pater N. (2017). Calculation of uniform coefficient, soil moisture distribution and analysis of level of biofouls strategy under SDI. *International Journal of Current Microbiology and Applied Science* **6**, 713–726.
VSN International (2019). *Genstat for Windows*, 20th Edn. Hemel Hempstead: VSN International.
Zapp J. (2019). Using Harvesting Machines with Drip Lines. Netafim Australia Blog. Available at https://www.netafim.com.au/blog/trials-of-macadamia-harvesting-over-driplines-show-positive-results/ (accessed 31 July 2021).

Cite this article: Bhattarai SP, Pendergast L, Shuyan L, and Midmore DJ (2021). Effects of spatial and temporal regulation of drip emitters and tube configurations on water productivity of juvenile macadamia trees in the tropics. *Experimental Agriculture* **57**, 338–351. https://doi.org/10.1017/S0014479722000011