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Abstract: Growth control of container-grown hardy nursery stock generally requires substantial labour investment. Therefore the possibility of alternative growth control using deficit irrigation is appealing. Increasing water costs and limited availability of abstraction licences have added further incentives for nursery stock producers to use deficit irrigation. There are still, however, concerns that inherent non-uniformity of water uptake under commonly used overhead irrigation, and differing irrigation requirements of diverse crops and substrates, may limit the commercial relevance of a protocol developed for single crops growing in 100% peat and irrigated with a high precision drip system. The aim of this research was to determine whether growth control of hardy nursery stock is possible using deficit irrigation applied with conventional overhead irrigation. Over two years, crop growth under an overhead irrigation system was compared under full irrigation and two severities of deficit irrigation. Initially, two crops of contrasting canopy structure i.e. Cornus alba and Lonicera periclymenum were grown. In a subsequent experiment one crop (Forsythia × intermedia) was grown in two substrates with contrasting quantities of peat (60 and 100%). Deficit irrigation was found to be highly effective in controlling vegetative growth when applied using overhead irrigation - with similar results as when drip irrigation was used. This comparable response suggests that deficit irrigation can be applied without precision drip irrigation. Scheduling two very different crops with respect to their water use and uptake potential, however, highlighted challenges with respect to application of appropriate deficits for very different crops under one system; responses to deficit irrigation will be more consistent where nursery management allows for scheduling of crops with very different architecture and water use under different regimes. The effectiveness of deficit irrigation in controlling the growth of Forsythia was similar when a reduced peat based substrate was compared with pure peat; additionally, flowering was enhanced.

Application of deficit irrigation to hardy ornamental nursery stock via overhead irrigation

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ABSTRACT

Growth control of hardy nursery stock generally requires substantial labour investment. Therefore the possibility of alternative growth control using deficit irrigation is appealing. Increasing water costs and limited availability of abstraction licences have added further incentives for nursery stock producers to use deficit irrigation. There are still, however, concerns that inherent non-uniformity of water uptake under commonly used overhead irrigation, and differing irrigation requirements of diverse crops and substrates, may limit the commercial relevance of a protocol developed for single crops growing in 100% peat and irrigated with a high precision drip system. The aim of this research was to determine whether growth control of hardy nursery stock is possible using deficit irrigation applied with conventional overhead irrigation. Over two years, crop growth under an overhead irrigation system was compared under full irrigation and two severities of deficit irrigation. Initially, two crops of contrasting canopy structure i.e. Cornus and Lonicera were grown. In a subsequent experiment one crop was grown in two substrates with contrasting quantities of peat (60 and 100%). Deficit irrigation was found to be highly effective in controlling vegetative growth when applied using overhead irrigation – with similar results as when drip irrigation was used. This comparable response suggests that deficit irrigation can be applied without precision drip irrigation. Scheduling two very different crops with respect to their water use and uptake potential, however, highlighted challenges with respect to application of appropriate deficits for very different crops under one system; responses to deficit irrigation will be more consistent where nursery management allows for scheduling of crops with very different architecture and water use under different regimes. The effectiveness of deficit irrigation in controlling the growth of Forsythia was similar when a reduced peat based substrate was compared with pure peat; additionally, flowering was enhanced.

1. Introduction

Future global irrigation management will require users to look for methods of application which are efficient (Bacci et al., 2008; Kim et al., 2011; Majsztrik et al., 2011; Lea-Cox et al., 2013). For example, metrics such as water use and water productivity (Fereres and Soriano, 2006) may be required to justify irrigation practices. The use of deficit irrigation not only provides the means by which water use can be reduced and its use efficiency enhanced, but also enables crop growth and quality to be controlled (Jensen et al., 2010; Cirillo et al., 2014). Deficit irrigation is the application of less water than a crop would lose by evapotranspiration if water availability was not limiting (Fereres et al., 2003). However, for deficit irrigation to be effective requires understanding crop growth patterns, and some commentators suggest that use of advanced irrigations systems is also essential (Evans and Sadler, 2008; O'Meara et al. 2013). Deficit irrigation is applied either as sustained deficit irrigation i.e. by systematically applying water at a constant fraction of potential evapotranspiration through the season, or as regulated deficit irrigation, in which case soil moisture deficits are imposed only at certain plant developmental stages (Costa et al., 2007; Bacci et al., 2008).

The primary challenges in the development of effective application of deficit irrigation to control growth and quality in container grown crops, such as hardy nursery stock, are a multitude of species and cultivars with different water requirements, and sensitivities to deficit irrigation, combined with a general absence of economic justification for the use of sophisticated precision irrigation systems (Kim et al., 2011; Majsztrik et al., 2011). There are examples, however, where economic assessment reveals apparently good initial savings and returns from investment in irrigation automation (Majsztrik et al., 2011; Belayneh et al., 2013). The successful application of deficit irrigation in hardy nursery stock production offers environmental and economic benefits, such as reduced container leaching of nutrients and pesticides and a reduction in fertiliser and pesticide costs associated with wastage (Caron et al., 1998; Burnet and van Iersel, 2008; Warsaw et al., 2009; Majsztrik et al., 2011). This combination of economic with environmental benefits has been recently highlighted (Levidow et al., 2014) as critical if producers are to take up opportunities for improved water management. Other benefits may arise from nursery production of more robust plants when subjected to environmental stresses, such as drought (Cameron et al., 2008). Some studies have now begun to elucidate the mechanisms by which deficit irrigation approaches achieve these ‘carry-over’ effects in the container crop production cycle (Sanchez-Blanco et al., 2004; Bañón et al., 2006; Cameron et al., 2006; Franco et al., 2006).

HNS production approaches are economically constricted by the need for mass production to consistently high crop quality (Warsaw et al., 2009). Despite retailer requirements for producers to meet precise crop-specific quality criteria (Álvarez et al., 2009; Majsztrik et al., 2011), retail margins often mean that investment in sophisticated irrigation approaches is not easily justified. Despite the high labour costs in nurseries’ budgets, at least in UK, Dutch, and Irish production (Thorne et al., 2002), and the potential for deficit irrigation to remove or reduce the need for costly operations such as manual pruning (Cameron et al., 1999; 2006), there is still a lack of commercial confidence in the application of the approach (Kim et al., 2011). There are a number of questions which need answering before widespread uptake of deficit irrigation for container production is likely (Belayneh et al., 2013).

One of the concerns with respect to commercial application of deficit irrigation is whether approaches developed for high precision drip irrigation can be adapted for extensive commercial practice, which still relies heavily on overhead irrigation (Briercliffe et al., 2000; Pettitt 2014). The drawbacks of overhead irrigation are well described and for hardy nursery stock focus on a lack of spatial uniformity of irrigation supply meeting crop water ‘demand’; this may have considerable implications for crop uniformity when deficit irrigation reduces container substrate water availability (Beeson and Knox, 1991; Beeson and Yeager, 2003; Grant et al., 2011). Related to the use of overhead irrigation is the tendency to grow several crops under one system. Differences in water use and uptake amongst species may mean that a deficit appropriate for one crop is detrimental for another.

The capacity of the container substrate to sustain the applied deficit irrigation regime must also be considered. Most commercial experience lies with the use of pure peat, but continued reliance on pure peat production is not sustainable (Barkham, 1993; Chapman et al., 2003; Alexander et al., 2008). Substrate producers are therefore looking into alternative media (Alexander et al., 2008), at least to reduce, if not completely replace, peat consumption (Alexander et al., 2008). Changing the constituents in growing media, however, frequently alters the water holding capacity of the substrate (Yu and Zinati, 2006).

The aim of this research was to provide a more robust evaluation of the challenges involved in using deficit irrigation for commercial practice; here we focus on comparing overhead with drip irrigation, the impact of crop type, and the use of an alternative growing media to pure peat.

2. Materials and methods

2.1. Plant material and the growing environment

Lonicera periclymenum 'Graham Thomas', Cornus alba 'Elegantissima', and Forsythia × intermedia, cultivar 'Lynwood' were purchased as liners (New Place Nurseries Ltd, Pulborough, UK) and transferred to 2 L pots. Limestone (1.5 kg m^{-3}) and controlled release fertiliser [Osmocote Plus Spring (15+9+11+2 MgO + trace elements), 6 kg m^{-3}] were incorporated into the substrate. Vigorous growth is characteristic of all the cultivars selected. L. periclymenum, a climber, was supported with pot canes.

The experiments were conducted in a closed plastic tunnel, to prevent rainfall and strong winds interfering with irrigation treatments (side ventilation panels were opened as required to avoid over-heating). The standing surface was a thick, rolled (to provide a level surface), layer of course gravel covered with woven polypropylene fabric (MyPex, Monro Horticulture, Maidstone, UK). The tunnel was divided into six separate bays (5 m × 2.4 m ground area) using sheets of polythene to contain the overhead irrigation spray within the application bay. The plastic sheets were suspended above drain gutters, which prevented the irrigation spray contacting the MyPex. Pots were arranged, at a spacing of 25 × 25 cm, in rows of 18 plants, with the outer rows in each bay acting as guard plants.

2.2. Irrigation systems and scheduling

Irrigation was scheduled to replace a predetermined percentage of the potential crop evapotranspiration (i.e. the actual evapotranspiration, ET_A, if water availability was not limiting). Two different deficit irrigation treatments were applied each year, in comparison with a full irrigation treatment, with two bays used for each treatment;

treatments were allocated randomly to the different bays. In the case of full irrigation, 150% ET_A was applied to ensure that even if irrigation delivery was non-uniform, all plants would receive at least 100% ET_A. Excess water ran through the pot bases, and drained freely through the MyPex and the gravel beneath, showing no signs of ground surface accumulation. High quality mains supply water was used for irrigation.

Drip irrigation was applied via 2 L h^{-1} drippers (Netafim C.N.L. Junior Drippers, Access Irrigation, Northampton, UK), with one dripper per pot. Dripper output was quantified and drippers were replaced as necessary to achieve maximal uniformity across all drippers. Overhead irrigation was applied using six 50 L h^{-1} Eindor 861 sprinklers (Access Irrigation, Northampton, UK) per bay arranged at distances of 2.25 m between sprinklers along the bay and across the bay at 1.5 m between the central pair and 1.2 m between the other two pairs. This arrangement was shown to have the highest uniformity of application as determined by measuring Christiansen's coefficient of uniformity (Christiansen, 1942) for several different arrangements. Irrigation outputs for both the overhead and drip irrigation systems were measured before the experiment and after, to determine any degradation during use. Mean application rate and scheduling coefficient were calculated for each bay. The scheduling coefficient is the (mean application rate)/(minimum application rate), where mean reflects the measurements made over the entire bed and minimum refers to the area of the bed that received the lowest application (see Grant et al., 2009). Water delivery to pots was also frequently measured by weight gain during an irrigation event.

ET_A was determined every two weeks by weighing plants in the full irrigation treatments after irrigation (after allowing for pot gravity draining, and water intercepted by the canopy to run off) and again a day later. Wet leaf temperature depression was determined simultaneously with a sensor (Evaposensor, Skye, Powys, UK) located in the crop. The sensor continuously measures temperature differences between wet and dry artificial leaves (Harrison-Murray, 1991), with the accumulated difference recorded and logged via a dedicated meter (Evapometer, Skye), as °C h, where 1°C h equates to a difference of 1°C for a duration of 1 h. Thus, for example, if a plant uses 100 mL water during an accumulation of 100°C h, this plant will require 1 mL of irrigation for every 1°C h accumulated, if the intention is to apply 100% of ET_A. Combining water use per °C h with the time required to apply the determined irrigation volume (the measured scheduling coefficient of each system) computes the length of the irrigation event to replace 1°C h. This value can then be multiplied by the appropriate ET_A percentage depending on treatment. The result was then multiplied by the daily accumulated °C h over the previous 24 h to determine the irrigation requirement that day. This duration was then programmed into an irrigation timer (Heron Electric Company Limited, Ford, Nr. Arundel, UK), to trigger morning irrigation to each bay. For a more complete description of Evaposenor use see Grant et al. (2009) or Grant (2012).

2.3. A single species scheduling approach applied to crops of contrasting canopy structure

Lonicera and Cornus growing in 100% sphagnum peat (Shamrock Premium Grade, Bord na Móna, Newbridge, Co. Kildare, Ireland) were compared in year 1. Plants were arranged in five rows per bay, with Lonicera on one half of the bed and Cornus on the other, providing 21 experimental plants of each species, which were fully guarded. The deficit irrigation treatments applied were 50% ET_A and 25% ET_A i.e. crops were irrigated to replace 50% or 25% of water used by the fully irrigated plants. These two deficit irrigation treatments were selected to represent a deficit of sufficient severity to have a noticeable impact on growth (50%), and a very severe deficit that might risk reducing plant quality (25%). Results from the two different severities would thus be expected to provide a guideline for a range appropriate for use on nurseries. Irrigation for both the crops was scheduled on the basis of crop factors obtained for Lonicera. The reasoning for this is that different crops are often grown together on single beds, and with overhead irrigation will inevitably be irrigated by the same amount. Treatments were applied from the start of August, for eight weeks.

2.4. Comparison of substrates

100% peat (as above) was compared with a reduced peat mix [60% peat: 40% bark (Melcourt Potting bark, Melcourt Industries Ltd., Tetbury, Gloucestershire, UK)]. For the reduced peat mix, 1 g ammonium nitrate per L of bark was incorporated to compensate for the low nitrogen availability in bark (see recommendation by Wright et al., 1999). The two substrate treatments were replicated randomly in each bay. Plants of Forsythia were arranged in four rows per bay and DI treatments of 70% and 50% ET_A applied. These treatments were selected following analysis of the first experiment, with the 70% ET_A representing a mild deficit – potentially the smallest reduction in water supply likely to show a significant reduction in growth. Crop evapotranspiration of Forsythia in 100% peat and in the reduced peat mix was similar, and therefore crop factors for irrigation scheduling were based on average crop ET_A (measured by pot weighing as above) across both substrates.

Irrigation treatments were applied from mid-May. At the end of June, 10 plants per irrigation treatment (% ET_A), per irrigation system (drip vs. overhead), per substrate (100% peat vs. reduced peat mix) were pruned to a height of 20-30 cm (as is commercial practice). Four plants per irrigation treatment × irrigation system × substrate were kept un-pruned. For one week in mid-August, plants in the 50% ET_A treatments were given 70% ET_A irrigation, to encourage bud-break and shoot growth, which was previously limited. At the end of August, the numbers of buds breaking per pot from pruned branches was counted. Final heights and widths of all plants were measured in mid-September.

2.5. Substrate moisture content

Substrate volumetric moisture content (θ) was measured 6 cm deep from the top of each pot for all experimental plants every week using a soil moisture sensor (SM200 and HH2 meter, Delta-T Devices, Cambridge, UK). At the end of the experiments, substrate volumetric moisture content was also measured 6 cm from the base of the pot (inserting the probe at the base). In the substrate comparison experiment, volumetric moisture content was also measured in the middle of pots (by inserting the probe from the sides). The variability in volumetric moisture content within pots at different depths was determined from measurements taken in four horizontal locations per pot at the top and half-way down the pot. Calibration curves were produced for the substrates used (measuring wet and dry substrate, and determining water content gravimetrically, following the SM200 sensor manual), and the voltage output, used with the resulting calibration coefficients to obtain substrate volumetric moisture content as volume of water per volume of substrate.

2.6. Plant growth, biomass allocation, and flowering

Heights of all plants were measured weekly, while for Cornus and Forsythia, final leaf canopy width was measured from two perpendicular measurements at the canopy's widest point. At the end of experiments, half of the experimental plants were harvested and the shoots separated from the root system, the latter washed and both oven dried at 80°C for 48 h. Root and shoot dry masses were obtained, and root:shoot ratios calculated. Remaining plants were over-wintered, for flowering assessment in spring. At around 80% full bloom, numbers of flowers and numbers of internodes on a selected shoot of average length on each plant were counted, and the length of all shoots measured, allowing calculation of numbers of flowers per cm shoot length, numbers of flowers per node, and internode length.

2.7. Statistical analysis

The significance of treatment differences was assessed by analysis of variance (ANOVA), followed by LSD tests where appropriate, in Genstat software (Genstat 9.1, Rothamsted Experimental Station, UK). A repeated measures ANOVA was used where variables were measured repeatedly on the same individual plants or pots.

3. Results

3.1. A single species scheduling approach applied to crops of contrasting canopy structure

The overhead sprinkler arrangement achieved a Christiansen’s coefficient of uniformity of 91%, a scheduling coefficient of 1.2, and a mean application rate of 7.7 mm per hour. Drip irrigation resulted in a Christiansen’s coefficient of uniformity of 96-98% and a scheduling coefficient of 1.0 to 1.1. While there was evidence during irrigation that pot weight gain was less homogenous under overhead compared to drip irrigation (example in Fig. 1a), variation in substrate volumetric moisture content was not consistently greater under overhead irrigation (example in Fig. 1b). Measurements of water uptake indicated that Cornus under overhead irrigation took up less water than Lonicera (Fig. 1a), while water uptake with drip was similar for both crops.

Over the course of the experiment, deficit irrigation significantly ($P < 0.05$) reduced substrate volumetric moisture content (Fig. 2a), on average, across all pots, and resulted in reduced growth (Fig. 2b). For both Lonicera and Cornus, there was an interaction between irrigation quantity (% ET_A) and method of application on substrate volumetric moisture content ($P < 0.001$). For Lonicera, there was no difference between drip and overhead irrigation with respect to plant growth over the experiment (Fig. 2b). For Cornus, there was an interaction of irrigation system and % ET_A applied ($P = 0.003$) over the experiment, resulting in final plant heights being reduced under overhead compared to drip irrigation when full irrigation was applied, but not when deficit irrigation was applied. Cornus plants showed wider leaf canopy diameters at the end of the experiment when drip irrigated compared to overhead, and reduced canopy diameters under deficit compared to full irrigation (both $P < 0.001$; Table 1).

At the end of the experiment, an interaction between irrigation system and % ET_A ($P < 0.001$) was detected on mean substrate volumetric moisture content, both at the top and at the bottom of the pot, for both species. Substrate volumetric moisture content was lower under overhead than drip irrigation for both deficit irrigation treatments. On the other hand, it was higher under overhead than drip irrigation when full irrigation was applied (Fig. 3a, b). For Lonicera, shoot dry mass was not significantly affected by the type of irrigation (drip vs. overhead) within a given % ET_A. However, there was a significant effect of % ET_A on plant mass ($P < 0.001$ for shoots and $P = 0.025$ for roots). Under drip irrigation both deficit treatments showed reduced shoot, but not root, dry mass, whereas under overhead irrigation only the more severe deficit reduced shoot dry mass (Fig. 3c, d). Root:shoot ratio decreased as % ET_A increased ($P < 0.001$, data not shown). For Cornus, both shoot dry mass and root dry mass were affected by % ET_A ($P < 0.001$), with increasing dry mass at the higher % ET_A (Fig. 3c, d). Both shoot and root mass was greater under drip irrigation compared to overhead ($P < 0.001$). Root:shoot ratio was affected by % ET_A ($P < 0.001$), with a lower root: shoot ratio under 25% ET_A than under the other two treatments (data not shown).

3.2. Comparison of substrates

Substrate volumetric moisture content was reduced by deficit irrigation throughout the second experiment ($P < 0.001$) (Fig. 4a). A frequent but less consistent effect of irrigation system also occurred, but only occasionally were differences in substrate volumetric moisture content seen between the two types of substrate. Growth slowed in the 50% ET_A DI treatment from 14 days after treatments started ($P \leq 0.012$; Fig. 4b). Five weeks from the start of the experiment, an interaction with respect to cumulative plant height increment was seen between irrigation quantity and system ($P = 0.013$). Differences between treatments in shoot growth were reflected in the average mass of shoot material per plant obtained during pruning: 10–12 g for 50% ET_A, 12–18 g for 70% ET_A, and 22–24 g for full irrigation. After pruning, rapid growth was seen under full irrigation, with growth much reduced under deficit irrigation (Fig. 4b). From pruning onwards, there was no interaction between substrate and irrigation quantity or system, and no interaction between irrigation quantity and system i.e. reduced growth occurred with deficit irrigation using both drip and overhead and with both 100% peat and the reduced peat substrates. Growth was greater in the reduced peat substrate ($P < 0.001$).

Post-pruning bud break was significantly lower ($P < 0.001$) in the deficit irrigation treatments (around 7–9 bud breaks per plant) than in the full irrigation treatment (around 16 bud breaks per plant). Combined with reduced height, this resulted in deficit irrigation producing more compact plants than full irrigation (Fig. 5, left). The sub-set of plants not pruned in June showed excessive growth in response to full irrigation (Fig. 5, right); growth was restricted in response to deficit irrigation.

Early in August, Forsythia plants were removed from their pots and variation in substrate volumetric moisture content determined. Coefficients of variation (100% × standard deviation/mean) between the four measurements per layer (top, middle, or bottom) of the substrate showed that greatest variation most frequently occurred at the top (Table 2). Variation within a substrate layer was generally much greater when DI was applied using drip irrigation rather than overhead. Variation was also generally greater for the more severe deficit. Generally across all pots, independently of whether full or deficit irrigation was applied, the substrate was drier in the top layer with both substrate types and both irrigation systems ($P < 0.001$, Fig. 6). Substrate volumetric moisture content tended to be greater using overhead irrigation compared to drip.

In autumn, shoot dry mass was affected only by % ET_A applied ($P < 0.001$, Fig. 7a), with shoot dry mass increasing with % ET_A. Root dry mass was also affected by the interaction of % ET_A with type of irrigation ($P = 0.02$, Fig. 7b). With overhead irrigation, root dry mass increased with increasing % ET_A, but this response was less clear with drip irrigation. Thus, when drip was used, compared to overhead irrigation, root dry mass was not as reduced by the more severe deficit relative to full irrigation. Root:shoot ratio was also affected by the interaction of % ET_A and type of irrigation ($P < 0.001$, Fig. 7c). The root:shoot ratio decreased with increasing % ET_A under drip irrigation, but this did not occur under overhead irrigation.

The following spring, number of flowers per unit shoot length was affected by the % ET_A applied ($P < 0.001$, Fig. 8a). The plants receiving full irrigation had approximately half the number of flowers per unit shoot length compared to those receiving 50% ET_A. The increased number of flowers over a given length of shoot in the deficit irrigation treatments was a result of an increased number of flowers per node ($P = 0.018$, Fig. 8b) and shorter internode lengths ($P < 0.001$, Fig. 8c).

4. Discussion

A reduction of substrate volumetric moisture content, in response to deficit irrigation, led to a reduction in the shoot growth of all the species used here, as it does with other species (Cameron et al., 1999; Grant et al., 2004; Chaves et al., 2007). This reduction is also known to influence a number of different growth variables, both above and below ground (Franco et al., 2006). In most previous research, however, deficit irrigation has been applied using a high-precision drip irrigation system. Our novel approach was to validate the potential of deficit irrigation to control growth through the utilisation of overhead irrigation – which is still an important and much used system in commercial ornamental plant production. Different irrigation systems are known to impact on plant dry matter production even when full irrigation is applied (Klock-Moore and Broschat, 2001), and deficit irrigation might accentuate such effects.

Here we show that irrespective of type of irrigation system used (drip or overhead) to apply deficit irrigation, reduced growth was apparent in response to a decline in substrate volumetric moisture content. The experiment with Cornus, however, showed that plant size was dependent on the irrigation system used, with reduced canopy diameter and biomass with overhead irrigation compared to drip. The reason Cornus grew less with overhead irrigation relates to this crop taking up less water than Lonicera. This response was visually apparent during irrigation events, where applied water was deflected by the Cornus canopy while the supported upright structure of Lonicera promoted water funnelling into the pots. Cornus growth was excessively reduced by the application of the severe deficit, highlighting the difficulty of scheduling deficit irrigation for different species using the same irrigation system. We strongly recommend that users grow crops together which have similar canopy architectural and structural attributes along with similar water uptake. Several factors not included here are known to exacerbate non-uniformity of overhead irrigation delivery (Grant, 2012).

In addition to reducing plant growth, deficit irrigation impacted on plant quality. Forsythia subjected to deficit irrigation developed an increased number of flowers per node, and this increase in flowering density can provide a more aesthetically appealing plant at retail. Some caution is required with respect to differences in species sensitivity, tissue type, age at which flowers are initiated, and the timing of application of the deficit in relation to flower initiation. A study with Rhododendron showed that deficit application during flower induction (late summer) could reduce flower production (Cameron et al., 1999), although in general across a range of hardy nursery stock, the effects of deficit irrigation on flower production were small (Cameron et al., 2006).

The increased root:shoot ratio apparent for Forsythia as a result of deficit irrigation has important implications in the production of ‘robust’ plants which are able to establish rapidly when transplanted. This is particularly true for better establishment under semi-arid conditions (Franco et al., 2006). How this occurs, beyond improvement in the plant’s ability to capture water relative to that lost via transpiration, is likely to be species-specific. In Nerium oleander, for example, dehydration of the finer roots during transplanting is detrimental; deficit irrigation induces thick roots, which increase the potential for water storage, leading to better establishment of deficit irrigated plants (Bañón et al., 2006). In the current research with Forsythia, however, it should be noted that an increased root:shoot ratio as a result of deficit irrigation only occurred when irrigation was applied using a drip system. The reduction in root biomass using overhead irrigation compared to drip may have negative implications on transplanting and establishment. On the other hand, drip irrigation can result in localised abundant root production in relation to the dripper positioning in the container, where a high rooting density makes effective use of applied water, but will limit the rate at which roots exploit the soil on transplanting. The greater variation in volumetric moisture content within a layer shown here for drip compared to overhead irrigation highlights the potential for localised root formation under drip systems. Substrate types can also accentuate differences in water distribution: coarse textured substrates lack small pore spaces to promote capillary movement and water holding capacity (Klock-Moore and Broschat, 2001). Neither of the substrates used in this study, however, accentuated variation in volumetric moisture content compared to the other.

There was no interaction of irrigation quantity and substrate on final plant height, implying that deficit irrigation can be used to control growth in a reduced peat substrate, without any need to alter irrigation scheduling protocols developed for 100% peat. Reduced peat did not impact on root:shoot ratio, or variation within or between pots in substrate volumetric moisture content. This may reflect limited variation in water holding capacity between substrates with peat substitution from 40 to 70% (Caron et al., 1998). Yu and Zinati (2006) found that increasing the percentage of bark from 40% to 90% in parallel with a decreasing percentage of peat led to decreased substrate water holding capacity, from 63% to 49%. This difference is small and would be easily managed within a deficit irrigation strategy and would have little impact on its effectiveness with respect to growth control. The substrate-derived differences in growth seen here with Forsythia are likely to relate to nutritional differences. To compensate for an expected reduction in nitrogen availability when peat is partially substituted with bark (Wright et al., 1999), ammonium nitrate was added initially. This apparently overcompensated, with enhanced growth in the reduced peat substrate – which was seen under full as well as deficit irrigation. Variation in growth when using a diverse range of growing media is well documented (Guérin et al., 2001).

Currently it is not possible to predict exact % ET_A deficits to induce well-defined levels of growth control or increases in production quality across the wide range of species and cultivars in hardy nursery stock production. That innate differences in response to limited water availability exist between species is well known, and this variability interacts with factors such as variation in the growing environment (Evans and Sadler, 2008). Another challenge is how to easily determine the actual water input corresponding to the desired % ET_A (Fereres and Soriano, 2006): if entire crops are being deficit irrigated, fully irrigated plants may not be available for gravimetric calibration, as used in this current study. One solution would be through adjustment of scheduling coefficients on the basis of plant size (canopy area and hence transpiring area). Where the Evaposensor has been used to schedule (full) irrigation, this approach has been shown to be effective for diverse species (Grant et al., 2012). Alternatively, coefficients (K_c) can be estimated from variables such as plant height, to use with reference evapotranspiration (ET_o) calculated from meteorological variables (Incrocci et al., 2014).

5. Conclusions

Deficit irrigation applied by overhead irrigation can be used to control growth and quality of container grown crops as effectively as when applied by drip irrigation. Therefore effective deficit does not rely solely on more expensive and less frequently used drip irrigation. This conclusion should encourage commercial uptake of deficit irrigation. Addressing the challenge of identifying a deficit irrigation regime that is appropriate for specific cultivars and level of growth control will require more experimentation. Additionally, approaches to scheduling that can be easily applied commercially (e.g. monitoring evapotranspiration or substrate θ) merit further consideration.

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References

Alexander, P.D., Bragg, N.C., Meade, R., Padelopoulos, G., Watts, O., 2008. Peat in horticulture and conservation: the UK response to a changing world. Mires & Peat 3, article 8.

Álvarez, S., Navarro, A., Bañón, S., Sánchez-Blanco, M.J., 2009. Regulated deficit irrigation in potted Dianthus plants: Effects of severe and moderate water stress on growth and physiological responses. Sci. Hort. 122, 579-585.

Bacci, L., Battista, P., Rapi B., 2008. An integrated method for irrigation scheduling of potted plants. Sci. Hort. 116, 89–97.

Bañón, S., Ochoa, J., Franco, J.A., Alarcón, J.J., Sánchez-Blanco, M.J., 2006. Hardening of oldeander seedlings by deficit irrigation and low air humidity. Env. Exp. Bot. 56:36-43.

Barkham, J.P., 1993. For peat's sake: conservation or exploitation? Biodiversity & Conservation 2, 556-566.

Belayneh, B.E., Lea-Cox, J.D., Lichtenber, E., 2013. Costs and benefits of implementing sensor-controlled irrigation in a commercial pot-in-pot container nursery. HortTech. 23, 760-769.

Beeson, R.C. Jr., Knox, G.W., 1991. Analysis of efficiency of overhead irrigation in container production. HortSci. 26, 848-850.

Beeson, R.C. Jr., Yeager, T.H., 2003. Plant canopy affects sprinkler irrigation application efficiency of container-grown ornamentals. HortSci. 38, 1373-1377.

Briercliffe, T., Hewson, A., Brough, W. 2000. Independent water audits for container grown nursery stock producers. MAFF Water Audits - 2000. Horticulture and Potatoes Division, Ministry of Agriculture Fisheries and Food. Summary Report - Summer 2000.

Burnett, S.E., van Iersel, M.W., 2008. Morphology and irrigation efficiency of Gaura lindheimeri grown with capacitance sensor-controlled irrigation. HortSci. 43, 1555–1560.

Cameron, R., Harrison-Murray, R., Fordham, M., Wilkinson, S., Davies, W., Atkinson, C., Else, M., 2008. Regulated irrigation of woody ornamentals to improve plant quality and precondition against drought stress. Ann. App. Biol. 15, 49-61.

Cameron, R.W.F., Harrison-Murray. R., Scott, M.A., 1999. The use of controlled water stress to manipulate growth of container-grown Rhododendron cv. Hoppy. J. Hort. Sci. Biotech. 74, 161-169.

Cameron, R.W.F., Harrison-Murray, R.S., Atkinson, C.J., Judd, H.L., 2006. Regulated deficit irrigation – a means to control growth in woody ornamentals. J. Hort. Sci. Biotech. 81, 435-443.

Caron, J., Xu, H.L., Bernier, P.Y., Duchesne, I., Tardif, P., 1998. Water availability in three artificial substrates during Prunus × cistena growth: Variable threshold values. J. Am. Soc. Hort. Sci. 123, 931-936.

Chapman, S., Buttler, A., Francez, A.-J., Laggoun-Défarge, F., Vasander, H., Schloter, M., Combe, J., Grosvernier, P., Harms, H., Epron, D., Gilbert, D., Mitchell, E., 2003. Exploitation of northern peatlands and biodiversity maintenance: a conflict between economy and ecology. Frontiers in Ecology and the Environment 1, 525–532.

Chaves, M.M., Santos, T.P., Souza, C.R., Ortuño, M.F., Rodrigues, M.L., Lopes, C.M, Maroco, J.P., Pereira, J.S., 2007. Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. Ann. App. Biol. 150, 237–252.

Christiansen, J.E., 1942. Irrigation by sprinkling. Berkeley. California Agricultural Experiment Station. Bulletin No. 670.

Cirillo, C., Rouphael, Y., Caputo, R., Raimondi, G., De Pascale, S., 2014. The influence of deficit irrigation on growth, ornamental quality, and water use efficiency of three potted Bougainvillea genotypes grown in two shapes. HortSci. 49, 1284-1291.

Costa, J.M., Ortuño, M.F., Chaves, M.M., 2007. Deficit irrigation as a strategy to save water: physiology and potential application to horticulture. J. Integ. Plant Biol. 49, 1421-1434.

Evans, R.G., Sadler, E.J., 2008. Methods and technologies to improve efficiency of water use. Wat. Res. Res. 44, 1-15.

Fereres, E., Goldhamer, D.A., Parsons, L.R., 2003. Irrigation water management of horticultural crops. HortSci. 38, 1036-1042.

Fereres, E., Soriano, M.A., 2006. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147-159.

Franco, J.A., Martínez-Sánchez, J.J., Fernández, J.A., Bañón, S., 2006. Selection and nursery production of ornamental plants for landscaping and xerogardening in semi-arid environments. J. Hort. Sci. Biotech. 81, 3-17.

Grant, O.M., Stoll, M., Jones, H.G., 2004. Partial rootzone drying does not affect fruit yield of raspberries. J. Hort. Sci. Biotech. 79, 125-130.

Grant, O.M., Davies, M.J., Longbottom, H., Atkinson, C.J., 2009. Irrigation scheduling and irrigation systems: optimising irrigation efficiency for container ornamental shrubs. Irrig. Sci. 27, 139-153.

Grant, O.M., Davies, M.J., Longbottom, H., Herrero, A., Harrison-Murray, R., 2011. Application of deficit irrigation to controlling growth of hardy nursery stock. Acta Hort. 889, 409-416.

Grant, O.M., 2012. Measuring evapotranspiration of hardy ornamental nursery stock: A hurdle for irrigation management, in: Er-Raki, S. (Ed.), Evapotranspiration: Processes, sources and environmental implications. Nova Science Publishers, Inc.

Grant, O.M., Davies, M.J., Longbottom, H., Harrison-Murray, R., 2012. Evapotranspiration of container ornamental shrubs: modelling crop-specific factors for a diverse range of crops. Irrig. Sci. 30, 1-12.

Guérin, V., Lemaire, F., Marfà, O., 2001. Growth of Viburnum tinus in peat-based and peat-substitute growing media. Sci. Hort. 89, 129-142.

Harrison-Murray, R.S., 1991. An electrical sensor for potential transpiration: principle and prototype. J. Hort. Sci., 66, 141-149.

Incrocci, L., Marzialetti, P., Incrocci, G., Di Vita, A., Balendonck, J., Bibbiani, C., Spagnol. S., Pardossi, A., 2014. Substrate water status and evapotranspiration irrigation scheduling in heterogenous container nursery crops. Agric. Water. Manage. 131, 30-40.

Jensen, C.R., Battilani, A., Plauborg, F., Psarras, G., Chartzoulakis, K., Janowiak, F., Stikic, R., Jovanovic, Z., Li, G., Qi, X., Liu, F., Jacobsen, S., Andersen, M.N. 2010. Deficit irrigation based on drought tolerance and root signalling in potatoes and tomatoes. Agric. Water Manage. 98, 403–413.

Kim, J., van Iersel, M.W., Burnett, S.E., 2011. Estimating daily water use of two petunia cultivars based on plant and environmental factors. HortSci. 46, 1287–1293.

Klock-Moore, K.A., Broschat, T.K., 2001. Effect of four growing substrates on growth of ornamental plants in two irrigation systems. HortTech. 11, 456-460.

Lea-Cox, J.D., Bauerle, W.L., van Iersel, M.W., Kantor, G.F., Bauerle, T.L., Lichtenberg, E., King, D.M., Crawford, L., 2013. Advancing wireless sensor networks for irrigation management of ornamental crops: An overview. HortTech. 23, 717-724.

Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., Scardigno, A., 2014. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. Ag. Water Manage. 146, 84-94.

Majsztrik, J.C., Ristvey, A.G., Lea-Cox, J.D., 2011. Water and nutrient management in the production of container-grown ornamentals. Hort. Rev. 38, 253-297.

O'Meara, L., van Iersel, M.W., Chappell, M.R., 2013. Modeling daily water use of Hydrangea macrophylla and Gardenia jasminoides as affected by environmental conditions. HortSci. 48, 1040-1046.

Pettitt T.R., 2014. Irrigation water and the health of nursery crops, in: Hong, C. X., Moorman, G. W., Wohanka, W., Büttner, C. (Eds.), Biology, detection and management of plant pathogens in irrigation water. American Phytopathological Society.

Sánchez-Blanco, M.J., Ferrández, T., Navarro, A., Bañón, S., Alarcón, J.J., 2004. Effects of irrigation and air humidity preconditioning on water relations, growth and survival of Rosmarinus officinalis plants during and after transplanting. J. Plant Physiol. 161, 1133-1142.

Thorne, F.S., Kelly, P.W., Maher, M.J., Harte, L.N., 2002. The Irish hardy nursery stock industry: recent trends and competitive position. Teagasc report RMIS4748.

Warsaw, A.L., Fernandez, R.T., Cregg, B.M., Andresen, J.A., 2009. Water conservation, growth, and water use efficiency of container grown woody ornamentals irrigated based on daily water use. HortSci. 44, 1308–1318.

Wright, A.N., Niemiera, A.X., Harris, R., Wright, R.D., 1999. Preplant lime and micronutrient amendments to pine bark affect growth of seedlings of nine container-grown tree species. HortSci. 34, 669-673.

Yu, S., Zinati, G.M., 2006. Physical and chemical changes in container media in response to bark substitution for peat. Comp. Sci Util.14, 222-230.

Figure captions

Fig. 1. Variation between pots in water delivery, measured as weight gain of pots during an irrigation event (a), and in volumetric substrate moisture content (θ, b) during an experiment with deficit-irrigated Lonicera periclymenum 'Graham Thomas' (top) and Cornus alba 'Elegantissima' (bottom) under drip (shaded symbols) and overhead (open symbols) irrigation. Boxes indicate the 25th to 75th percentile range, whiskers extend another 15% either way, and outliers are represented by circles, n = 20. Application of 100% ET_A in (a) on that date would have equalled 165 mL irrigation. Data in (b) were obtained following 7 weeks of irrigation treatments.

Fig. 2. Volumetric substrate moisture content (θ) in pots (a) and plant height (b) of Lonicera periclymenum 'Graham Thomas' (top) and Cornus alba 'Elegantissima' (bottom) measured at intervals in an experiment comparing full irrigation (circles) and deficit irrigation (50% ET_A – triangles – or 25% ET_A – squares), imposed via drip (closed symbols) or overhead (open symbols) irrigation. Data are means ± s.e., n = 10.

Fig. 3. Volumetric substrate moisture content (θ) at the top (a) and bottom (b) of pots, and shoot (c) and root (d) dry mass of Lonicera periclymenum 'Graham Thomas' (top) and Cornus alba 'Elegantissima' (bottom) following 8 weeks of full or deficit irrigation (50% or 25% ET_A), applied via drip (closed symbols) or overhead (open symbols). Bars represent means ± s.e., n = 10. Within a single graph, different letters represent significant differences between means (LSD) at $P < 0.05$.

Fig. 4. Volumetric substrate moisture content (θ, a) and increase in plant height (shown as the cumulative increase from the start of the experiment or after pruning) (b) during application of full (circles) or deficit (70% ET_A – triangles – or 50% ET_A – squares) irrigation, applied via drip (closed symbols) or overhead (open symbols) to Forsythia × intermedia 'Lynwood' grown in 100% peat (top) or a reduced peat substrate (bottom). Symbols represent means ± s.e., n = 16 before pruning and n = 10 following pruning.

Fig. 5. Appearance of Forsythia × intermedia 'Lynwood' that were pruned in June (left) or left un-pruned (right) and photographed in early October. In each photo, the plants on the left and centre were deficit irrigated, receiving irrigation to match 50% (left), or 70% (centre) of the ET_A of a fully watered crop, and the plant on the right received full irrigation. **COLOUR**

Fig. 6. Volumetric substrate moisture content (θ) at the top (a), middle (b) and bottom (c) of pots filled with 100% peat (top) or a reduced peat substrate (bottom), and in which Forsythia × intermedia 'Lynwood' was grown under full or deficit (70% or 50% ET_A) irrigation, applied via drip (closed columns) or overhead (open columns), measured in August, n = 5 pots. Asterisks denote significant differences between drip and overhead irrigation, as indicated by post-hoc tests (LSD) following ANOVA, $P < 0.05$.

Fig. 7. Final dry mass of shoots (a), and roots (b), and the ratio of root to shoot dry mass (c) of Forsythia × intermedia 'Lynwood' harvested in autumn, following full or deficit (70% or 50% ET_A) irrigation, applied with drip (closed bars) or overhead (open bars) irrigation. n = 10 plants (data are pooled over two substrates). Within a single graph, different letters represent significant differences between means (LSD) at $P < 0.05$, following a significant effect of irrigation quantity (a) and a significant interaction of irrigation quantity and system (b, c), according to ANOVA.

Fig. 8. Number of flowers produced on Forsythia × intermedia 'Lynwood' per length of stem (a) and per node (b), and average internode length (c) in the spring following application of full or deficit (70% or 50% ET_A) irrigation, applied with drip (closed bars) or overhead (open bars) irrigation. Data are means ± s.e., n = 10. Plants had been pruned in June. Within a single graph, different letters represent significant differences between means (LSD) at $P < 0.05$, following a significant effect of irrigation quantity, according to ANOVA.

Tables

Table 1

Final plant canopy width of Cornus alba 'Elegantissima' following eight weeks of full or deficit (50% or 25% ET_A) irrigation.

Irrigation quantity	**Irrigation system**	**Plant width (cm)**
Full	Drip	80.7 ± 2.6 e*
	Overhead	67.7 ± 2.1 d
50% ET_A	Drip	53.0 ± 0.9 c
	Overhead	46.1 ± 2.4 b
25% ET_A	Drip	45.7 ± 1.5 b
	Overhead	32.1 ± 1.2 a

* Data are means ± s.e.; means with different letters differ significantly, $P < 0.05$, LSD following ANOVA. Plant width is the average of the width at the widest point in the canopy and the width perpendicular to that measurement.

Table 2

Coefficients of variation (%)[a] of volumetric substrate moisture content in different layers of two types of substrate (100% peat or reduced peat) under two irrigation systems (drip or overhead) and three different quantities of irrigation (full or deficit – 70% or 50% ET_A) to Forsythia.

Quantity	System	Substrate (% peat)	Layer of substrate: Top	Middle	Bottom
Full	Drip	100%	14.2 ± 3.2	10.5 ± 2.5	11.0 ± 1.5
		Reduced	13.0 ± 2.8	9.7 ± 1.8	8.5 ± 1.1
Full	Overhead	100%	8.9 ± 1.0	6.5 ± 1.4	5.3 ± 0.9
		Reduced	10.2 ± 2.6	9.5 ± 2.4	9.7 ± 2.4
70%	Drip	100%	56.9 ± 12.2	16.7 ± 3.1	9.3 ± 2.7
		Reduced	58.7 ± 3.9	15.9 ± 1.6	5.3 ± 1.0
70%	Overhead	100%	13.0 ± 1.5	10.2 ± 1.6	5.2 ± 0.7
		Reduced	9.4 ± 2.0	7.2 ± 1.7	9.9 ± 2.7
50%	Drip	100%	73.7 ± 6.4	33.3 ± 3.0	16.9 ± 4.0
		Reduced	66.3 ± 8.4	33.4 ± 6.7	16.7 ± 3.1
50%	Overhead	100%	13.4 ± 2.9	9.9 ± 2.9	6.7 ± 1.0
		Reduced	16.0 ± 2.7	12.8 ± 3.0	8.7 ± 2.5

[a] Coefficients were calculated from four measurements per layer per pot. Coefficients shown are means of 5 pots per irrigation quantity × irrigation system × substrate ± s.e.

Application of deficit irrigation to container-grown hardy ornamental nursery stock via overhead irrigation, compared to drip irrigation

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ABSTRACT

Growth control of container-grown hardy nursery stock generally requires substantial labour investment. Therefore the possibility of alternative growth control using deficit irrigation is appealing. Increasing water costs and limited availability of abstraction licences have added further incentives for nursery stock producers to use deficit irrigation. There are still, however, concerns that inherent non-uniformity of water uptake under commonly used overhead irrigation, and differing irrigation requirements of diverse crops and substrates, may limit the commercial relevance of a protocol developed for single crops growing in 100% peat and irrigated with a high precision drip system. The aim of this research was to determine whether growth control of hardy nursery stock is possible using deficit irrigation applied with conventional overhead irrigation. Over two years, crop growth under an overhead irrigation system was compared under full irrigation and two severities of deficit irrigation. Initially, two crops of contrasting canopy structure i.e. Cornus alba and Lonicera periclymenum were grown. In a subsequent experiment one crop (Forsythia × intermedia) was grown in two substrates with contrasting quantities of peat (60 and 100%). Deficit irrigation was found to be highly effective in controlling vegetative growth when applied using overhead irrigation – with similar results as when drip irrigation was used. This comparable response suggests that deficit irrigation can be applied without precision drip irrigation. Scheduling two very different crops with respect to their water use and uptake potential, however, highlighted challenges with respect to application of appropriate deficits for very different crops under one system; responses to deficit irrigation will be more consistent where nursery management allows for scheduling of crops with very different architecture and water use under different regimes. The effectiveness of deficit irrigation in controlling the growth of Forsythia was similar when a reduced peat based substrate was compared with pure peat; additionally, flowering was enhanced.

1. Introduction

Future global irrigation management will require users to look for methods of application which are efficient (Bacci et al., 2008; Kim et al., 2011; Majsztrik et al., 2011; Lea-Cox et al., 2013). For example, metrics such as water use and water productivity (Fereres and Soriano, 2006) may be required to justify irrigation practices. The use of deficit irrigation not only provides the means by which water use can be reduced and its use efficiency enhanced, but also enables crop growth and quality to be controlled (Jensen et al., 2010; Cirillo et al., 2014). Deficit irrigation is the application of less water than a crop would lose by evapotranspiration if water availability was not limiting (Fereres et al., 2003). However, for deficit irrigation to be effective requires understanding crop growth patterns, and some commentators suggest that use of advanced irrigations systems is also essential (Evans and Sadler, 2008; O'Meara et al., 2013). Deficit irrigation is applied either as sustained deficit irrigation i.e. by systematically applying water at a constant fraction of potential evapotranspiration through the season, or as regulated deficit irrigation, in which case soil moisture deficits are imposed only at certain plant developmental stages (Costa et al., 2007).

The primary challenges in the development of effective application of deficit irrigation to control growth and quality in container grown crops, such as hardy nursery stock, are a multitude of species and cultivars with different water requirements, and sensitivities to deficit irrigation, combined with a general absence of economic justification for the use of sophisticated precision irrigation systems (Kim et al., 2011; Majsztrik et al., 2011). There are examples, however, where economic assessment reveals apparently good initial savings and returns from investment in irrigation automation (Majsztrik et al., 2011; Belayneh et al., 2013). The successful application of deficit irrigation in hardy nursery stock production offers environmental and economic benefits, such as reduced container leaching of nutrients and pesticides and a reduction in fertiliser and pesticide costs associated with wastage (Caron et al., 1998). This combination of economic with environmental benefits has been recently highlighted (Levidow et al., 2014) as critical if producers are to take up opportunities for improved water management. Other benefits may arise from nursery production of more robust plants when subjected to environmental stresses, such as drought (Cameron et al. 2008). Some studies have now begun to elucidate the mechanisms by which deficit irrigation approaches achieve these 'carry-over' effects in the container crop production cycle (Sanchez-Blanco et al., 2004; Bañón et al., 2006; Cameron et al., 2006; Franco et al., 2006).

HNS production approaches are economically constricted by the need for mass production to consistently high crop quality (Warsaw et al., 2009). Despite retailer requirements for producers to meet precise crop-specific quality criteria (Álvarez et al., 2009; Majsztrik et al., 2011), retail margins often mean that investment in sophisticated irrigation approaches is not easily justified. Despite the high labour costs in nurseries' budgets, at least in UK, Dutch, and Irish production (Thorne et al., 2002), and the potential for deficit irrigation to remove or reduce the need for costly operations such as manual pruning (Cameron et al., 1999), there is still a lack of commercial confidence in the application of the approach (Kim et al., 2011). There are a number of questions which need answering before widespread uptake of deficit irrigation for container production is likely (Belayneh et al., 2013).

One of the concerns with respect to commercial application of deficit irrigation is whether approaches developed for high precision drip irrigation can be adapted for extensive commercial practice, which still relies heavily on overhead irrigation (Briercliffe et al., 2000; Pettitt 2014). The drawbacks of overhead irrigation are well described and for hardy nursery stock focus on a lack of spatial uniformity of irrigation supply meeting crop water 'demand'; this may have considerable implications for crop uniformity when deficit irrigation reduces container substrate water availability (Beeson and Knox, 1991; Beeson and Yeager, 2003; Grant et al., 2011). Related to the use of overhead irrigation is the tendency to grow several crops under one system. Differences in water use and uptake amongst species may mean that a deficit appropriate for one crop is detrimental for another.

The capacity of the container substrate to sustain the applied deficit irrigation regime must also be considered. Most commercial experience lies with the use of pure peat, but continued reliance on pure peat production is not sustainable (Barkham, 1993; Chapman et al., 2003; Alexander et al., 2008). Substrate producers are therefore looking into alternative media, at least to reduce, if not completely replace, peat consumption (Alexander et al., 2008). Changing the constituents in growing media, however, frequently alters the water holding capacity of the substrate (Yu and Zinati, 2006).

The aim of this research was to provide a more robust evaluation of the challenges involved in using deficit irrigation for commercial practice; here we ~~focus on~~investigate ~~comparing overhead with drip irrigation, ~~the impact of irrigation system (overhead vs. drip),~~of~~ crop type, and ~~the use of an alternative ~~growing media (alternative vs.~~to~~ pure peat).

2. Materials and methods

2.1. Plant material and the growing environment

Lonicera periclymenum 'Graham Thomas', Cornus alba 'Elegantissima', and Forsythia × intermedia, cultivar 'Lynwood' were purchased as liners (New Place Nurseries Ltd, Pulborough, UK) and transferred to 2 L pots. Limestone (1.5 kg m^{-3}) and controlled release fertiliser [Osmocote Plus Spring (15+9+11+2 MgO + trace elements), 6 kg m^{-3}] were incorporated into the substrate. Vigorous growth is characteristic of all the cultivars selected. L. periclymenum, a climber, was supported with pot canes. The typical habit of the three cultivars is shown in Fig. 1.

The experiments were conducted in a closed plastic tunnel, to prevent rainfall and strong winds interfering with irrigation treatments (side ventilation panels were opened as required to avoid over-heating). The standing surface was a thick, rolled (to provide a level surface), layer of course gravel covered with woven polypropylene fabric (MyPex, Monro Horticulture, Maidstone, UK). The tunnel was divided into six separate bays (5 m × 2.4 m ground area) using sheets of polythene to contain the overhead irrigation spray within the application bay. The plastic sheets were suspended above drain gutters, which prevented the irrigation spray contacting the MyPex. Pots were arranged, at a spacing of 25 × 25 cm, in rows of 18 plants, with the outer rows in each bay acting as guard plants.

2.2. Irrigation systems and scheduling

Irrigation was scheduled to replace a predetermined percentage of the potential crop evapotranspiration (i.e. the actual evapotranspiration, ET_A, if water availability was not limiting). Two different deficit irrigation treatments were applied each year, in comparison with a full irrigation treatment, with two bays used for each treatment; treatments were allocated randomly to the different bays. In the case of full irrigation, 150% ET_A was applied to ensure that even if irrigation delivery was non-uniform, all plants would receive at least 100% ET_A. Excess water ran through the pot bases, and drained freely through the MyPex and the gravel beneath, showing no signs of ground surface accumulation. High quality mains supply water was used for irrigation.

Drip irrigation was applied via 2 L h^{-1} drippers (Netafim C.N.L. Junior Drippers, Access Irrigation, Northampton, UK), with one dripper per pot. Dripper output was quantified and drippers were replaced as necessary to achieve maximal uniformity across all drippers. Overhead irrigation was applied using six 50 L h^{-1} Eindor 861 sprinklers (Access Irrigation, Northampton, UK) per bay arranged at distances of 2.25 m between sprinklers along the bay and across the bay at 1.5 m between the central pair and 1.2 m between the other two pairs. This arrangement was shown to have the highest uniformity of application as determined by measuring Christiansen's coefficient of uniformity (Christiansen, 1942) for several different arrangements. Irrigation outputs for both the overhead and drip irrigation systems were measured before the experiment and after, to determine any degradation during use. Mean application rate and scheduling coefficient were calculated for each bay. The scheduling coefficient is the (mean application rate)/(minimum application rate), where mean reflects the measurements made over the entire bed and minimum refers to the area of the bed that received the lowest application (see Grant et al., 2009). Water delivery to pots was also frequently measured by weight gain during an irrigation event.

ET_A was determined every two weeks by weighing plants in the full irrigation treatments after irrigation (after allowing for pot gravity draining, and water intercepted by the canopy to run off) and again a day later. Wet leaf temperature depression was determined simultaneously with a sensor (Evaposensor, Skye, Powys, UK) located in the crop. The sensor continuously measures temperature differences between wet and dry artificial leaves (Harrison-Murray, 1991), with the accumulated difference recorded and logged via a dedicated meter (Evapometer, Skye), as °C h, where 1°C h equates to a difference of 1°C for a duration of 1 h. Thus, for example, if a plant uses 100 mL water during an accumulation of 100°C h, this plant will require 1 mL of irrigation for every 1°C h accumulated, if the intention is to apply 100% of

ET_A. Combining water use per °C h with the time required to apply the determined irrigation volume (the measured scheduling coefficient of each system) computes the length of the irrigation event to replace 1°C h. This value can then be multiplied by the appropriate ET_A percentage depending on treatment. The result was then multiplied by the daily accumulated °C h over the previous 24 h to determine the irrigation requirement that day. This duration was then programmed into an irrigation timer (Heron Electric Company Limited, Ford, Nr. Arundel, UK), to trigger morning irrigation to each bay. For a more complete description of Evaposenor use see Grant et al. (2009) or Grant (2012).

2.3. A single species scheduling approach applied to crops of contrasting canopy structure

Lonicera and Cornus growing in 100% sphagnum peat (Shamrock Premium Grade, Bord na Móna, Newbridge, Co. Kildare, Ireland) were compared in year 1 (2006). This peat consists of particles up to 14 mm, including 50% in the range 6-12 mm, and has an approximate air filled porosity of 12% and electrical conductivity < 1 mS cm^{-1}. Plants were arranged in five rows per bay, with Lonicera on one half of the bed and Cornus on the other, providing 21 experimental plants of each species, which were fully guarded. The deficit irrigation treatments applied were 50% ET_A and 25% ET_A i.e. crops were irrigated to replace 50% or 25% of water used by the fully irrigated plants. These two deficit irrigation treatments were selected to represent a deficit of sufficient severity to have a noticeable impact on growth (50%), and a very severe deficit that might risk reducing plant quality (25%). Results from the two different severities would thus be expected to provide a guideline for a range appropriate for use on nurseries. Irrigation for both the crops was scheduled on the basis of crop factors obtained for Lonicera. The reasoning for this is that different crops are often grown together on single beds, and with overhead irrigation will inevitably be irrigated by the same amount. Treatments were applied from the start of August, for eight weeks. During this time, daily mean air temperature in the tunnel was on average 21.4°C, ranging from 16.3°C to 24.9°C. Relative humidity was on average 82.9%. Average mean and maximum daytime global radiation were 188 and 455 W m^{-2}, respectively, with the maximum global radiation reached equalling 655

W m^{-2}. Meteorological data were recorded from sensors integrated with a data-logger (Datahog, Skye Instruments Ltd., Powys, UK).

2.4. Comparison of substrates

100% peat (as above) was compared with a reduced peat mix [60% peat: 40% bark (Melcourt Potting bark, Melcourt Industries Ltd., Tetbury, Gloucestershire, UK)]. Particles in the selected bark are predominantly in the range 3-15 mm, and its air filled porosity is approximately 62%, with an electrical conductivity of about 0.1 mS cm^{-1}. For the reduced peat mix, 1 g ammonium nitrate per L of bark was incorporated to compensate for the low nitrogen availability in bark (see recommendation by Wright et al., 1999). The two substrate treatments were replicated randomly in each bay. Plants of Forsythia were arranged in four rows per bay and DI treatments of 70% and 50% ET_A applied. These treatments were selected following analysis of the first experiment, with the 70% ET_A representing a mild deficit – potentially the smallest reduction in water supply likely to show a significant reduction in growth. Crop evapotranspiration of Forsythia in 100% peat and in the reduced peat mix was similar, and therefore crop factors for irrigation scheduling were based on average crop ET_A (measured by pot weighing as above) across both substrates.

Irrigation treatments were applied from mid-May 2007. At the end of June, 10 plants per irrigation treatment (% ET_A), per irrigation system (drip vs. overhead), per substrate (100% peat vs. reduced peat mix) were pruned to a height of 20-30 cm (as is commercial practice). Four plants per irrigation treatment × irrigation system × substrate were kept un-pruned. For one week in mid-August, plants in the 50% ET_A treatments were given 70% ET_A irrigation, to encourage bud-break and shoot growth, which was previously limited. At the end of August, the numbers of buds breaking per pot from pruned branches was counted. Final heights and widths of all plants were measured in mid-September. Meteorological data are not available for inside the tunnel during this experiment. External air temperature and relative humidity averaged 17.2°C and 76.9% during the same duration (Grant et al., 2011). Average mean and maximum daytime global radiation recorded nearby at the East Malling Water Centre were 505 and 960 W m^{-2}, respectively. Radiation in the tunnel would be expected to be considerably lower, with higher air temperature and humidity.

2.5. Substrate moisture content

Substrate volumetric moisture content (θ) was measured 6 cm deep from the top of each pot for all experimental plants every week using a soil moisture sensor (SM200 and HH2 meter, Delta-T Devices, Cambridge, UK). At the end of the experiments, substrate volumetric moisture content was also measured 6 cm from the base of the pot (inserting the probe at the base). In the substrate comparison experiment, volumetric moisture content was also measured in the middle of pots (by inserting the probe from the sides). The variability in volumetric moisture content within pots at different depths was determined from measurements taken in four horizontal locations per pot at the top and half-way down the pot. Calibration curves were produced for the substrates used (measuring wet and dry substrate, and determining water content gravimetrically, following the SM200 sensor manual), and the voltage output, used with the resulting calibration coefficients to obtain substrate volumetric moisture content as volume of water per volume of substrate.

2.6. Plant growth, biomass allocation, and flowering

Heights of all plants were measured weekly, while for Cornus and Forsythia, final leaf canopy width was calculated from two perpendicular measurements at the canopy's widest point. At the end of experiments, half of the experimental plants were harvested and the shoots separated from the root system, the latter washed and both oven dried at 80°C for 48 h. Root and shoot dry masses were obtained, and root:shoot ratios calculated. Remaining plants were over-wintered, for flowering assessment in spring. At around 80% full bloom, numbers of flowers and numbers of internodes on a selected shoot of average length on each plant were counted, and the length of all shoots measured, allowing calculation of numbers of flowers per cm shoot length, numbers of flowers per node, and internode length.

2.7. Statistical analysis

The significance of treatment differences was assessed by analysis of variance (ANOVA), followed by LSD tests where appropriate, in Genstat software (Genstat 9.1, Rothamsted Experimental Station, UK). A repeated measures ANOVA was used where variables were measured repeatedly on the same individual plants or pots.

3. Results

3.1. A single species scheduling approach applied to crops of contrasting canopy structure

The overhead sprinkler arrangement achieved a Christiansen's coefficient of uniformity of 91%, a scheduling coefficient of 1.2, and a mean application rate of 7.7 mm per hour. Drip irrigation resulted in a Christiansen's coefficient of uniformity of 96-98% and a scheduling coefficient of 1.0 to 1.1. While there was evidence during irrigation that pot weight gain was less homogenous under overhead compared to drip irrigation (example in Fig. 2~~1~~a), variation in substrate volumetric moisture content was not consistently greater under overhead irrigation (example in Fig. 2~~1~~b). Measurements of water uptake indicated that Cornus under overhead irrigation took up less water than Lonicera (Fig. 2~~1~~a), while water uptake with drip was similar for both crops.

Evapotranspiration of the fully irrigated Lonicera crop during the first experiment was on average 2.2 mm day^{-1}, while that of Cornus was 3.2 mm day^{-1}, accumulating to 133 and 195 mm respectively during the course of the experiment. Daily averages of 4.4, 1.1, and 0.5 mm day^{-1} irrigation were applied to the full, 50% ET_A and 25% ET_A treatments, respectively. It is important to note, however, that irrigation was adjusted on a daily basis according to the accumulated wet leaf temperature depression for the previous 24 h, to allow for fluctuating weather, as opposed to applying these average values throughout the experiment. In total over the experiment, 267 mm irrigation was applied to the fully irrigated crop, and 67 and 33 mm to the milder and more severe deficit treatments, respectively.

Over the course of the experiment, deficit irrigation significantly ($P < 0.05$) reduced substrate volumetric moisture content (Fig. 3~~2~~a), on average, across all pots, and resulted in reduced growth (Fig. 3~~2~~b). For both Lonicera and Cornus, there was an interaction between irrigation quantity (% ET_A) and method of application on substrate volumetric moisture content ($P < 0.001$). For Lonicera, there was no difference between drip and overhead irrigation with respect to plant growth over the experiment (Fig. 32b). For Cornus, there was an interaction of irrigation system and % ET_A applied ($P = 0.003$) over the experiment, resulting in final plant heights being reduced under overhead compared to drip irrigation when full irrigation was applied, but not when deficit irrigation was applied. Cornus plants showed wider leaf canopy diameters at the end of the experiment when drip irrigated compared to overhead, and reduced canopy diameters under deficit compared to full irrigation (both $P < 0.001$; Table 1).

At the end of the experiment, an interaction between irrigation system and % ET_A ($P < 0.001$) was detected on mean substrate volumetric moisture content, both at the top and at the bottom of the pot, for both species. Substrate volumetric moisture content was lower under overhead than drip irrigation for both deficit irrigation treatments. On the other hand, it was higher under overhead than drip irrigation when full irrigation was applied (Fig. 43a, b). For Lonicera, shoot dry mass was not significantly affected by the type of irrigation (drip vs. overhead) within a given % ET_A. However, there was a significant effect of % ET_A on plant mass ($P < 0.001$ for shoots and $P = 0.025$ for roots). Under drip irrigation both deficit treatments showed reduced shoot, but not root, dry mass, whereas under overhead irrigation only the more severe deficit reduced shoot dry mass (Fig. 43c, d). Root:shoot ratio decreased as % ET_A increased ($P < 0.001$, data not shown). For Cornus, both shoot dry mass and root dry mass were affected by % ET_A ($P < 0.001$), with increasing dry mass at the higher % ET_A (Fig. 43c, d). Both shoot and root mass was greater under drip irrigation compared to overhead ($P < 0.001$). Root:shoot ratio was affected by % ET_A ($P < 0.001$), with a lower root: shoot ratio under 25% ET_A than under the other two treatments (data not shown).

3.2. Comparison of substrates

During the second experiment, evapotranspiration of the fully irrigated crop was on average 3.2 mm day^{-1}, accumulating to 445 mm over the whole season. Thus daily averages of 4.9, 2.3, and 1.6 mm day^{-1} irrigation was applied to the full (150% ET_A), 70% ET_A and 50% ET_A treatments, respectively. As a result, over the entire growing season, 667 mm irrigation was applied to the fully irrigated crop, and 311 and 222 mm to the milder and more severe deficit treatments, respectively. Substrate volumetric moisture content was reduced by deficit irrigation throughout thise second experiment ($P < 0.001$) (Fig. 54a). A frequent but less consistent effect of irrigation system also occurred, but only occasionally were differences in substrate volumetric moisture content seen between the two types of substrate. Growth slowed in the 50% ET_A DI treatment from 14 days after treatments started ($P \leq 0.012$; Fig. 54b). Five weeks from the start of the experiment, an interaction with respect to cumulative plant height increment was seen between irrigation quantity and system ($P = 0.013$). Differences between treatments in shoot growth were reflected in the average mass of shoot material per plant obtained during pruning: 10–12 g for 50% ET_A, 12–18 g for 70% ET_A, and 22–24 g for full irrigation. Post-pruning bud break was significantly lower ($P < 0.001$) in the deficit irrigation treatments (around 7–9 bud breaks per plant) than in the full irrigation treatment (around 16 bud breaks per plant). After pruning, rapid growth was seen under full irrigation, with growth much reduced under deficit irrigation (Fig. 54b). From pruning onwards, there was no interaction between substrate and irrigation quantity or system, and no interaction between irrigation quantity and system i.e. reduced growth occurred with deficit irrigation using both drip and overhead and with both 100% peat and the reduced peat substrates. The combination of fewer bud breaks and reduced shoot elongation under deficit irrigation led to more compact plants. Growth was greater in the reduced peat substrate ($P < 0.001$).

Post-pruning bud break was significantly lower ($P < 0.001$) in the deficit irrigation treatments (around 7–9 bud breaks per plant) than in the full irrigation treatment (around 16 bud breaks per plant). Combined with reduced height, this resulted in deficit irrigation producing more compact plants than full irrigation (Fig. 5, left). The sub-set of plants not pruned in June showed excessive growth in response to full irrigation (Fig. 5, right); growth was restricted in response to deficit irrigation.

Early in August, Forsythia plants were removed from their pots and variation in substrate volumetric moisture content determined. Coefficients of variation (100% × standard deviation/mean) between the four measurements per layer (top, middle, or bottom) of the substrate showed that greatest variation most frequently occurred at the top (Table 2). Variation within a substrate layer was generally much greater when DI was applied using drip irrigation rather than overhead. Variation was also generally greater for the more severe deficit. Generally across all pots, independently of whether full or deficit irrigation was applied, the substrate was drier in the top layer with both substrate types and both irrigation systems ($P < 0.001$, Fig. 6). Substrate volumetric moisture content tended to be greater using overhead irrigation compared to drip.

In autumn, shoot dry mass was affected only by % ET_A applied ($P < 0.001$, Fig. 7a), with shoot dry mass increasing with % ET_A. Root dry mass was also affected by the interaction of % ET_A with type of irrigation ($P = 0.02$, Fig. 7b). With overhead irrigation, root dry mass increased with increasing % ET_A, but this response was less clear with drip irrigation. Thus, when drip was used, compared to overhead irrigation, root dry mass was not as reduced by the more severe deficit relative to full irrigation. Root:shoot ratio was also affected by the interaction of % ET_A and type of irrigation ($P < 0.001$, Fig. 7c). The root:shoot ratio decreased with increasing % ET_A under drip irrigation, but this did not occur under overhead irrigation.

The following spring, number of flowers per unit shoot length was affected by the % ET_A applied ($P < 0.001$, Fig. 8a). The plants receiving full irrigation had approximately half the number of flowers per unit shoot length compared to those receiving 50% ET_A. The increased number of flowers over a given length of shoot in the deficit irrigation treatments was a result of an increased number of flowers per node ($P = 0.018$, Fig. 8b) and shorter internode lengths ($P < 0.001$, Fig. 8c).

4. Discussion

A reduction of substrate volumetric moisture content, in response to deficit irrigation, led to a reduction in the shoot growth of all the species used here, as it does with other species (Beeson 1992; Cameron et al. 1999; Grant et al. 2004; Chaves et al. 2007). This reduction is also known to influence a number of different growth variables, both above and below ground (Franco et al., 2006). In most previous research, however, deficit irrigation has been applied using a high-precision drip irrigation system. Our novel approach was to validate the potential of deficit irrigation to control growth through the utilisation of overhead irrigation – which is still an important and much used system in commercial ornamental plant production. Different irrigation systems are known to impact on plant dry matter production even when full irrigation is applied (Klock-Moore and Broschat, 2001), and deficit irrigation might accentuate such effects.

Here we show that irrespective of type of irrigation system used (drip or overhead) to apply deficit irrigation, reduced growth was apparent in response to a decline in substrate volumetric moisture content. The experiment with Cornus, however, showed that plant size was dependent on the irrigation system used, with reduced canopy diameter and biomass with overhead irrigation compared to drip. The reason Cornus grew less with overhead irrigation relates to this crop taking up less water than Lonicera. This response was visually apparent during irrigation events, where applied water was deflected by the Cornus canopy while the supported upright structure of Lonicera promoted water funnelling into the pots. Cornus growth was excessively reduced by the application of the severe deficit, highlighting the difficulty of scheduling deficit irrigation for different species using the same irrigation system. We strongly recommend that users grow crops together which have similar canopy architectural and structural attributes along with similar water uptake. Several factors not included here are known to exacerbate non-uniformity of overhead irrigation delivery (Li 1998; Grant 2012).

In addition to reducing plant growth, deficit irrigation impacted on plant quality. Forsythia subjected to deficit irrigation developed an increased number of flowers per node, and this increase in flowering density can provide a more aesthetically appealing plant at retail. Some caution is required with respect to differences in species sensitivity, tissue type, age at which flowers are initiated, and the timing of application of the deficit in relation to flower initiation. A study with Rhododendron showed that deficit application during flower induction (late summer) could reduce flower production (Cameron et al., 1999), although in general across a range of hardy nursery stock, the effects of deficit irrigation on flower production were small (Cameron et al., 2006).

The increased root:shoot ratio apparent for Forsythia as a result of deficit irrigation has important implications in the production of ‘robust’ plants which are able to establish rapidly when transplanted. This is particularly true for better establishment under semi-arid conditions (Franco et al., 2006). How this occurs, beyond improvement in the plant’s ability to capture water relative to that lost via transpiration, is likely to be species-specific. In Nerium oleander, for example, dehydration of the finer roots during transplanting is detrimental; deficit irrigation induces thick roots, which increase the potential for water storage, leading to better establishment of deficit irrigated plants (Bañón et al., 2006). In the current research with Forsythia, however, it should be noted that an increased root:shoot ratio as a result of deficit irrigation only occurred when irrigation was applied using a drip system. The reduction in root biomass using overhead irrigation compared to drip may have negative implications on transplanting and establishment. On the other hand, drip irrigation can result in localised abundant root production in relation to the dripper positioning in the container, where a high rooting density makes effective use of applied water, but will limit the rate at which roots exploit the soil on transplanting. The greater variation in volumetric moisture content within a layer shown here for drip compared to overhead irrigation highlights the potential for localised root formation under drip systems. Substrate types can also accentuate differences in water distribution: coarse textured substrates lack small pore spaces to promote capillary movement and water holding capacity (Klock-Moore and Broschat, 2001). Neither of the substrates used in this study, however, accentuated variation in volumetric moisture content compared to the other.

There was no interaction of irrigation quantity and substrate on final plant height, implying that deficit irrigation can be used to control growth in a reduced peat substrate, without any need to alter irrigation scheduling protocols developed for 100% peat. Reduced peat did not impact on root:shoot ratio, or variation within or between pots in substrate volumetric moisture content. This may reflect limited variation in water holding capacity between substrates with peat substitution from 40 to 70% (Caron et al., 1998). Yu and Zinati (2006) found that increasing the percentage of bark from 40% to 90% in parallel with a decreasing percentage of peat led to decreased substrate water holding capacity, from 63% to 49%. This difference is small and would be easily managed within a deficit irrigation strategy and would have little impact on its effectiveness with respect to growth control. Comparing two peat-sand mixes, at 10% volumetric substrate moisture content, Bunt (1976) reported a decrease in water tension of over 0.3 MPa for the 50:50 mix compared to the 75:25 mix, falling to a difference of only about 0.1 MPa at 20% volumetric moisture content. Walczak et al. (2002) found substantial reductions in water retention only when the peat content was far lower than in the current mixed substrate. Nonetheless, hydraulic conductivity should be determined for different substrates. Londra (2010) found considerable increases in hydraulic conductivity with the addition of perlite or coir over pure peat (1.32 cm min^{-1}). Hydraulic conductivity has been frequently assessed for pure peat (e.g. Walczak et al., 2002; Naasz et al., 2005; Londra, 2010), but given the wide range of alternative substrates, used in different proportions with peat, uncertainty remains regarding the hydraulic properties of specific substrate mixes.

The substrate-derived differences in growth seen here with Forsythia are likely to relate to nutritional differences. To compensate for an expected reduction in nitrogen availability when peat is partially substituted with bark (Wright et al., 1999), ammonium nitrate was added initially. This apparently overcompensated, with enhanced growth in the reduced peat substrate – which was seen under full as well as deficit irrigation. Variation in growth when using a diverse range of growing media is well documented (Guérin et al., 2001).

Currently it is not possible to predict exact % ET_A deficits to induce well-defined levels of growth control or increases in production quality across the wide range of species and cultivars in hardy nursery stock production. That innate differences in response to limited water availability exist between cultivars and species is well known (Zwack et al., 1998), and this variability interacts with factors such as variation in the growing environment (Evans and Sadler, 2008). Another challenge is how to easily determine the actual water input corresponding to the desired % ET_A (Fereres and Soriano, 2006): if entire crops are being deficit irrigated, fully irrigated plants may not be available for gravimetric calibration, as used in this current study. One solution would be through adjustment of scheduling coefficients on the basis of plant size (canopy area and hence transpiring area). Where the Evaposensor has been used to schedule (full) irrigation, this approach has been shown to be effective for diverse species (Grant et al., 2012). Alternatively, coefficients (K_c) can be estimated from variables such as plant height, to use with reference evapotranspiration (ET_o) calculated from meteorological variables (Incrocci et al., 2014).

5. Conclusions

Deficit irrigation applied by overhead irrigation can be used to control growth and quality of container grown crops as effectively as when applied by drip irrigation. Therefore effective deficit does not rely solely on more expensive and less frequently used drip irrigation. This conclusion should encourage commercial uptake of deficit irrigation. Addressing the challenge of identifying a deficit irrigation regime that is appropriate for specific cultivars and level of growth control will require more experimentation. Additionally, approaches to scheduling that can be easily applied commercially (e.g. monitoring evapotranspiration or substrate volumetric moisture content) merit further consideration.

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References

Alexander, P.D., Bragg, N.C., Meade, R., Padelopoulos, G., Watts, O., 2008. Peat in horticulture and conservation: the UK response to a changing world. Mires & Peat 3, article 8.

Álvarez, S., Navarro, A., Bañón, S., Sánchez-Blanco, M.J., 2009. Regulated deficit irrigation in potted Dianthus plants: Effects of severe and moderate water stress on growth and physiological responses. Sci. Hort. 122, 579-585.

Bacci, L., Battista, P., Rapi B., 2008. An integrated method for irrigation scheduling of potted plants. Sci. Hort. 116, 89–97.

Bañón, S., Ochoa, J., Franco, J.A., Alarcón, J.J., Sánchez-Blanco, M.J., 2006. Hardening of oldeander seedlings by deficit irrigation and low air humidity. Env. Exp. Bot. 56:36-43.

Barkham, J.P., 1993. For peat's sake: conservation or exploitation? Biodiversity & Conservation 2, 556-566.

Beeson, R.C., 1992. Restricting overhead irrigation to dawn limits growth in container-grown woody ornamentals. HortSci. 27, 996-999.

Beeson, R.C. Jr., Knox, G.W., 1991. Analysis of efficiency of overhead irrigation in container production. HortSci. 26, 848-850.

Beeson, R.C. Jr., Yeager, T.H., 2003. Plant canopy affects sprinkler irrigation application efficiency of container-grown ornamentals. HortSci. 38, 1373-1377.

Belayneh, B.E., Lea-Cox, J.D., Lichtenber, E., 2013. Costs and benefits of implementing sensor-controlled irrigation in a commercial pot-in-pot container nursery. HortTech. 23, 760-769.

Briercliffe, T., Hewson, A., Brough, W. 2000. Independent water audits for container grown nursery stock producers. MAFF Water Audits - 2000. Horticulture and Potatoes Division, Ministry of Agriculture Fisheries and Food. Summary Report - Summer 2000.

Bunt, A.C., 1976. Modern potting composts. The Pennsylvania State University Press.

Burnett, S.E., van Iersel, M.W., 2008. Morphology and irrigation efficiency of Gaura lindheimeri grown with capacitance sensor-controlled irrigation. HortSci. 43, 1555–1560.

Cameron, R., Harrison-Murray, R., Fordham, M., Wilkinson, S., Davies, W., Atkinson, C., Else, M., 2008. Regulated irrigation of woody ornamentals to improve plant quality and precondition against drought stress. Ann. App. Biol. 15, 49-61.

Cameron, R.W.F., Harrison-Murray. R., Scott, M.A., 1999. The use of controlled water stress to manipulate growth of container-grown Rhododendron cv. Hoppy. J. Hort. Sci. Biotech. 74, 161-169.

Cameron, R.W.F., Harrison-Murray, R.S., Atkinson, C.J., Judd, H.L., 2006. Regulated deficit irrigation – a means to control growth in woody ornamentals. J. Hort. Sci. Biotech. 81, 435-443.

Caron, J., Xu, H.L., Bernier, P.Y., Duchesne, I., Tardif, P., 1998. Water availability in three artificial substrates during Prunus × cistena growth: Variable threshold values. J. Am. Soc. Hort. Sci. 123, 931-936.

Chapman, S., Buttler, A., Francez, A.-J., Laggoun-Défarge, F., Vasander, H., Schloter, M., Combe, J., Grosvernier, P., Harms, H., Epron, D., Gilbert, D., Mitchell, E., 2003. Exploitation of northern peatlands and biodiversity maintenance: a conflict between economy and ecology. Frontiers in Ecology and the Environment 1, 525–532.

Chaves, M.M., Santos, T.P., Souza, C.R., Ortuño, M.F., Rodrigues, M.L., Lopes, C.M, Maroco, J.P., Pereira, J.S., 2007. Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. Ann. App. Biol. 150, 237–252.

Christiansen, J.E., 1942. Irrigation by sprinkling. Berkeley. California Agricultural Experiment Station. Bulletin No. 670.

Cirillo, C., Rouphael, Y., Caputo, R., Raimondi, G., De Pascale, S., 2014. The influence of deficit irrigation on growth, ornamental quality, and water use efficiency of three potted Bougainvillea genotypes grown in two shapes. HortSci. 49, 1284-1291.

Costa, J.M., Ortuño, M.F., Chaves, M.M., 2007. Deficit irrigation as a strategy to save water: physiology and potential application to horticulture. J. Integ. Plant Biol. 49, 1421-1434.

Evans, R.G., Sadler, E.J., 2008. Methods and technologies to improve efficiency of water use. Wat. Res. Res. 44, 1-15.

Fereres, E., Goldhamer, D.A., Parsons, L.R., 2003. Irrigation water management of horticultural crops. HortSci. 38, 1036-1042.

Fereres, E., Soriano, M.A., 2006. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147-159.

Franco, J.A., Martínez-Sánchez, J.J., Fernández, J.A., Bañón, S., 2006. Selection and nursery production of ornamental plants for landscaping and xerogardening in semi-arid environments. J. Hort. Sci. Biotech. 81, 3-17.

Grant, O.M., Stoll, M., Jones, H.G., 2004. Partial rootzone drying does not affect fruit yield of raspberries. J. Hort. Sci. Biotech. 79, 125-130.

Grant, O.M., Davies, M.J., Longbottom, H., Atkinson, C.J., 2009. Irrigation scheduling and irrigation systems: optimising irrigation efficiency for container ornamental shrubs. Irrig. Sci. 27, 139-153.

Grant, O.M., Davies, M.J., Longbottom, H., Herrero, A., Harrison-Murray, R., 2011. Application of deficit irrigation to controlling growth of hardy nursery stock. Acta Hort. 889, 409-416.

Grant, O.M., 2012. Measuring evapotranspiration of hardy ornamental nursery stock: A hurdle for irrigation management, in: Er-Raki, S. (Ed.), Evapotranspiration: Processes, sources and environmental implications. Nova Science Publishers, Inc.

Grant, O.M., Davies, M.J., Longbottom, H., Harrison-Murray, R., 2012. Evapotranspiration of container ornamental shrubs: modelling crop-specific factors for a diverse range of crops. Irrig. Sci. 30, 1-12.

Guérin, V., Lemaire, F., Marfà, O., 2001. Growth of Viburnum tinus in peat-based and peat-substitute growing media. Sci. Hort. 89, 129-142.

Harrison-Murray, R.S., 1991. An electrical sensor for potential transpiration: principle and prototype. J. Hort. Sci., 66, 141-149.

Incrocci, L., Marzialetti, P., Incrocci, G., Di Vita, A., Balendonck, J., Bibbiani, C., Spagnol. S., Pardossi, A., 2014. Substrate water status and evapotranspiration irrigation scheduling in heterogenous container nursery crops. Agric. Water. Manage. 131, 30-40.

Jensen, C.R., Battilani, A., Plauborg, F., Psarras, G., Chartzoulakis, K., Janowiak, F., Stikic, R., Jovanovic, Z., Li, G., Qi, X., Liu, F., Jacobsen, S., Andersen, M.N. 2010. Deficit irrigation based on drought tolerance and root signalling in potatoes and tomatoes. Agric. Water Manage. 98, 403–413.

Kim, J., van Iersel, M.W., Burnett, S.E., 2011. Estimating daily water use of two petunia cultivars based on plant and environmental factors. HortSci. 46, 1287–1293.

Klock-Moore, K.A., Broschat, T.K., 2001. Effect of four growing substrates on growth of ornamental plants in two irrigation systems. HortTech. 11, 456-460.

Lea-Cox, J.D., Bauerle, W.L., van Iersel, M.W., Kantor, G.F., Bauerle, T.L., Lichtenberg, E., King, D.M., Crawford, L., 2013. Advancing wireless sensor networks for irrigation management of ornamental crops: An overview. HortTech. 23, 717-724.

Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., Scardigno, A., 2014. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. Ag. Water Manage. 146, 84-94.

Li, J.S., 1998. Modeling crop yield as affected by uniformity of sprinkler irrigation system. Ag. Water Manage. 38, 135-146.

Londra, P.A., 2010. Simultaneous determination of water retention curve and unsaturated hydraulic conductivity of substrates using a steady-state laboratory method. HortSci. 45, 1106-1112.

Majsztrik, J.C., Ristvey, A.G., Lea-Cox, J.D., 2011. Water and nutrient management in the production of container-grown ornamentals. Hort. Rev. 38, 253-297.

Naasz, R., Michel, J.C., Charpentier, S., 2005. Modeling oxygen and water flows in peat sustrates with root uptakes. Acta Hort. 779, 191-197.

O'Meara, L., van Iersel, M.W., Chappell, M.R., 2013. Modeling daily water use of Hydrangea macrophylla and Gardenia jasminoides as affected by environmental conditions. HortSci. 48, 1040-1046.

Pettitt T.R., 2014. Irrigation water and the health of nursery crops, in: Hong, C. X., Moorman, G. W., Wohanka, W., Büttner, C. (Eds.), Biology, detection and management of plant pathogens in irrigation water. American Phytopathological Society.

Sánchez-Blanco, M.J., Ferrández, T., Navarro, A., Bañón, S., Alarcón, J.J., 2004. Effects of irrigation and air humidity preconditioning on water relations, growth and survival of Rosmarinus officinalis plants during and after transplanting. J. Plant Physiol. 161, 1133-1142.

Thorne, F.S., Kelly, P.W., Maher, M.J., Harte, L.N., 2002. The Irish hardy nursery stock industry: recent trends and competitive position. Teagasc report RMIS4748.

Walczak, R., Rovdan, E., Witkowska-Walczak, B., 2002. Water retention characteristics of peat and sand mixtures. Int. Agrophysics 16, 161-165.

Warsaw, A.L., Fernandez, R.T., Cregg, B.M., Andresen, J.A., 2009. Water conservation, growth, and water use efficiency of container grown woody ornamentals irrigated based on daily water use. HortSci. 44, 1308–1318.

Wright, A.N., Niemiera, A.X., Harris, R., Wright, R.D., 1999. Preplant lime and micronutrient amendments to pine bark affect growth of seedlings of nine container-grown tree species. HortSci. 34, 669-673.

Yu, S., Zinati, G.M., 2006. Physical and chemical changes in container media in response to bark substitution for peat. Comp. Sci Util.14, 222-230.

Zwak, J.A., Graves, W.R., Townsend, A.M., 1998. Leaf water relations and plant development of three Freeman maple cultivars subjected to drought. J. Am. Soc. Hort. Sci. 123, 371-375.

Figure captions

Fig. 1. Typical habit of Lonicera periclymenum 'Graham Thomas' (left), Cornus alba 'Elegantissima' (middle) and Forsythia × intermedia 'Lynwood' (right).

Fig. 2~~1~~. Variation between pots in water delivery, measured as weight gain of pots during an irrigation event (a), and in volumetric substrate moisture content (θ, b) during an experiment with deficit-irrigated Lonicera periclymenum 'Graham Thomas' (top) and Cornus alba 'Elegantissima' (bottom) under drip (shaded symbols) and overhead (open symbols) irrigation. Boxes indicate the 25^{th} to 75^{th} percentile range, whiskers extend another 15% either way, and outliers are represented by circles, n = 20. Application of 100% ET_A in (a) on that date would have equalled 165 mL irrigation. Data in (b) were obtained following 7 weeks of irrigation treatments.

Fig. 3~~2~~. Volumetric substrate moisture content (θ) in pots (a) and plant height (b) of Lonicera periclymenum 'Graham Thomas' (top) and Cornus alba 'Elegantissima' (bottom) measured at intervals in an experiment comparing full irrigation (circles) and deficit irrigation (50% ET_A – triangles – or 25% ET_A – squares), imposed via drip (closed symbols) or overhead (open symbols) irrigation. Data are means ± s.e., n = 10.

Fig. 4~~3~~. Volumetric substrate moisture content (θ) at the top (a) and bottom (b) of pots, and shoot (c) and root (d) dry mass of Lonicera periclymenum 'Graham Thomas' (top) and Cornus alba 'Elegantissima' (bottom) following 8 weeks of full or deficit irrigation (50% or 25% ET_A), applied via drip (closed symbols) or overhead (open symbols). Bars represent means ± s.e., n = 10. Within a single graph, different letters represent significant differences between means (LSD) at $P < 0.05$.

Fig. 5~~4~~. Volumetric substrate moisture content (θ, a) and increase in plant height (shown as the cumulative increase from the start of the experiment or after pruning) (b) during application of full (circles) or deficit (70% ET_A – triangles – or 50% ET_A – squares) irrigation, applied via drip (closed symbols) or overhead (open symbols) to Forsythia × intermedia 'Lynwood' grown in 100% peat (top) or a reduced peat substrate (bottom). Symbols represent means ± s.e., n = 16 before pruning and n = 10 following pruning.

~~**Fig. 5.** Appearance of Forsythia × intermedia 'Lynwood' that were pruned in June (left) or left un-pruned (right) and photographed in early October. In each photo, the plants on the left and centre were deficit irrigated, receiving irrigation to match 50% (left), or 70% (centre) of the ET_A of a fully watered crop, and the plant on the right received full irrigation. **COLOUR**~~

Fig. 6. Volumetric substrate moisture content (θ) at the top (a), middle (b) and bottom (c) of pots filled with 100% peat (top) or a reduced peat substrate (bottom), and in which Forsythia × intermedia 'Lynwood' was grown under full or deficit (70% or 50% ET_A) irrigation, applied via drip (closed columns) or overhead (open columns), measured in August, n = 5 pots. Asterisks denote significant differences between drip and overhead irrigation, as indicated by post-hoc tests (LSD) following ANOVA, $P < 0.05$.

Fig. 7. Final dry mass of shoots (a), and roots (b), and the ratio of root to shoot dry mass (c) of Forsythia × intermedia 'Lynwood' harvested in autumn, following full or deficit (70% or 50% ET_A) irrigation, applied with drip (closed bars) or overhead (open bars) irrigation. n = 10 plants (data are pooled over two substrates). Within a single graph, different letters represent significant differences between means (LSD) at $P < 0.05$, following a significant effect of irrigation quantity (a) and a significant interaction of irrigation quantity and system (b, c), according to ANOVA.

Fig. 8. Number of flowers produced on Forsythia × intermedia 'Lynwood' per length of stem (a) and per node (b), and average internode length (c) in the spring following application of full or deficit (70% or 50% ET_A) irrigation, applied with drip (closed bars) or overhead (open bars) irrigation. Data are means ± s.e., n = 10. Plants had been pruned in June. Within a single graph, different letters represent significant differences between means (LSD) at $P < 0.05$, following a significant effect of irrigation quantity, according to ANOVA.

Tables

Table 1

Final plant canopy width of Cornus alba 'Elegantissima' following eight weeks of full or deficit (50% or 25% ET_A) irrigation.

Irrigation quantity	**Irrigation system**	**Plant width (cm)**
Full	Drip	80.7 ± 2.6 e*
	Overhead	67.7 ± 2.1 d
50% ET_A	Drip	53.0 ± 0.9 c
	Overhead	46.1 ± 2.4 b
25% ET_A	Drip	45.7 ± 1.5 b
	Overhead	32.1 ± 1.2 a

* Data are means ± s.e.; means with different letters differ significantly, $P < 0.05$, LSD following ANOVA. Plant width is the average of the width at the widest point in the canopy and the width perpendicular to that measurement.

Table 2

Coefficients of variation (%)[a] of volumetric substrate moisture content in different layers of two types of substrate (100% peat or reduced peat) under two irrigation systems (drip or overhead) and three different quantities of irrigation (full or deficit – 70% or 50% ET_A) to Forsythia.

Quantity	**System**	**Substrate (% peat)**	**Layer of substrate**		
			Top	**Middle**	**Bottom**
Full	Drip	100%	14.2 ± 3.2	10.5 ± 2.5	11.0 ± 1.5
		Reduced	13.0 ± 2.8	9.7 ± 1.8	8.5 ± 1.1
Full	Overhead	100%	8.9 ± 1.0	6.5 ± 1.4	5.3 ± 0.9
		Reduced	10.2 ± 2.6	9.5 ± 2.4	9.7 ± 2.4
70%	Drip	100%	56.9 ± 12.2	16.7 ± 3.1	9.3 ± 2.7
		Reduced	58.7 ± 3.9	15.9 ± 1.6	5.3 ± 1.0
70%	Overhead	100%	13.0 ± 1.5	10.2 ± 1.6	5.2 ± 0.7
		Reduced	9.4 ± 2.0	7.2 ± 1.7	9.9 ± 2.7
50%	Drip	100%	73.7 ± 6.4	33.3 ± 3.0	16.9 ± 4.0
		Reduced	66.3 ± 8.4	33.4 ± 6.7	16.7 ± 3.1
50%	Overhead	100%	13.4 ± 2.9	9.9 ± 2.9	6.7 ± 1.0
		Reduced	16.0 ± 2.7	12.8 ± 3.0	8.7 ± 2.5

[a] Coefficients were calculated from four measurements per layer per pot. Coefficients shown are means of 5 pots per irrigation quantity × irrigation system × substrate ± s.e.

Figure 1
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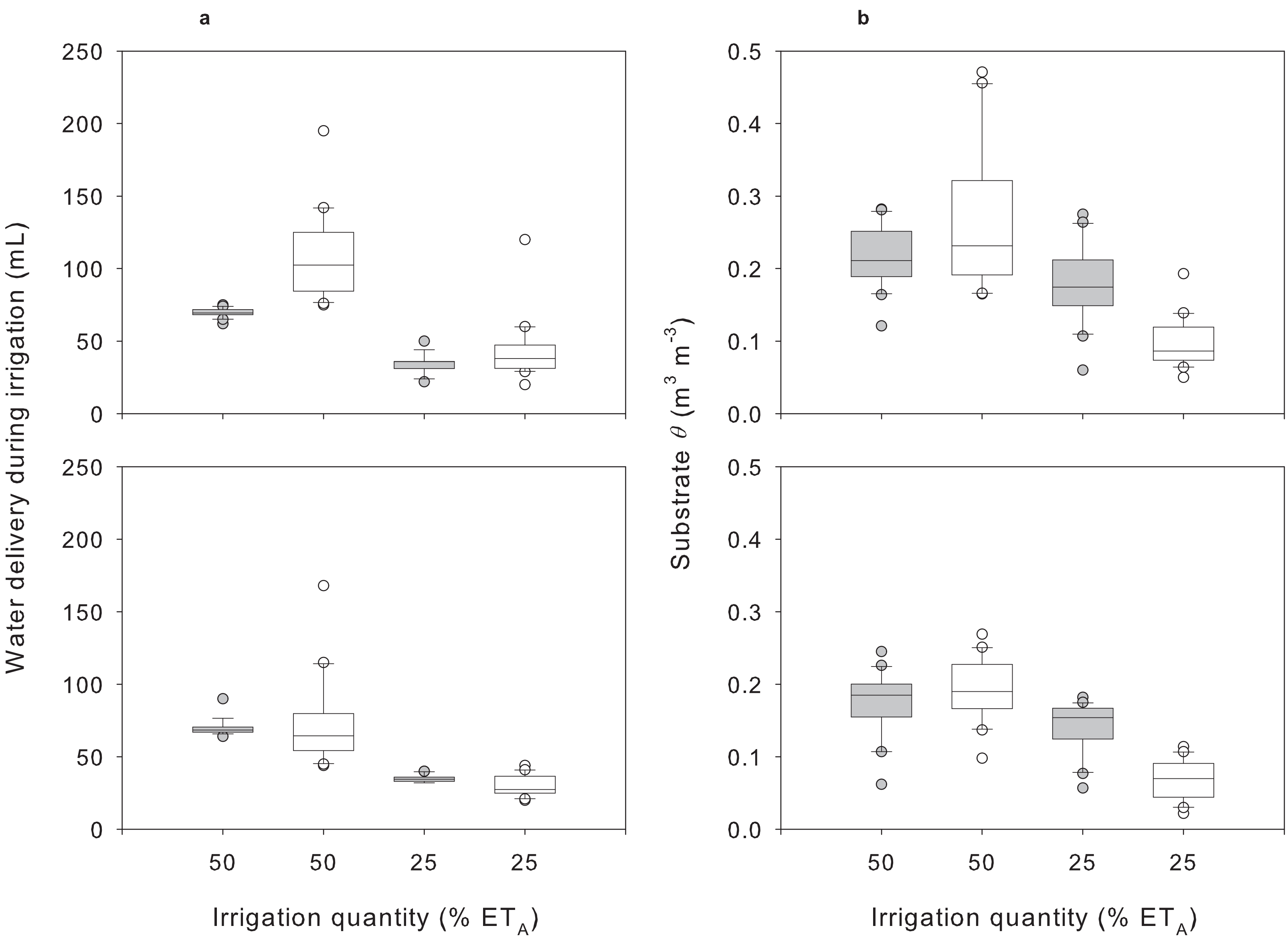
Figure 2



a
b
Water delivery during irrigation (mL)
Substrate θ (m³ m⁻³)
250
200
150
100
50
0
0.5
0.4
0.3
0.2
0.1
0.0
50
50
25
25
Irrigation quantity (% ET_A)
Irrigation quantity (% ET_A)

Figure 3

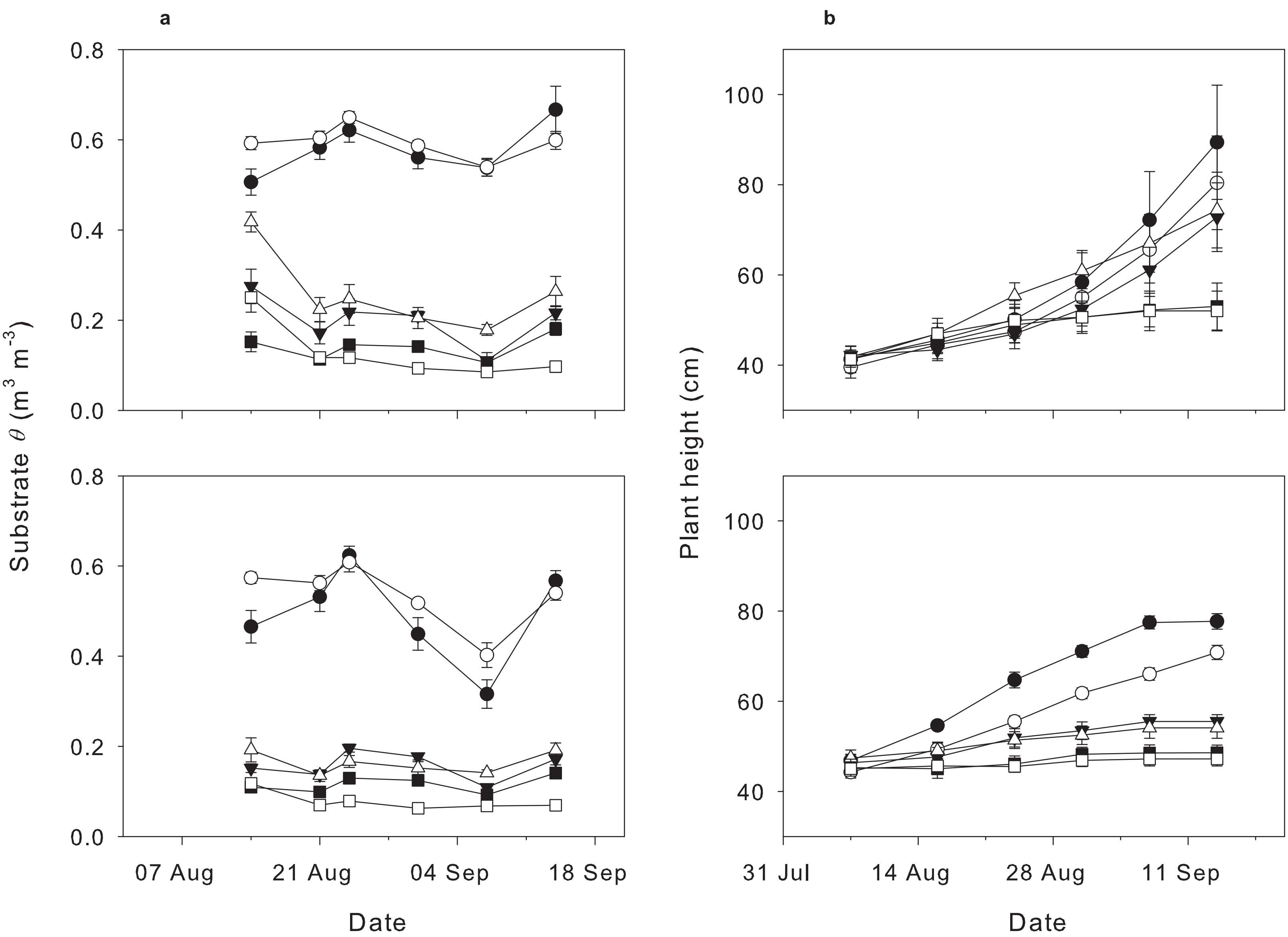
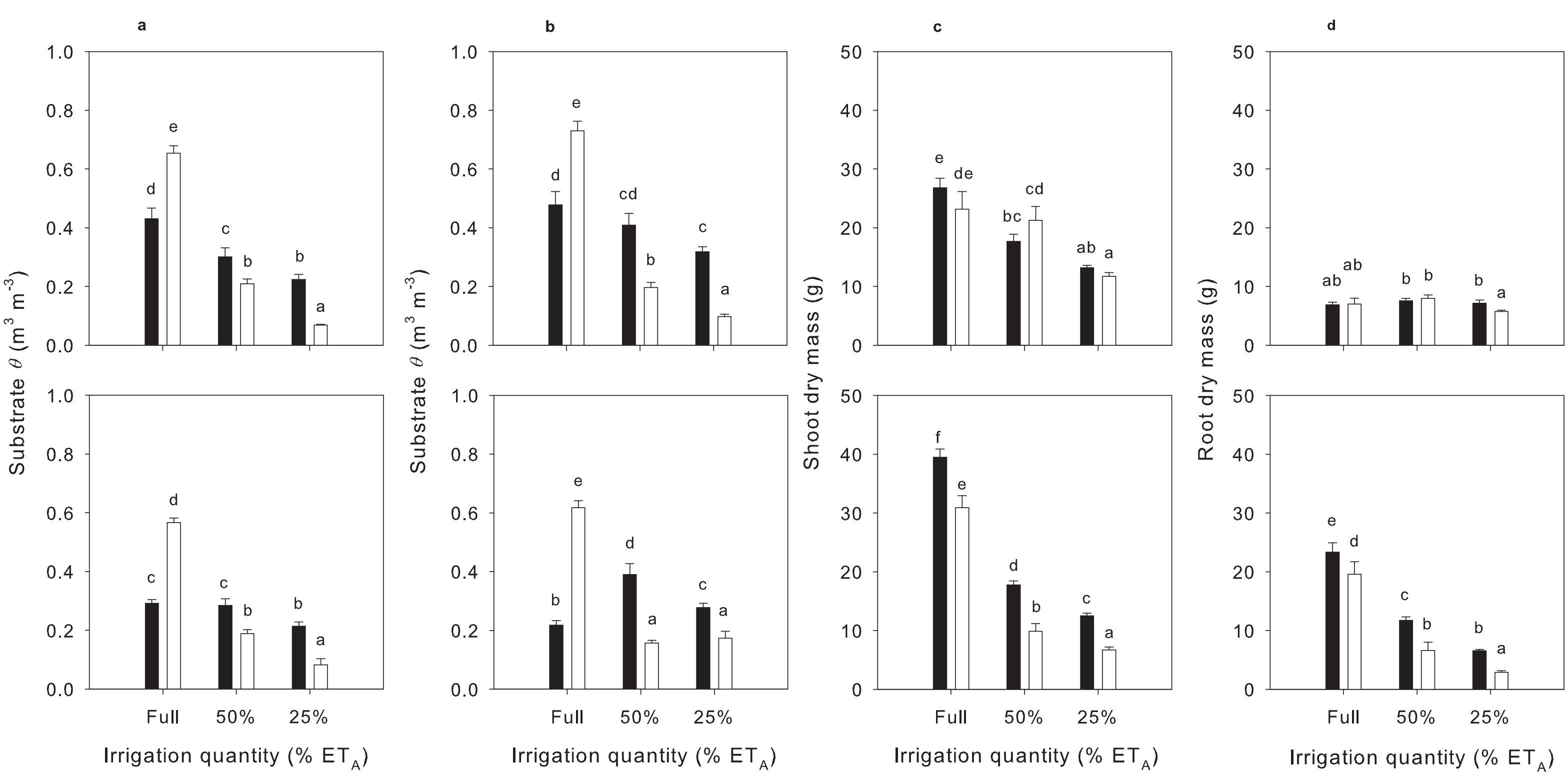

a
b
0.8
0.6
0.4
0.2
0.0
Substrate θ (m³ m⁻³)
07 Aug
21 Aug
04 Sep
18 Sep
Date
100
80
60
40
Plant height (cm)
31 Jul
14 Aug
28 Aug
11 Sep
Date

Figure 4



a
b
c
d
Substrate θ (m³ m⁻³)
Shoot dry mass (g)
Root dry mass (g)
Full
50%
25%
Irrigation quantity (% ET_A)

Figure 5

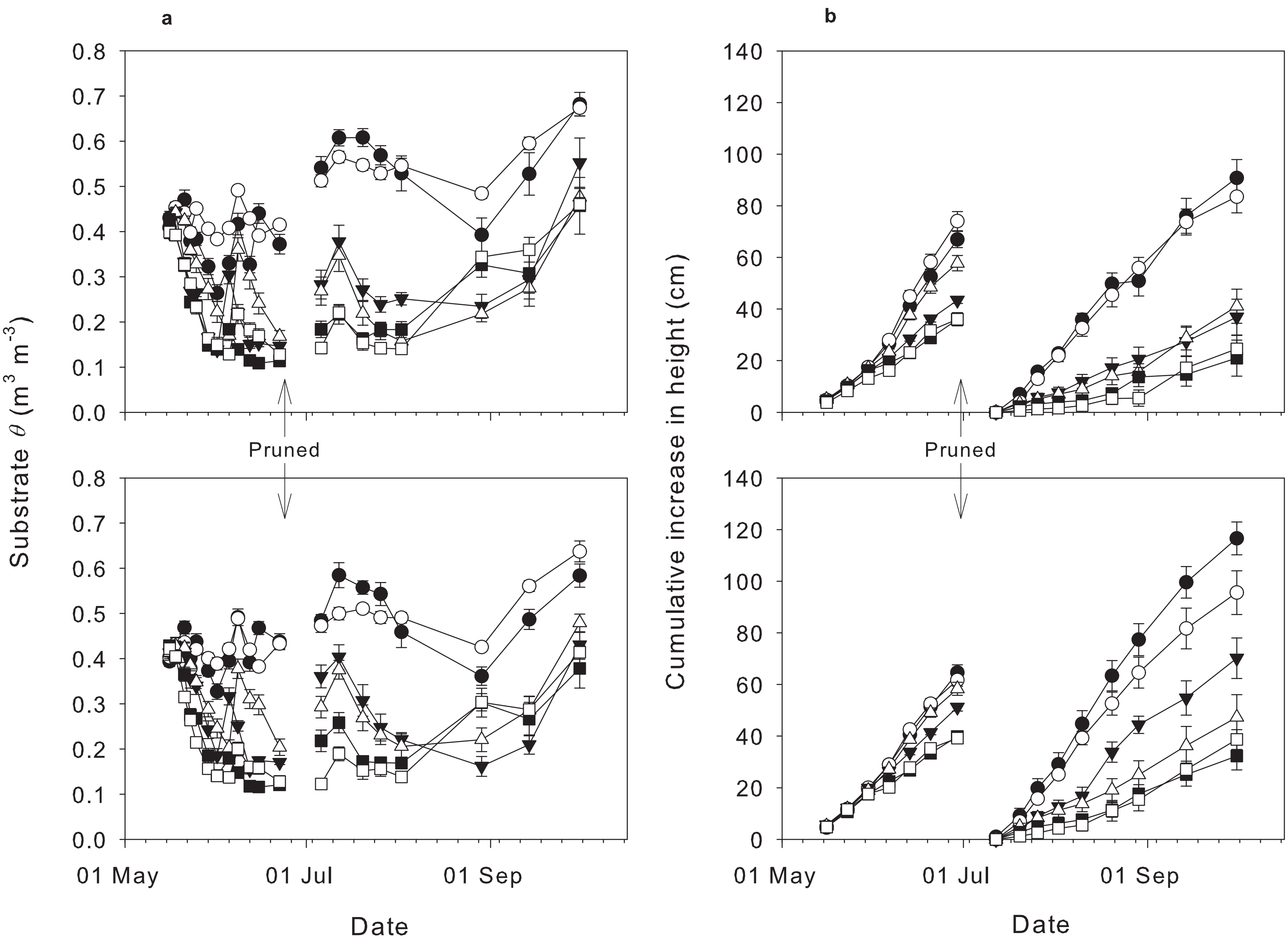
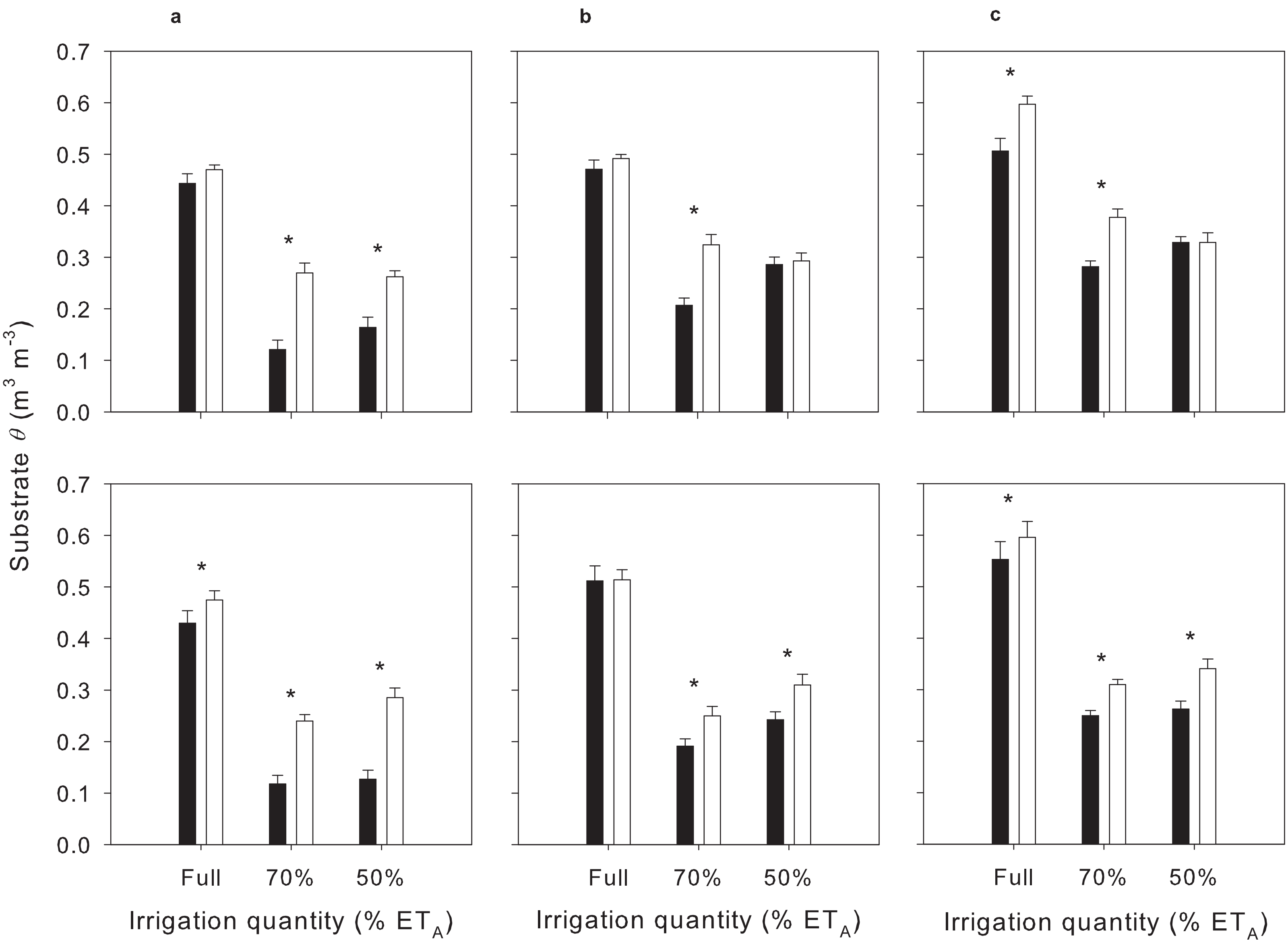

a
b
Substrate θ (m³ m⁻³)
Cumulative increase in height (cm)
Pruned
Pruned
01 May
01 Jul
01 Sep
Date
Date
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
20
40
60
80
100
120
140

Figure 6



a
b
c
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Substrate θ (m³ m⁻³)
*
Full
70%
50%
Irrigation quantity (% ET_A)

Figure 7

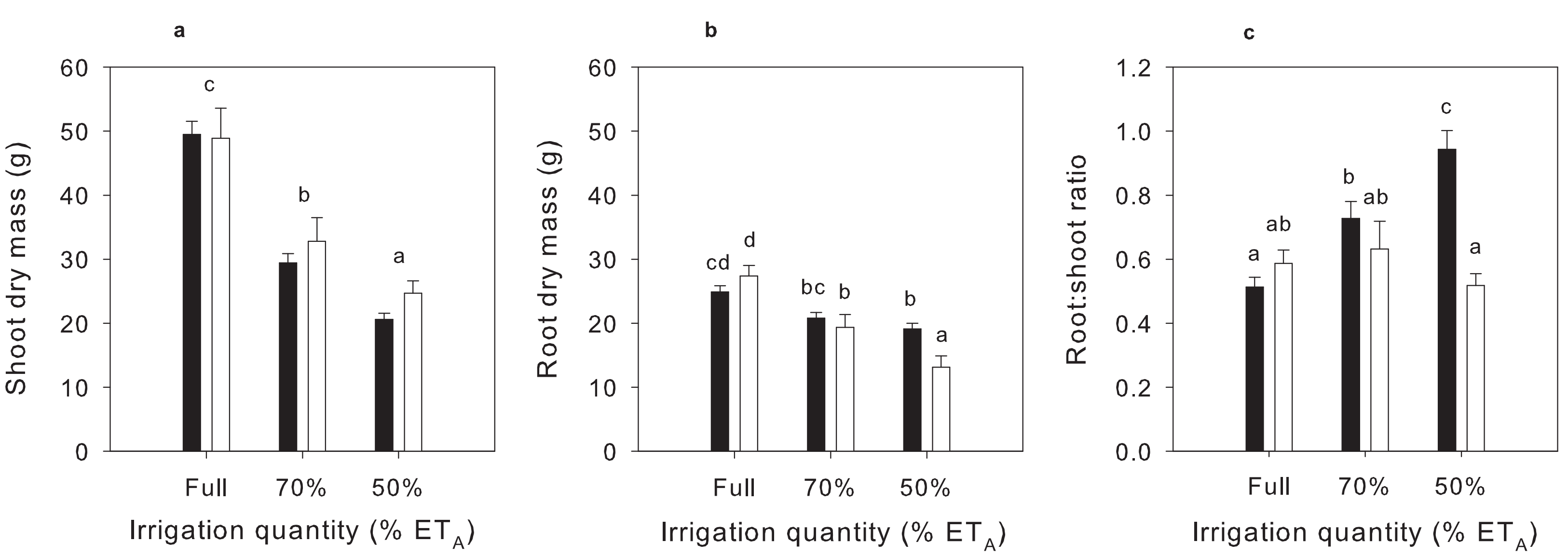
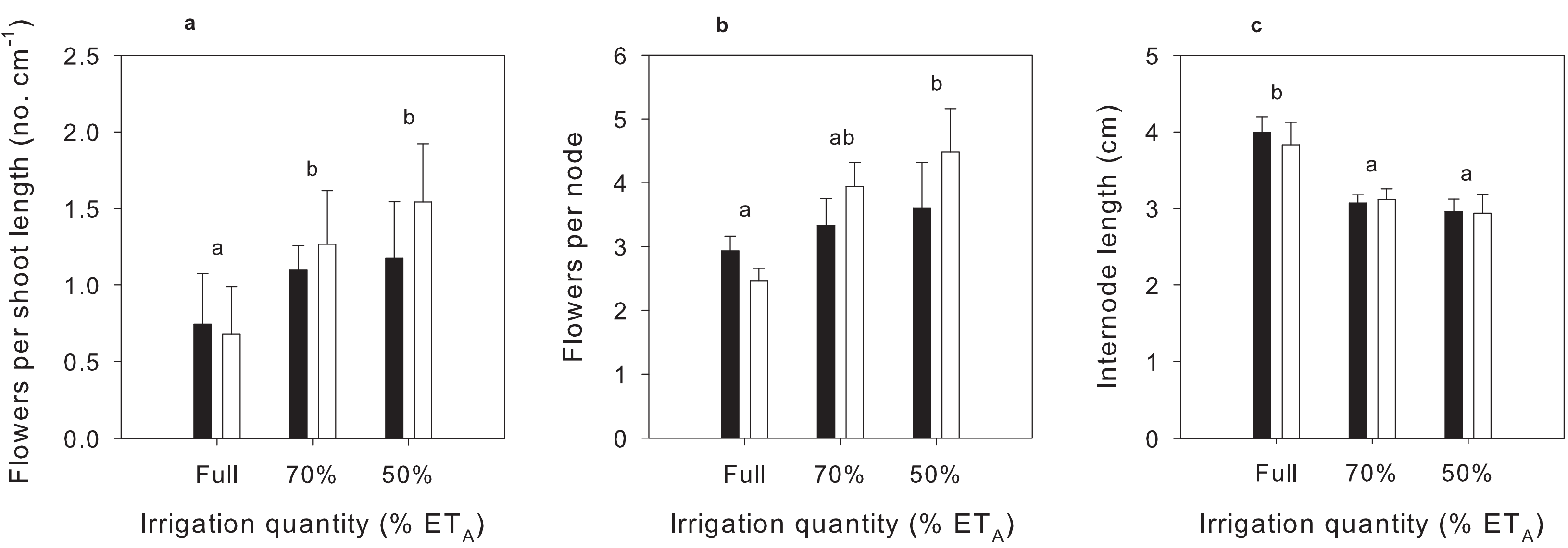

a
Shoot dry mass (g)
60
50
40
30
20
10
0
c
b
a
Full
70%
50%
Irrigation quantity (% ET_A)
b
Root dry mass (g)
60
50
40
30
20
10
0
cd
d
bc
b
b
a
Full
70%
50%
Irrigation quantity (% ET_A)
c
Root:shoot ratio
1.2
1.0
0.8
0.6
0.4
0.2
0.0
a
ab
b
ab
c
a
Full
70%
50%
Irrigation quantity (% ET_A)

Figure 8



a
Flowers per shoot length (no. cm^{-1})
0.0
0.5
1.0
1.5
2.0
2.5
a
b
b
Full
70%
50%
Irrigation quantity (% ET_A)
b
Flowers per node
0
1
2
3
4
5
6
a
ab
b
Full
70%
50%
Irrigation quantity (% ET_A)
c
Internode length (cm)
0
1
2
3
4
5
b
a
a
Full
70%
50%
Irrigation quantity (% ET_A)

Figure 1

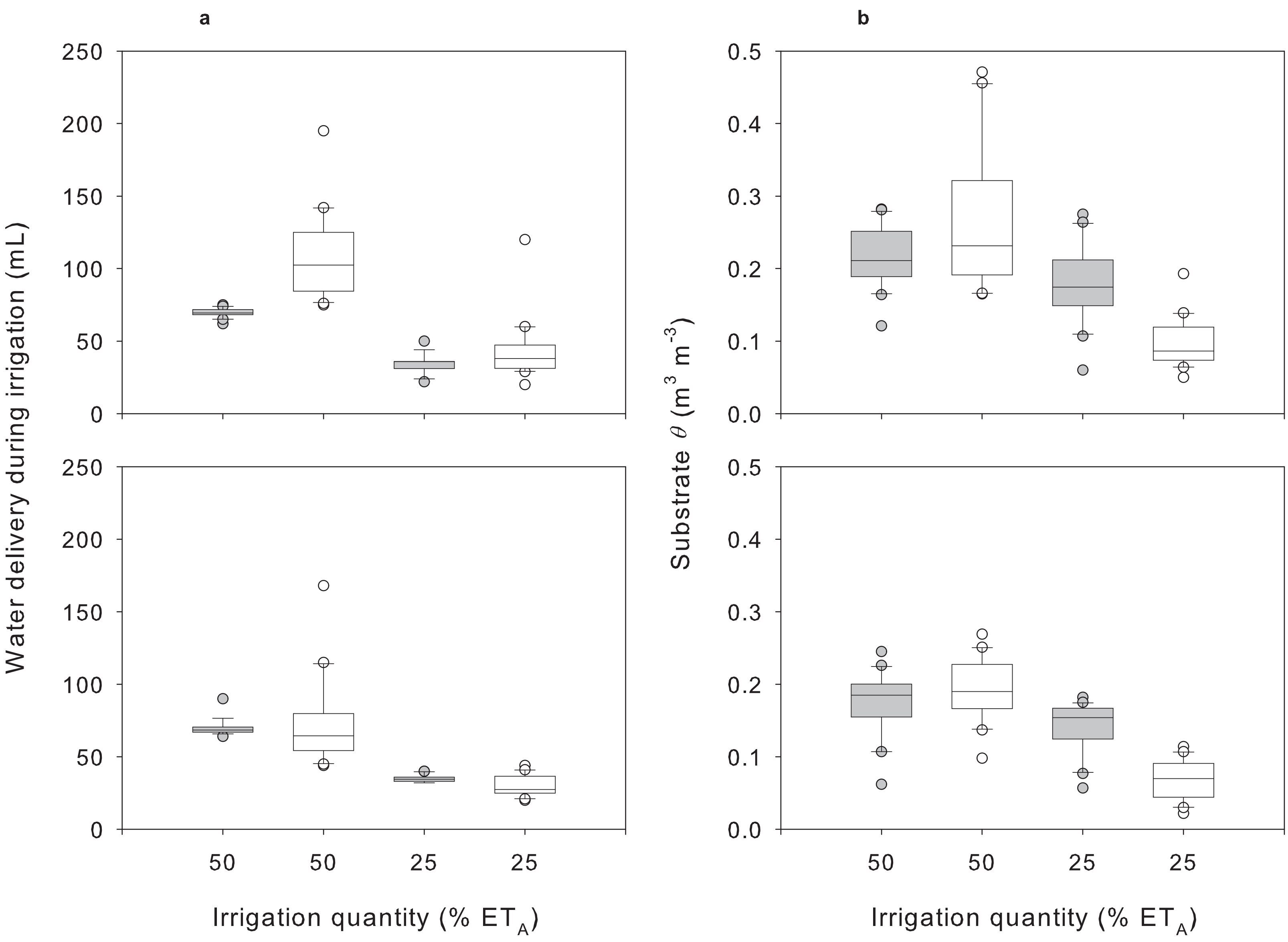

a
b
Water delivery during irrigation (mL)
Substrate θ (m3 m-3)
Irrigation quantity (% ETA)
Irrigation quantity (% ETA)
50
50
25
25
50
50
25
25
0
50
100
150
200
250
0.0
0.1
0.2
0.3
0.4
0.5

Figure 3

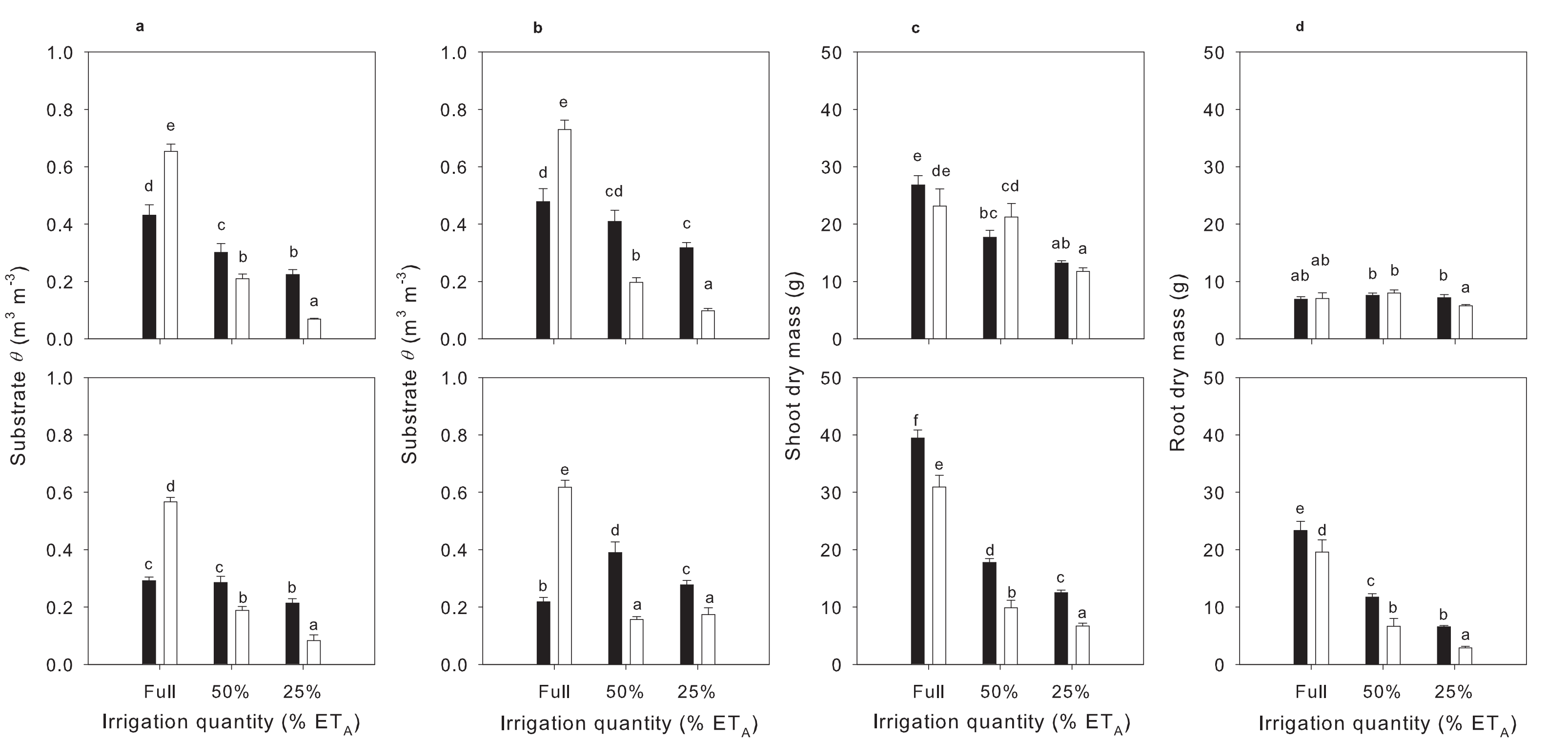

a
b
c
d
Substrate θ (m³ m⁻³)
Shoot dry mass (g)
Root dry mass (g)
Full
50%
25%
Irrigation quantity (% ET_A)

Figure 5
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Application of deficit irrigation to container-grown hardy ornamental nursery stock via overhead irrigation, compared to drip irrigation

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Keywords:
Container production
Irrigation scheduling
Irrigation systems
Peat alternatives
Plant growth management
Resource use efficiency

ABSTRACT

Growth control of container-grown hardy nursery stock generally requires substantial labour investment. Therefore the possibility of alternative growth control using deficit irrigation is appealing. Increasing water costs and limited availability of abstraction licences have added further incentives for nursery stock producers to use deficit irrigation. There are still, however, concerns that inherent non-uniformity of water uptake under commonly used overhead irrigation, and differing irrigation requirements of diverse crops and substrates, may limit the commercial relevance of a protocol developed for single crops growing in 100% peat and irrigated with a high precision drip system. The aim of this research was to determine whether growth control of hardy nursery stock is possible using deficit irrigation applied with conventional overhead irrigation. Over two years, crop growth under an overhead irrigation system was compared under full irrigation and two severities of deficit irrigation. Initially, two crops of contrasting canopy structure i.e. Cornus alba and Lonicera periclymenum were grown. In a subsequent experiment one crop (Forsythia × intermedia) was grown in two substrates with contrasting quantities of peat (60 and 100%). Deficit irrigation was found to be highly effective in controlling vegetative growth when applied using overhead irrigation – with similar results as when drip irrigation was used. This comparable response suggests that deficit irrigation can be applied without precision drip irrigation. Scheduling two very different crops with respect to their water use and uptake potential, however, highlighted challenges with respect to application of appropriate deficits for very different crops under one system; responses to deficit irrigation will be more consistent where nursery management allows for scheduling of crops with very different architecture and water use under different regimes. The effectiveness of deficit irrigation in controlling the growth of Forsythia was similar when a reduced peat based substrate was compared with pure peat; additionally, flowering was enhanced.

1. Introduction

Future global irrigation management will require users to look for methods of application which are efficient (Bacci et al., 2008; Kim et al., 2011; Majsztrik et al., 2011; Lea-Cox et al., 2013). For example, metrics such as water use and water productivity (Fereres and Soriano, 2006) may be required to justify irrigation practices. The use of deficit irrigation not only provides the means by which water use can be reduced and its use efficiency enhanced, but also enables crop growth and quality to be controlled (Jensen et al., 2010; Cirillo et al., 2014). Deficit irrigation is the application of less water than a crop would lose by evapotranspiration if water availability was not limiting (Fereres et al., 2003). However, for deficit irrigation to be effective requires understanding crop growth patterns, and some commentators suggest that use of advanced irrigations systems is also essential (Evans and Sadler, 2008; O'Meara et al., 2013). Deficit irrigation is applied either as sustained deficit irrigation i.e. by systematically applying water at a constant fraction of potential evapotranspiration through the season, or as regulated deficit irrigation, in which case soil moisture deficits are imposed only at certain plant developmental stages (Costa et al., 2007).

The primary challenges in the development of effective application of deficit irrigation to control growth and quality in container grown crops, such as hardy nursery stock, are a multitude of species and cultivars with different water requirements, and sensitivities to deficit irrigation, combined with a general absence of economic justification for the use of sophisticated precision irrigation systems (Kim et al., 2011; Majsztrik et al., 2011). There are examples, however, where economic assessment reveals apparently good initial savings and returns from investment in irrigation automation (Majsztrik et al., 2011; Belayneh et al., 2013). The successful application of deficit irrigation in hardy nursery stock production offers environmental and economic benefits, such as reduced container leaching of nutrients and pesticides and a reduction in fertiliser and pesticide costs associated with wastage (Caron et al., 1998). This combination of economic with environmental benefits has been recently highlighted (Levidow et al., 2014) as critical if producers are to take up opportunities for improved water management. Other benefits may arise from nursery production of more robust plants when subjected to environmental stresses, such as drought (Cameron et al. 2008). Some studies have now begun to elucidate the mechanisms by which deficit irrigation approaches achieve these ‘carry-over’ effects in the container crop production cycle (Sanchez-Blanco et al., 2004; Bañón et al., 2006; Cameron et al., 2006; Franco et al., 2006).

HNS production approaches are economically constricted by the need for mass production to consistently high crop quality (Warsaw et al., 2009). Despite retailer requirements for producers to meet precise crop-specific quality criteria (Álvarez et al., 2009; Majsztrik et al., 2011), retail margins often mean that investment in sophisticated irrigation approaches is not easily justified. Despite the high labour costs in nurseries’ budgets, at least in UK, Dutch, and Irish production (Thorne et al., 2002), and the potential for deficit irrigation to remove or reduce the need for costly operations such as manual pruning (Cameron et al., 1999), there is still a lack of commercial confidence in the application of the approach (Kim et al., 2011). There are a number of questions which need answering before widespread uptake of deficit irrigation for container production is likely (Belayneh et al., 2013).

One of the concerns with respect to commercial application of deficit irrigation is whether approaches developed for high precision drip irrigation can be adapted for extensive commercial practice, which still relies heavily on overhead irrigation (Briercliffe et al., 2000; Pettitt 2014). The drawbacks of overhead irrigation are well described and for hardy nursery stock focus on a lack of spatial uniformity of irrigation supply meeting crop water ‘demand’; this may have considerable implications for crop uniformity when deficit irrigation reduces container substrate water availability (Beeson and Knox, 1991; Beeson and Yeager, 2003; Grant et al., 2011). Related to the use of overhead irrigation is the tendency to grow several crops under one system. Differences in water use and uptake amongst species may mean that a deficit appropriate for one crop is detrimental for another.

The capacity of the container substrate to sustain the applied deficit irrigation regime must also be considered. Most commercial experience lies with the use of pure peat, but continued reliance on pure peat production is not sustainable (Barkham, 1993; Chapman et al., 2003; Alexander et al., 2008). Substrate producers are therefore looking into alternative media, at least to reduce, if not completely replace, peat consumption (Alexander et al., 2008). Changing the constituents in growing media, however, frequently alters the water holding capacity of the substrate (Yu and Zinati, 2006).

The aim of this research was to provide a more robust evaluation of the challenges involved in using deficit irrigation for commercial practice; here we investigate the impact of irrigation system (overhead vs. drip), crop type, and growing media (alternative vs. pure peat).

2. Materials and methods

2.1. Plant material and the growing environment

Lonicera periclymenum 'Graham Thomas', Cornus alba 'Elegantissima', and Forsythia × intermedia, cultivar 'Lynwood' were purchased as liners (New Place Nurseries Ltd, Pulborough, UK) and transferred to 2 L pots. Limestone (1.5 kg m^{-3}) and controlled release fertiliser [Osmocote Plus Spring (15+9+11+2 MgO + trace elements), 6 kg m^{-3}] were incorporated into the substrate. Vigorous growth is characteristic of all the cultivars selected. L. periclymenum, a climber, was supported with pot canes. The typical habit of the three cultivars is shown in Fig. 1.

The experiments were conducted in a closed plastic tunnel, to prevent rainfall and strong winds interfering with irrigation treatments (side ventilation panels were opened as required to avoid over-heating). The standing surface was a thick, rolled (to provide a level surface) layer of course gravel covered with woven polypropylene fabric (MyPex, Monro Horticulture, Maidstone, UK). The tunnel was divided into six separate bays (5 m × 2.4 m ground area) using sheets of polythene to contain the overhead irrigation spray within the application bay. The plastic sheets were suspended above drain gutters, which prevented the irrigation spray contacting the MyPex. Pots were arranged, at a spacing of 25 × 25 cm, in rows of 18 plants, with the outer rows in each bay acting as guard plants.

2.2. Irrigation systems and scheduling

Irrigation was scheduled to replace a predetermined percentage of the potential crop evapotranspiration (i.e. the actual evapotranspiration, ET_A, if water availability was not limiting). Two different deficit irrigation treatments were applied each year, in comparison with a full irrigation treatment, with two bays used for each treatment;

treatments were allocated randomly to the different bays. In the case of full irrigation, 150% ET_A was applied to ensure that even if irrigation delivery was non-uniform, all plants would receive at least 100% ET_A. Excess water ran through the pot bases, and drained freely through the MyPex and the gravel beneath, showing no signs of ground surface accumulation. High quality mains supply water was used for irrigation.

Drip irrigation was applied via 2 L h^{-1} drippers (Netafim C.N.L. Junior Drippers, Access Irrigation, Northampton, UK), with one dripper per pot. Dripper output was quantified and drippers were replaced as necessary to achieve maximal uniformity across all drippers. Overhead irrigation was applied using six 50 L h^{-1} Eindor 861 sprinklers (Access Irrigation, Northampton, UK) per bay arranged at distances of 2.25 m between sprinklers along the bay and across the bay at 1.5 m between the central pair and 1.2 m between the other two pairs. This arrangement was shown to have the highest uniformity of application as determined by measuring Christiansen's coefficient of uniformity (Christiansen, 1942) for several different arrangements. Irrigation outputs for both the overhead and drip irrigation systems were measured before the experiment and after, to determine any degradation during use. Mean application rate and scheduling coefficient were calculated for each bay. The scheduling coefficient is the (mean application rate)/(minimum application rate), where mean reflects the measurements made over the entire bed and minimum refers to the area of the bed that received the lowest application (see Grant et al., 2009). Water delivery to pots was also frequently measured by weight gain during an irrigation event.

ET_A was determined every two weeks by weighing plants in the full irrigation treatments after irrigation (after allowing for pot gravity draining, and water intercepted by the canopy to run off) and again a day later. Wet leaf temperature depression was determined simultaneously with a sensor (Evaposensor, Skye, Powys, UK) located in the crop. The sensor continuously measures temperature differences between wet and dry artificial leaves (Harrison-Murray, 1991), with the accumulated difference recorded and logged via a dedicated meter (Evapometer, Skye), as °C h, where 1°C h equates to a difference of 1°C for a duration of 1 h. Thus, for example, if a plant uses 100 mL water during an accumulation of 100°C h, this plant will require 1 mL of irrigation for every 1°C h accumulated, if the intention is to apply 100% of ET_A. Combining water use per °C h with the time required to apply the determined irrigation volume (the measured scheduling coefficient of each system) computes the length of the irrigation event to replace 1°C h. This value can then be multiplied by the appropriate ET_A percentage depending on treatment. The result was then multiplied by the daily accumulated °C h over the previous 24 h to determine the irrigation requirement that day. This duration was then programmed into an irrigation timer (Heron Electric Company Limited, Ford, Nr. Arundel, UK), to trigger morning irrigation to each bay. For a more complete description of Evaposenor use see Grant et al. (2009) or Grant (2012).

2.3. A single species scheduling approach applied to crops of contrasting canopy structure

Lonicera and Cornus growing in 100% sphagnum peat (Shamrock Premium Grade, Bord na Móna, Newbridge, Co. Kildare, Ireland) were compared in year 1 (2006). This peat consists of particles up to 14 mm, including 50% in the range 6-12 mm, and has an approximate air filled porosity of 12% and electrical conductivity < 1 mS cm^{-1}. Plants were arranged in five rows per bay, with Lonicera on one half of the bed and Cornus on the other, providing 21 experimental plants of each species, which were fully guarded. The deficit irrigation treatments applied were 50% ET_A and 25% ET_A i.e. crops were irrigated to replace 50% or 25% of water used by the fully irrigated plants. These two deficit irrigation treatments were selected to represent a deficit of sufficient severity to have a noticeable impact on growth (50%), and a very severe deficit that might risk reducing plant quality (25%). Results from the two different severities would thus be expected to provide a guideline for a range appropriate for use on nurseries. Irrigation for both the crops was scheduled on the basis of crop factors obtained for Lonicera. The reasoning for this is that different crops are often grown together on single beds, and with overhead irrigation will inevitably be irrigated by the same amount. Treatments were applied from the start of August, for eight weeks. During this time, daily mean air temperature in the tunnel was on average 21.4°C, ranging from 16.3°C to 24.9°C. Relative humidity was on average 82.9%. Average mean and maximum daytime global radiation were 188 and 455 W m^{-2}, respectively, with the maximum global radiation reached equalling 655

W m^{-2}. Meteorological data were recorded from sensors integrated with a data-logger (Datahog, Skye Instruments Ltd., Powys, UK).

2.4. Comparison of substrates

100% peat (as above) was compared with a reduced peat mix [60% peat: 40% bark (Melcourt Potting bark, Melcourt Industries Ltd., Tetbury, Gloucestershire, UK)]. Particles in the selected bark are predominantly in the range 3-15 mm, and its air filled porosity is approximately 62%, with an electrical conductivity of about 0.1 mS cm^{-1}. For the reduced peat mix, 1 g ammonium nitrate per L of bark was incorporated to compensate for the low nitrogen availability in bark (see recommendation by Wright et al., 1999). The two substrate treatments were replicated randomly in each bay. Plants of Forsythia were arranged in four rows per bay and DI treatments of 70% and 50% ET_A applied. These treatments were selected following analysis of the first experiment, with the 70% ET_A representing a mild deficit – potentially the smallest reduction in water supply likely to show a significant reduction in growth. Crop evapotranspiration of Forsythia in 100% peat and in the reduced peat mix was similar, and therefore crop factors for irrigation scheduling were based on average crop ET_A (measured by pot weighing as above) across both substrates.

Irrigation treatments were applied from mid-May 2007. At the end of June, 10 plants per irrigation treatment (% ET_A), per irrigation system (drip vs. overhead), per substrate (100% peat vs. reduced peat mix) were pruned to a height of 20-30 cm (as is commercial practice). Four plants per irrigation treatment × irrigation system × substrate were kept un-pruned. For one week in mid-August, plants in the 50% ET_A treatments were given 70% ET_A irrigation, to encourage bud-break and shoot growth, which was previously limited. At the end of August, the numbers of buds breaking per pot from pruned branches was counted. Final heights and widths of all plants were measured in mid-September. Meteorological data are not available for inside the tunnel during this experiment. External air temperature and relative humidity averaged 17.2°C and 76.9% during the same duration (Grant et al., 2011). Average mean and maximum daytime global radiation recorded nearby at the East Malling Water Centre were 505 and 960 W m^{-2}, respectively. Radiation in the tunnel would be expected to be considerably lower, with higher air temperature and humidity.

2.5. Substrate moisture content

Substrate volumetric moisture content (θ) was measured 6 cm deep from the top of each pot for all experimental plants every week using a soil moisture sensor (SM200 and HH2 meter, Delta-T Devices, Cambridge, UK). At the end of the experiments, substrate volumetric moisture content was also measured 6 cm from the base of the pot (inserting the probe at the base). In the substrate comparison experiment, volumetric moisture content was also measured in the middle of pots (by inserting the probe from the sides). The variability in volumetric moisture content within pots at different depths was determined from measurements taken in four horizontal locations per pot at the top and half-way down the pot. Calibration curves were produced for the substrates used (measuring wet and dry substrate, and determining water content gravimetrically, following the SM200 sensor manual), and the voltage output, used with the resulting calibration coefficients to obtain substrate volumetric moisture content as volume of water per volume of substrate.

2.6. Plant growth, biomass allocation, and flowering

Heights of all plants were measured weekly, while for Cornus and Forsythia, final leaf canopy width was calculated from two perpendicular measurements at the canopy's widest point. At the end of experiments, half of the experimental plants were harvested and the shoots separated from the root system, the latter washed and both oven dried at 80°C for 48 h. Root and shoot dry masses were obtained, and root:shoot ratios calculated. Remaining plants were over-wintered, for flowering assessment in spring. At around 80% full bloom, numbers of flowers and numbers of internodes on a selected shoot of average length on each plant were counted, and the length of all shoots measured, allowing calculation of numbers of flowers per cm shoot length, numbers of flowers per node, and internode length.

2.7. Statistical analysis

The significance of treatment differences was assessed by analysis of variance (ANOVA), followed by LSD tests where appropriate, in Genstat software (Genstat 9.1, Rothamsted Experimental Station, UK). A repeated measures ANOVA was used where variables were measured repeatedly on the same individual plants or pots.

3. Results

3.1. A single species scheduling approach applied to crops of contrasting canopy structure

The overhead sprinkler arrangement achieved a Christiansen's coefficient of uniformity of 91%, a scheduling coefficient of 1.2, and a mean application rate of 7.7 mm per hour. Drip irrigation resulted in a Christiansen's coefficient of uniformity of 96-98% and a scheduling coefficient of 1.0 to 1.1. While there was evidence during irrigation that pot weight gain was less homogenous under overhead compared to drip irrigation (example in Fig. 2a), variation in substrate volumetric moisture content was not consistently greater under overhead irrigation (example in Fig. 2b). Measurements of water uptake indicated that Cornus under overhead irrigation took up less water than Lonicera (Fig. 2a), while water uptake with drip was similar for both crops.

Evapotranspiration of the fully irrigated Lonicera crop during the first experiment was on average 2.2 mm day^{-1}, while that of Cornus was 3.2 mm day^{-1}, accumulating to 133 and 195 mm respectively during the course of the experiment. Daily averages of 4.4, 1.1, and 0.5 mm day^{-1} irrigation were applied to the full, 50% ET_A and 25% ET_A treatments, respectively. It is important to note, however, that irrigation was adjusted on a daily basis according to the accumulated wet leaf temperature depression for the previous 24 h, to allow for fluctuating weather, as opposed to applying these average values throughout the experiment. In total over the experiment, 267 mm irrigation was applied to the fully irrigated crop, and 67 and 33 mm to the milder and more severe deficit treatments, respectively.

Over the course of the experiment, deficit irrigation significantly ($P < 0.05$) reduced substrate volumetric moisture content (Fig. 3a), on average, across all pots, and resulted in reduced growth (Fig. 3b). For both Lonicera and Cornus, there was an interaction between irrigation quantity (% ET_A) and method of application on substrate volumetric moisture content ($P < 0.001$). For Lonicera, there was no difference between drip and overhead irrigation with respect to plant growth over the experiment (Fig. 3b). For Cornus, there was an interaction of irrigation system and % ET_A applied ($P = 0.003$) over the experiment, resulting in final plant heights being reduced under overhead compared to drip irrigation when full irrigation was applied, but not when deficit irrigation was applied. Cornus plants showed wider leaf canopy diameters at the end of the experiment when drip irrigated compared to overhead, and reduced canopy diameters under deficit compared to full irrigation (both $P < 0.001$; Table 1).

At the end of the experiment, an interaction between irrigation system and % ET_A ($P < 0.001$) was detected on mean substrate volumetric moisture content, both at the top and at the bottom of the pot, for both species. Substrate volumetric moisture content was lower under overhead than drip irrigation for both deficit irrigation treatments. On the other hand, it was higher under overhead than drip irrigation when full irrigation was applied (Fig. 4a, b). For Lonicera, shoot dry mass was not significantly affected by the type of irrigation (drip vs. overhead) within a given % ET_A. However, there was a significant effect of % ET_A on plant mass ($P < 0.001$ for shoots and $P = 0.025$ for roots). Under drip irrigation both deficit treatments showed reduced shoot, but not root, dry mass, whereas under overhead irrigation only the more severe deficit reduced shoot dry mass (Fig. 4c, d). Root:shoot ratio decreased as % ET_A increased ($P < 0.001$, data not shown). For Cornus, both shoot dry mass and root dry mass were affected by % ET_A ($P < 0.001$), with increasing dry mass at the higher % ET_A (Fig. 4c, d). Both shoot and root mass was greater under drip irrigation compared to overhead ($P < 0.001$). Root:shoot ratio was affected by % ET_A ($P < 0.001$), with a lower root: shoot ratio under 25% ET_A than under the other two treatments (data not shown).

3.2. Comparison of substrates

During the second experiment, evapotranspiration of the fully irrigated crop was on average 3.2 mm day^{-1}, accumulating to 445 mm over the whole season. Thus daily averages of 4.9, 2.3, and 1.6 mm day^{-1} irrigation was applied to the full (150% ET_A), 70% ET_A and 50% ET_A treatments, respectively. As a result, over the entire growing season, 667 mm irrigation was applied to the fully irrigated crop, and 311 and 222 mm to the milder and more severe deficit treatments, respectively. Substrate volumetric moisture content was reduced by deficit irrigation throughout this experiment ($P < 0.001$) (Fig. 5a). A frequent but less consistent effect of irrigation system also occurred, but only occasionally were differences in substrate volumetric moisture content seen between the two types of substrate. Growth slowed in the 50% ET_A DI treatment from 14 days after treatments started ($P \leq 0.012$; Fig. 5b). Five weeks from the start of the experiment, an interaction with respect to cumulative plant height increment was seen between irrigation quantity and system ($P = 0.013$). Differences between treatments in shoot growth were reflected in the average mass of shoot material per plant obtained during pruning: 10–12 g for 50% ET_A, 12–18 g for 70% ET_A, and 22–24 g for full irrigation. Post-pruning bud break was significantly lower ($P < 0.001$) in the deficit irrigation treatments (around 7–9 bud breaks per plant) than in the full irrigation treatment (around 16 bud breaks per plant). After pruning, rapid growth was seen under full irrigation, with growth much reduced under deficit irrigation (Fig. 5b). From pruning onwards, there was no interaction between substrate and irrigation quantity or system, and no interaction between irrigation quantity and system i.e. reduced growth occurred with deficit irrigation using both drip and overhead and with both 100% peat and the reduced peat substrates. The combination of fewer bud breaks and reduced shoot elongation under deficit irrigation led to more compact plants. Growth was greater in the reduced peat substrate ($P < 0.001$).

Early in August, Forsythia plants were removed from their pots and variation in substrate volumetric moisture content determined. Coefficients of variation (100% × standard deviation/mean) between the four measurements per layer (top, middle, or bottom) of the substrate showed that greatest variation most frequently occurred at the top (Table 2). Variation within a substrate layer was generally much greater when DI was applied using drip irrigation rather than overhead. Variation was also generally greater for the more severe deficit. Generally across all pots, independently of whether full or deficit irrigation was applied, the substrate was drier in the top layer with both substrate types and both irrigation systems ($P < 0.001$, Fig. 6). Substrate volumetric moisture content tended to be greater using overhead irrigation compared to drip.

In autumn, shoot dry mass was affected only by % ET_A applied ($P < 0.001$, Fig. 7a), with shoot dry mass increasing with % ET_A. Root dry mass was also affected by the interaction of % ET_A with type of irrigation ($P = 0.02$, Fig. 7b). With overhead irrigation, root dry mass increased with increasing % ET_A, but this response was less clear with drip irrigation. Thus, when drip was used, compared to overhead irrigation, root dry mass was not as reduced by the more severe deficit relative to full irrigation. Root:shoot ratio was also affected by the interaction of % ET_A and type of irrigation ($P < 0.001$, Fig. 7c). The root:shoot ratio decreased with increasing % ET_A under drip irrigation, but this did not occur under overhead irrigation.

The following spring, number of flowers per unit shoot length was affected by the % ET_A applied ($P < 0.001$, Fig. 8a). The plants receiving full irrigation had approximately half the number of flowers per unit shoot length compared to those receiving 50% ET_A. The increased number of flowers over a given length of shoot in the deficit irrigation treatments was a result of an increased number of flowers per node ($P = 0.018$, Fig. 8b) and shorter internode lengths ($P < 0.001$, Fig. 8c).

4. Discussion

A reduction of substrate volumetric moisture content, in response to deficit irrigation, led to a reduction in the shoot growth of all the species used here, as it does with other species (Beeson 1992; Cameron et al. 1999; Grant et al. 2004; Chaves et al. 2007). This reduction is also known to influence a number of different growth variables, both above and below ground (Franco et al., 2006). In most previous research, however, deficit irrigation has been applied using a high-precision drip irrigation system. Our novel approach was to validate the potential of deficit irrigation to control growth through the utilisation of overhead irrigation – which is still an important and much used system in commercial ornamental plant production. Different irrigation systems are known to impact on plant dry matter production even when full irrigation is applied (Klock-Moore and Broschat, 2001), and deficit irrigation might accentuate such effects.

Here we show that irrespective of type of irrigation system used (drip or overhead) to apply deficit irrigation, reduced growth was apparent in response to a decline in substrate volumetric moisture content. The experiment with Cornus, however, showed that plant size was dependent on the irrigation system used, with reduced canopy diameter and biomass with overhead irrigation compared to drip. The reason Cornus grew less with overhead irrigation relates to this crop taking up less water than Lonicera. This response was visually apparent during irrigation events, where applied water was deflected by the Cornus canopy while the supported upright structure of Lonicera promoted water funnelling into the pots. Cornus growth was excessively reduced by the application of the severe deficit, highlighting the difficulty of scheduling deficit irrigation for different species using the same irrigation system. We strongly recommend that users grow crops together which have similar canopy architectural and structural attributes along with similar water uptake. Several factors not included here are known to exacerbate non-uniformity of overhead irrigation delivery (Li 1998; Grant 2012).

In addition to reducing plant growth, deficit irrigation impacted on plant quality. Forsythia subjected to deficit irrigation developed an increased number of flowers per node, and this increase in flowering density can provide a more aesthetically appealing plant at retail. Some caution is required with respect to differences in species sensitivity, tissue type, age at which flowers are initiated, and the timing of application of the deficit in relation to flower initiation. A study with Rhododendron showed that deficit application during flower induction (late summer) could reduce flower production (Cameron et al., 1999), although in general across a range of hardy nursery stock, the effects of deficit irrigation on flower production were small (Cameron et al., 2006).

The increased root:shoot ratio apparent for Forsythia as a result of deficit irrigation has important implications in the production of ‘robust’ plants which are able to establish rapidly when transplanted. This is particularly true for better establishment under semi-arid conditions (Franco et al., 2006). How this occurs, beyond improvement in the plant’s ability to capture water relative to that lost via transpiration, is likely to be species-specific. In Nerium oleander, for example, dehydration of the finer roots during transplanting is detrimental; deficit irrigation induces thick roots, which increase the potential for water storage, leading to better establishment of deficit irrigated plants (Bañón et al., 2006). In the current research with Forsythia, however, it should be noted that an increased root:shoot ratio as a result of deficit irrigation only occurred when irrigation was applied using a drip system. The reduction in root biomass using overhead irrigation compared to drip may have negative implications on transplanting and establishment. On the other hand, drip irrigation can result in localised abundant root production in relation to the dripper positioning in the container, where a high rooting density makes effective use of applied water, but will limit the rate at which roots exploit the soil on transplanting. The greater variation in volumetric moisture content within a layer shown here for drip compared to overhead irrigation highlights the potential for localised root formation under drip systems. Substrate types can also accentuate differences in water distribution: coarse textured substrates lack small pore spaces to promote capillary movement and water holding capacity (Klock-Moore and Broschat, 2001). Neither of the substrates used in this study, however, accentuated variation in volumetric moisture content compared to the other.

There was no interaction of irrigation quantity and substrate on final plant height, implying that deficit irrigation can be used to control growth in a reduced peat substrate, without any need to alter irrigation scheduling protocols developed for 100% peat. Reduced peat did not impact on root:shoot ratio, or variation within or between pots in substrate volumetric moisture content. This may reflect limited variation in water holding capacity between substrates with peat substitution from 40 to 70% (Caron et al., 1998). Yu and Zinati (2006) found that increasing the percentage of bark from 40% to 90% in parallel with a decreasing percentage of peat led to decreased substrate water holding capacity, from 63% to 49%. This difference is small and would be easily managed within a deficit irrigation strategy and would have little impact on its effectiveness with respect to growth control. Comparing two peat-sand mixes, at 10% volumetric substrate moisture content, Bunt (1976) reported a decrease in water tension of over 0.3 MPa for the 50:50 mix compared to the 75:25 mix, falling to a difference of only about 0.1 MPa at 20% volumetric moisture content. Walczak et al. (2002) found substantial reductions in water retention only when the peat content was far lower than in the current mixed substrate. Nonetheless, hydraulic conductivity should be determined for different substrates. Londra (2010) found considerable increases in hydraulic conductivity with the addition of perlite or coir over pure peat (1.32 cm min^{-1}). Hydraulic conductivity has been frequently assessed for pure peat (e.g. Walczak et al., 2002; Naasz et al., 2005; Londra, 2010), but given the wide range of alternative substrates, used in different proportions with peat, uncertainty remains regarding the hydraulic properties of specific substrate mixes.

The substrate-derived differences in growth seen here with Forsythia are likely to relate to nutritional differences. To compensate for an expected reduction in nitrogen availability when peat is partially substituted with bark (Wright et al., 1999), ammonium nitrate was added initially. This apparently overcompensated, with enhanced growth in the reduced peat substrate – which was seen under full as well as deficit irrigation. Variation in growth when using a diverse range of growing media is well documented (Guérin et al., 2001).

Currently it is not possible to predict exact % ET_A deficits to induce well-defined levels of growth control or increases in production quality across the wide range of species and cultivars in hardy nursery stock production. That innate differences in response to limited water availability exist between cultivars and species is well known (Zwack et al., 1998), and this variability interacts with factors such as variation in the growing environment (Evans and Sadler, 2008). Another challenge is how to easily determine the actual water input corresponding to the desired % ET_A (Fereres and Soriano, 2006): if entire crops are being deficit irrigated, fully irrigated plants may not be available for gravimetric calibration, as used in this current study. One solution would be through adjustment of scheduling coefficients on the basis of plant size (canopy area and hence transpiring area). Where the Evaposensor has been used to schedule (full) irrigation, this approach has been shown to be effective for diverse species (Grant et al., 2012). Alternatively, coefficients (K_c) can be estimated from variables such as plant height, to use with reference evapotranspiration (ET_o) calculated from meteorological variables (Incrocci et al., 2014).

5. Conclusions

Deficit irrigation applied by overhead irrigation can be used to control growth and quality of container grown crops as effectively as when applied by drip irrigation. Therefore effective deficit does not rely solely on more expensive and less frequently used drip irrigation. This conclusion should encourage commercial uptake of deficit irrigation. Addressing the challenge of identifying a deficit irrigation regime that is appropriate for specific cultivars and level of growth control will require more experimentation. Additionally, approaches to scheduling that can be easily applied commercially (e.g. monitoring evapotranspiration or substrate volumetric moisture content) merit further consideration.

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References

Alexander, P.D., Bragg, N.C., Meade, R., Padelopoulos, G., Watts, O., 2008. Peat in horticulture and conservation: the UK response to a changing world. Mires & Peat 3, article 8.

Álvarez, S., Navarro, A., Bañón, S., Sánchez-Blanco, M.J., 2009. Regulated deficit irrigation in potted Dianthus plants: Effects of severe and moderate water stress on growth and physiological responses. Sci. Hort. 122, 579-585.

Bacci, L., Battista, P., Rapi B., 2008. An integrated method for irrigation scheduling of potted plants. Sci. Hort. 116, 89–97.

Bañón, S., Ochoa, J., Franco, J.A., Alarcón, J.J., Sánchez-Blanco, M.J., 2006. Hardening of oldeander seedlings by deficit irrigation and low air humidity. Env. Exp. Bot. 56:36-43.

Barkham, J.P., 1993. For peat’s sake: conservation or exploitation? Biodiversity & Conservation 2, 556-566.

Beeson, R.C., 1992. Restricting overhead irrigation to dawn limits growth in container-grown woody ornamentals. HortSci. 27, 996-999.

Beeson, R.C. Jr., Knox, G.W., 1991. Analysis of efficiency of overhead irrigation in container production. HortSci. 26, 848-850.

Beeson, R.C. Jr., Yeager, T.H., 2003. Plant canopy affects sprinkler irrigation application efficiency of container-grown ornamentals. HortSci. 38, 1373-1377.

Belayneh, B.E., Lea-Cox, J.D., Lichtenber, E., 2013. Costs and benefits of implementing sensor-controlled irrigation in a commercial pot-in-pot container nursery. HortTech. 23, 760-769.

Briercliffe, T., Hewson, A., Brough, W. 2000. Independent water audits for container grown nursery stock producers. MAFF Water Audits - 2000. Horticulture and Potatoes Division, Ministry of Agriculture Fisheries and Food. Summary Report - Summer 2000.

Bunt, A.C., 1976. Modern potting composts. The Pennsylvania State University Press.

Burnett, S.E., van Iersel, M.W., 2008. Morphology and irrigation efficiency of Gaura lindheimeri grown with capacitance sensor-controlled irrigation. HortSci. 43, 1555–1560.

Cameron, R., Harrison-Murray, R., Fordham, M., Wilkinson, S., Davies, W., Atkinson, C., Else, M., 2008. Regulated irrigation of woody ornamentals to improve plant quality and precondition against drought stress. Ann. App. Biol. 15, 49-61.

Cameron, R.W.F., Harrison-Murray. R., Scott, M.A., 1999. The use of controlled water stress to manipulate growth of container-grown Rhododendron cv. Hoppy. J. Hort. Sci. Biotech. 74, 161-169.

Cameron, R.W.F., Harrison-Murray, R.S., Atkinson, C.J., Judd, H.L., 2006. Regulated deficit irrigation – a means to control growth in woody ornamentals. J. Hort. Sci. Biotech. 81, 435-443.

Caron, J., Xu, H.L., Bernier, P.Y., Duchesne, I., Tardif, P., 1998. Water availability in three artificial substrates during Prunus × cistena growth: Variable threshold values. J. Am. Soc. Hort. Sci. 123, 931-936.

Chapman, S., Buttler, A., Francez, A.-J., Laggoun-Défarge, F., Vasander, H., Schloter, M., Combe, J., Grosvernier, P., Harms, H., Epron, D., Gilbert, D., Mitchell, E., 2003. Exploitation of northern peatlands and biodiversity maintenance: a conflict between economy and ecology. Frontiers in Ecology and the Environment 1, 525–532.

Chaves, M.M., Santos, T.P., Souza, C.R., Ortuño, M.F., Rodrigues, M.L., Lopes, C.M, Maroco, J.P., Pereira, J.S., 2007. Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. Ann. App. Biol. 150, 237–252.

Christiansen, J.E., 1942. Irrigation by sprinkling. Berkeley. California Agricultural Experiment Station. Bulletin No. 670.

Cirillo, C., Rouphael, Y., Caputo, R., Raimondi, G., De Pascale, S., 2014. The influence of deficit irrigation on growth, ornamental quality, and water use efficiency of three potted Bougainvillea genotypes grown in two shapes. HortSci. 49, 1284-1291.

Costa, J.M., Ortuño, M.F., Chaves, M.M., 2007. Deficit irrigation as a strategy to save water: physiology and potential application to horticulture. J. Integ. Plant Biol. 49, 1421-1434.

Evans, R.G., Sadler, E.J., 2008. Methods and technologies to improve efficiency of water use. Wat. Res. Res. 44, 1-15.

Fereres, E., Goldhamer, D.A., Parsons, L.R., 2003. Irrigation water management of horticultural crops. HortSci. 38, 1036-1042.

Fereres, E., Soriano, M.A., 2006. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147-159.

Franco, J.A., Martínez-Sánchez, J.J., Fernández, J.A., Bañón, S., 2006. Selection and nursery production of ornamental plants for landscaping and xerogardening in semi-arid environments. J. Hort. Sci. Biotech. 81, 3-17.

Grant, O.M., Stoll, M., Jones, H.G., 2004. Partial rootzone drying does not affect fruit yield of raspberries. J. Hort. Sci. Biotech. 79, 125-130.

Grant, O.M., Davies, M.J., Longbottom, H., Atkinson, C.J., 2009. Irrigation scheduling and irrigation systems: optimising irrigation efficiency for container ornamental shrubs. Irrig. Sci. 27, 139-153.

Grant, O.M., Davies, M.J., Longbottom, H., Herrero, A., Harrison-Murray, R., 2011. Application of deficit irrigation to controlling growth of hardy nursery stock. Acta Hort. 889, 409-416.

Grant, O.M., 2012. Measuring evapotranspiration of hardy ornamental nursery stock: A hurdle for irrigation management, in: Er-Raki, S. (Ed.), Evapotranspiration: Processes, sources and environmental implications. Nova Science Publishers, Inc.

Grant, O.M., Davies, M.J., Longbottom, H., Harrison-Murray, R., 2012. Evapotranspiration of container ornamental shrubs: modelling crop-specific factors for a diverse range of crops. Irrig. Sci. 30, 1-12.

Guérin, V., Lemaire, F., Marfà, O., 2001. Growth of Viburnum tinus in peat-based and peat-substitute growing media. Sci. Hort. 89, 129-142.

Harrison-Murray, R.S., 1991. An electrical sensor for potential transpiration: principle and prototype. J. Hort. Sci., 66, 141-149.

Incrocci, L., Marzialetti, P., Incrocci, G., Di Vita, A., Balendonck, J., Bibbiani, C., Spagnol. S., Pardossi, A., 2014. Substrate water status and evapotranspiration irrigation scheduling in heterogenous container nursery crops. Agric. Water. Manage. 131, 30-40.

Jensen, C.R., Battilani, A., Plauborg, F., Psarras, G., Chartzoulakis, K., Janowiak, F., Stikic, R., Jovanovic, Z., Li, G., Qi, X., Liu, F., Jacobsen, S., Andersen, M.N. 2010. Deficit irrigation based on drought tolerance and root signalling in potatoes and tomatoes. Agric. Water Manage. 98, 403–413.

Kim, J., van Iersel, M.W., Burnett, S.E., 2011. Estimating daily water use of two petunia cultivars based on plant and environmental factors. HortSci. 46, 1287–1293.

Klock-Moore, K.A., Broschat, T.K., 2001. Effect of four growing substrates on growth of ornamental plants in two irrigation systems. HortTech. 11, 456-460.

Lea-Cox, J.D., Bauerle, W.L., van Iersel, M.W., Kantor, G.F., Bauerle, T.L., Lichtenberg, E., King, D.M., Crawford, L., 2013. Advancing wireless sensor networks for irrigation management of ornamental crops: An overview. HortTech. 23, 717-724.

Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., Scardigno, A., 2014. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. Ag. Water Manage. 146, 84-94.

Li, J.S., 1998. Modeling crop yield as affected by uniformity of sprinkler irrigation system. Ag. Water Manage. 38, 135-146.

Londra, P.A., 2010. Simultaneous determination of water retention curve and unsaturated hydraulic conductivity of substrates using a steady-state laboratory method. HortSci. 45, 1106-1112.

Majsztrik, J.C., Ristvey, A.G., Lea-Cox, J.D., 2011. Water and nutrient management in the production of container-grown ornamentals. Hort. Rev. 38, 253-297.

Naasz, R., Michel, J.C., Charpentier, S., 2005. Modeling oxygen and water flows in peat sustrates with root uptakes. Acta Hort. 779, 191-197.

O'Meara, L., van Iersel, M.W., Chappell, M.R., 2013. Modeling daily water use of Hydrangea macrophylla and Gardenia jasminoides as affected by environmental conditions. HortSci. 48, 1040-1046.

Pettitt T.R., 2014. Irrigation water and the health of nursery crops, in: Hong, C. X., Moorman, G. W., Wohanka, W., Büttner, C. (Eds.), Biology, detection and management of plant pathogens in irrigation water. American Phytopathological Society.

Sánchez-Blanco, M.J., Ferrández, T., Navarro, A., Bañón, S., Alarcón, J.J., 2004. Effects of irrigation and air humidity preconditioning on water relations, growth and survival of Rosmarinus officinalis plants during and after transplanting. J. Plant Physiol. 161, 1133-1142.

Thorne, F.S., Kelly, P.W., Maher, M.J., Harte, L.N., 2002. The Irish hardy nursery stock industry: recent trends and competitive position. Teagasc report RMIS4748.

Walczak, R., Rovdan, E., Witkowska-Walczak, B., 2002. Water retention characteristics of peat and sand mixtures. Int. Agrophysics 16, 161-165.

Warsaw, A.L., Fernandez, R.T., Cregg, B.M., Andresen, J.A., 2009. Water conservation, growth, and water use efficiency of container grown woody ornamentals irrigated based on daily water use. HortSci. 44, 1308–1318.

Wright, A.N., Niemiera, A.X., Harris, R., Wright, R.D., 1999. Preplant lime and micronutrient amendments to pine bark affect growth of seedlings of nine container-grown tree species. HortSci. 34, 669-673.

Yu, S., Zinati, G.M., 2006. Physical and chemical changes in container media in response to bark substitution for peat. Comp. Sci Util.14, 222-230.Zwak, J.A., Graves, W.R., Townsend, A.M., 1998. Leaf water relations and plant development of three Freeman maple cultivars subjected to drought. J. Am. Soc. Hort. Sci. 123, 371-375.

Figure captions

Fig. 1. Typical habit of Lonicera periclymenum 'Graham Thomas' (left), Cornus alba 'Elegantissima' (middle) and Forsythia × intermedia 'Lynwood' (right).

Fig. 2. Variation between pots in water delivery, measured as weight gain of pots during an irrigation event (a), and in volumetric substrate moisture content (θ, b) during an experiment with deficit-irrigated Lonicera periclymenum 'Graham Thomas' (top) and Cornus alba 'Elegantissima' (bottom) under drip (shaded symbols) and overhead (open symbols) irrigation. Boxes indicate the 25th to 75th percentile range, whiskers extend another 15% either way, and outliers are represented by circles, n = 20. Application of 100% ET_A in (a) on that date would have equalled 165 mL irrigation. Data in (b) were obtained following 7 weeks of irrigation treatments.

Fig. 3. Volumetric substrate moisture content (θ) in pots (a) and plant height (b) of Lonicera periclymenum 'Graham Thomas' (top) and Cornus alba 'Elegantissima' (bottom) measured at intervals in an experiment comparing full irrigation (circles) and deficit irrigation (50% ET_A – triangles – or 25% ET_A – squares), imposed via drip (closed symbols) or overhead (open symbols) irrigation. Data are means ± s.e., n = 10.

Fig. 4. Volumetric substrate moisture content (θ) at the top (a) and bottom (b) of pots, and shoot (c) and root (d) dry mass of Lonicera periclymenum 'Graham Thomas' (top) and Cornus alba 'Elegantissima' (bottom) following 8 weeks of full or deficit irrigation (50% or 25% ET_A), applied via drip (closed symbols) or overhead (open symbols). Bars represent means ± s.e., n = 10. Within a single graph, different letters represent significant differences between means (LSD) at $P < 0.05$.

Fig. 5. Volumetric substrate moisture content (θ, a) and increase in plant height (shown as the cumulative increase from the start of the experiment or after pruning) (b) during application of full (circles) or deficit (70% ET_A – triangles – or 50% ET_A – squares) irrigation, applied via drip (closed symbols) or overhead (open symbols) to Forsythia × intermedia 'Lynwood' grown in 100% peat (top) or a reduced peat substrate (bottom). Symbols represent means ± s.e., n = 16 before pruning and n = 10

following pruning.

Fig. 6. Volumetric substrate moisture content (θ) at the top (a), middle (b) and bottom (c) of pots filled with 100% peat (top) or a reduced peat substrate (bottom), and in which Forsythia × intermedia 'Lynwood' was grown under full or deficit (70% or 50% ET_A) irrigation, applied via drip (closed columns) or overhead (open columns), measured in August, n = 5 pots. Asterisks denote significant differences between drip and overhead irrigation, as indicated by post-hoc tests (LSD) following ANOVA, $P < 0.05$.

Fig. 7. Final dry mass of shoots (a), and roots (b), and the ratio of root to shoot dry mass (c) of Forsythia × intermedia 'Lynwood' harvested in autumn, following full or deficit (70% or 50% ET_A) irrigation, applied with drip (closed bars) or overhead (open bars) irrigation. n = 10 plants (data are pooled over two substrates). Within a single graph, different letters represent significant differences between means (LSD) at $P < 0.05$, following a significant effect of irrigation quantity (a) and a significant interaction of irrigation quantity and system (b, c), according to ANOVA.

Fig. 8. Number of flowers produced on Forsythia × intermedia 'Lynwood' per length of stem (a) and per node (b), and average internode length (c) in the spring following application of full or deficit (70% or 50% ET_A) irrigation, applied with drip (closed bars) or overhead (open bars) irrigation. Data are means ± s.e., n = 10. Plants had been pruned in June. Within a single graph, different letters represent significant differences between means (LSD) at $P < 0.05$, following a significant effect of irrigation quantity, according to ANOVA.

Tables

Table 1

Final plant canopy width of Cornus alba 'Elegantissima' following eight weeks of full or deficit (50% or 25% ET_A) irrigation.

Irrigation quantity	Irrigation system	Plant width (cm)
Full	Drip	80.7 ± 2.6 e*
	Overhead	67.7 ± 2.1 d
50% ET_A	Drip	53.0 ± 0.9 c
	Overhead	46.1 ± 2.4 b
25% ET_A	Drip	45.7 ± 1.5 b
	Overhead	32.1 ± 1.2 a

* Data are means ± s.e.; means with different letters differ significantly, $P < 0.05$, LSD following ANOVA. Plant width is the average of the width at the widest point in the canopy and the width perpendicular to that measurement.

Table 2

Coefficients of variation (%)[a] of volumetric substrate moisture content in different layers of two types of substrate (100% peat or reduced peat) under two irrigation systems (drip or overhead) and three different quantities of irrigation (full or deficit – 70% or 50% ET_A) to Forsythia.

Quantity	**System**	**Substrate (% peat)**	**Layer of substrate**		
			Top	**Middle**	**Bottom**
Full	Drip	100%	14.2 ± 3.2	10.5 ± 2.5	11.0 ± 1.5
		Reduced	13.0 ± 2.8	9.7 ± 1.8	8.5 ± 1.1
Full	Overhead	100%	8.9 ± 1.0	6.5 ± 1.4	5.3 ± 0.9
		Reduced	10.2 ± 2.6	9.5 ± 2.4	9.7 ± 2.4
70%	Drip	100%	56.9 ± 12.2	16.7 ± 3.1	9.3 ± 2.7
		Reduced	58.7 ± 3.9	15.9 ± 1.6	5.3 ± 1.0
70%	Overhead	100%	13.0 ± 1.5	10.2 ± 1.6	5.2 ± 0.7
		Reduced	9.4 ± 2.0	7.2 ± 1.7	9.9 ± 2.7
50%	Drip	100%	73.7 ± 6.4	33.3 ± 3.0	16.9 ± 4.0
		Reduced	66.3 ± 8.4	33.4 ± 6.7	16.7 ± 3.1
50%	Overhead	100%	13.4 ± 2.9	9.9 ± 2.9	6.7 ± 1.0
		Reduced	16.0 ± 2.7	12.8 ± 3.0	8.7 ± 2.5

[a] Coefficients were calculated from four measurements per layer per pot. Coefficients shown are means of 5 pots per irrigation quantity × irrigation system × substrate ± s.e.