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Title: 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 **Application of deficit irrigation to hardy ornamental nursery stock**
2 **via overhead irrigation**

3

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16

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24

25 ABSTRACT

26

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

53

54

55 **1. Introduction**

56

57 Future global irrigation management will require users to look for methods of
58 application which are efficient (Bacci et al., 2008; Kim et al., 2011; Majsztrik et al.,
59 2011; Lea-Cox et al., 2013). For example, metrics such as water use and water
60 productivity (Fereres and Soriano, 2006) may be required to justify irrigation
61 practices. The use of deficit irrigation not only provides the means by which water use
62 can be reduced and its use efficiency enhanced, but also enables crop growth and
63 quality to be controlled (Jensen et al., 2010; Cirillo et al., 2014). Deficit irrigation is
64 the application of less water than a crop would lose by evapotranspiration if water
65 availability was not limiting (Fereres et al., 2003). However, for deficit irrigation to
66 be effective requires understanding crop growth patterns, and some commentators
67 suggest that use of advanced irrigations systems is also essential (Evans and Sadler,
68 2008; O’Meara et al. 2013). Deficit irrigation is applied either as sustained deficit
69 irrigation i.e. by systematically applying water at a constant fraction of potential
70 evapotranspiration through the season, or as regulated deficit irrigation, in which case
71 soil moisture deficits are imposed only at certain plant developmental stages (Costa et
72 al., 2007; Bacci et al., 2008).

73 The primary challenges in the development of effective application of deficit
74 irrigation to control growth and quality in container grown crops, such as hardy
75 nursery stock, are a multitude of species and cultivars with different water
76 requirements, and sensitivities to deficit irrigation, combined with a general absence
77 of economic justification for the use of sophisticated precision irrigation systems
78 (Kim et al., 2011; Majsztrik et al., 2011). There are examples, however, where
79 economic assessment reveals apparently good initial savings and returns from
80 investment in irrigation automation (Majsztrik et al., 2011; Belayneh et al., 2013).
81 The successful application of deficit irrigation in hardy nursery stock production
82 offers environmental and economic benefits, such as reduced container leaching of
83 nutrients and pesticides and a reduction in fertiliser and pesticide costs associated with
84 wastage (Caron et al., 1998; Burnet and van Iersel, 2008; Warsaw et al., 2009;
85 Majsztrik et al., 2011). This combination of economic with environmental benefits
86 has been recently highlighted (Levidow et al., 2014) as critical if producers are to take
87 up opportunities for improved water management. Other benefits may arise from
88 nursery production of more robust plants when subjected to environmental stresses,

89 such as drought (Cameron et al., 2008). Some studies have now begun to elucidate the
90 mechanisms by which deficit irrigation approaches achieve these ‘carry-over’ effects
91 in the container crop production cycle (Sanchez-Blanco et al., 2004; Bañón et al.,
92 2006; Cameron et al., 2006; Franco et al., 2006).

93 HNS production approaches are economically constricted by the need for mass
94 production to consistently high crop quality (Warsaw et al., 2009). Despite retailer
95 requirements for producers to meet precise crop-specific quality criteria (Álvarez et
96 al., 2009; Majsztrik et al., 2011), retail margins often mean that investment in
97 sophisticated irrigation approaches is not easily justified. Despite the high labour costs
98 in nurseries’ budgets, at least in UK, Dutch, and Irish production (Thorne et al.,
99 2002), and the potential for deficit irrigation to remove or reduce the need for costly
100 operations such as manual pruning (Cameron et al., 1999; 2006), there is still a lack of
101 commercial confidence in the application of the approach (Kim et al., 2011). There
102 are a number of questions which need answering before widespread uptake of deficit
103 irrigation for container production is likely (Belayneh et al., 2013).

104 One of the concerns with respect to commercial application of deficit irrigation is
105 whether approaches developed for high precision drip irrigation can be adapted for
106 extensive commercial practice, which still relies heavily on overhead irrigation
107 (Briercliffe et al., 2000; Pettitt 2014). The drawbacks of overhead irrigation are well
108 described and for hardy nursery stock focus on a lack of spatial uniformity of
109 irrigation supply meeting crop water ‘demand’; this may have considerable
110 implications for crop uniformity when deficit irrigation reduces container substrate
111 water availability (Beeson and Knox, 1991; Beeson and Yeager, 2003; Grant et al.,
112 2011). Related to the use of overhead irrigation is the tendency to grow several crops
113 under one system. Differences in water use and uptake amongst species may mean
114 that a deficit appropriate for one crop is detrimental for another.

115 The capacity of the container substrate to sustain the applied deficit irrigation
116 regime must also be considered. Most commercial experience lies with the use of pure
117 peat, but continued reliance on pure peat production is not sustainable (Barkham,
118 1993; Chapman et al., 2003; Alexander et al., 2008). Substrate producers are therefore
119 looking into alternative media (Alexander et al., 2008), at least to reduce, if not
120 completely replace, peat consumption (Alexander et al., 2008). Changing the
121 constituents in growing media, however, frequently alters the water holding capacity
122 of the substrate (Yu and Zinati, 2006).

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

127

128 **2. Materials and methods**

129

130 2.1. Plant material and the growing environment

131

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

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

149

150 2.2. Irrigation systems and scheduling

151

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

156 treatments were allocated randomly to the different bays. In the case of full irrigation,
157 150% ET_A was applied to ensure that even if irrigation delivery was non-uniform, all
158 plants would receive at least 100% ET_A . Excess water ran through the pot bases, and
159 drained freely through the MyPex and the gravel beneath, showing no signs of ground
160 surface accumulation. High quality mains supply water was used for irrigation.

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

178 ET_A was determined every two weeks by weighing plants in the full irrigation
179 treatments after irrigation (after allowing for pot gravity draining, and water
180 intercepted by the canopy to run off) and again a day later. Wet leaf temperature
181 depression was determined simultaneously with a sensor (Evaposensor, Skye, Powys,
182 UK) located in the crop. The sensor continuously measures temperature differences
183 between wet and dry artificial leaves (Harrison-Murray, 1991), with the accumulated
184 difference recorded and logged via a dedicated meter (Evapometer, Skye), as °C h,
185 where 1°C h equates to a difference of 1°C for a duration of 1 h. Thus, for example, if
186 a plant uses 100 mL water during an accumulation of 100°C h, this plant will require
187 1 mL of irrigation for every 1°C h accumulated, if the intention is to apply 100% of
188 ET_A . Combining water use per °C h with the time required to apply the determined

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

197

198 2.3. A single species scheduling approach applied to crops of contrasting canopy
199 structure

200

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

216

217 2.4. Comparison of substrates

218

219 100% peat (as above) was compared with a reduced peat mix [60% peat: 40% bark
220 (Melcourt Potting bark, Melcourt Industries Ltd., Tetbury, Gloucestershire, UK)]. For
221 the reduced peat mix, 1 g ammonium nitrate per L of bark was incorporated to
222 compensate for the low nitrogen availability in bark (see recommendation by Wright

223 et al., 1999). The two substrate treatments were replicated randomly in each bay.
224 Plants of Forsythia were arranged in four rows per bay and DI treatments of 70% and
225 50% ET_A applied. These treatments were selected following analysis of the first
226 experiment, with the 70% ET_A representing a mild deficit – potentially the smallest
227 reduction in water supply likely to show a significant reduction in growth. Crop
228 evapotranspiration of Forsythia in 100% peat and in the reduced peat mix was similar,
229 and therefore crop factors for irrigation scheduling were based on average crop ET_A
230 (measured by pot weighing as above) across both substrates.

231 Irrigation treatments were applied from mid-May. At the end of June, 10 plants per
232 irrigation treatment (% ET_A), per irrigation system (drip vs. overhead), per substrate
233 (100% peat vs. reduced peat mix) were pruned to a height of 20-30 cm (as is
234 commercial practice). Four plants per irrigation treatment \times irrigation system \times
235 substrate were kept un-pruned. For one week in mid-August, plants in the 50% ET_A
236 treatments were given 70% ET_A irrigation, to encourage bud-break and shoot growth,
237 which was previously limited. At the end of August, the numbers of buds breaking per
238 pot from pruned branches was counted. Final heights and widths of all plants were
239 measured in mid-September.

240

241 2.5. Substrate moisture content

242

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

256

257 2.6. Plant growth, biomass allocation, and flowering

258

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

269

270 2.7. Statistical analysis

271

272 The significance of treatment differences was assessed by analysis of variance
273 (ANOVA), followed by LSD tests where appropriate, in Genstat software (Genstat
274 9.1, Rothamsted Experimental Station, UK). A repeated measures ANOVA was used
275 where variables were measured repeatedly on the same individual plants or pots.

276

277 **3. Results**

278

279 3.1. A single species scheduling approach applied to crops of contrasting canopy 280 structure

281

282 The overhead sprinkler arrangement achieved a Christiansen's coefficient of
283 uniformity of 91%, a scheduling coefficient of 1.2, and a mean application rate of 7.7
284 mm per hour. Drip irrigation resulted in a Christiansen's coefficient of uniformity of
285 96-98% and a scheduling coefficient of 1.0 to 1.1. While there was evidence during
286 irrigation that pot weight gain was less homogenous under overhead compared to drip
287 irrigation (example in Fig. 1a), variation in substrate volumetric moisture content was
288 not consistently greater under overhead irrigation (example in Fig. 1b). Measurements

289 of water uptake indicated that *Cornus* under overhead irrigation took up less water
290 than *Lonicera* (Fig. 1a), while water uptake with drip was similar for both crops.

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

304 At the end of the experiment, an interaction between irrigation system and $\% ET_A$
305 ($P < 0.001$) was detected on mean substrate volumetric moisture content, both at the
306 top and at the bottom of the pot, for both species. Substrate volumetric moisture
307 content was lower under overhead than drip irrigation for both deficit irrigation
308 treatments. On the other hand, it was higher under overhead than drip irrigation when
309 full irrigation was applied (Fig. 3a, b). For *Lonicera*, shoot dry mass was not
310 significantly affected by the type of irrigation (drip vs. overhead) within a given $\% ET_A$.
311 However, there was a significant effect of $\% ET_A$ on plant mass ($P < 0.001$ for
312 shoots and $P = 0.025$ for roots). Under drip irrigation both deficit treatments showed
313 reduced shoot, but not root, dry mass, whereas under overhead irrigation only the
314 more severe deficit reduced shoot dry mass (Fig. 3c, d). Root:shoot ratio decreased as
315 $\% ET_A$ increased ($P < 0.001$, data not shown). For *Cornus*, both shoot dry mass and
316 root dry mass were affected by $\% ET_A$ ($P < 0.001$), with increasing dry mass at the
317 higher $\% ET_A$ (Fig. 3c, d). Both shoot and root mass was greater under drip irrigation
318 compared to overhead ($P < 0.001$). Root:shoot ratio was affected by $\% ET_A$ ($P <$
319 0.001), with a lower root: shoot ratio under 25% ET_A than under the other two
320 treatments (data not shown).

321

322 3.2. Comparison of substrates

323

324 Substrate volumetric moisture content was reduced by deficit irrigation
325 throughout the second experiment ($P < 0.001$) (Fig. 4a). A frequent but less consistent
326 effect of irrigation system also occurred, but only occasionally were differences in
327 substrate volumetric moisture content seen between the two types of substrate.
328 Growth slowed in the 50% ET_A DI treatment from 14 days after treatments started (P
329 ≤ 0.012 ; Fig. 4b). Five weeks from the start of the experiment, an interaction with
330 respect to cumulative plant height increment was seen between irrigation quantity and
331 system ($P = 0.013$). Differences between treatments in shoot growth were reflected in
332 the average mass of shoot material per plant obtained during pruning: 10–12 g for
333 50% ET_A , 12–18 g for 70% ET_A , and 22–24 g for full irrigation. After pruning, rapid
334 growth was seen under full irrigation, with growth much reduced under deficit
335 irrigation (Fig. 4b). From pruning onwards, there was no interaction between substrate
336 and irrigation quantity or system, and no interaction between irrigation quantity and
337 system i.e. reduced growth occurred with deficit irrigation using both drip and
338 overhead and with both 100% peat and the reduced peat substrates. Growth was
339 greater in the reduced peat substrate ($P < 0.001$).

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

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

356 to drip.

357 In autumn, shoot dry mass was affected only by % ET_A applied ($P < 0.001$, Fig.
358 7a), with shoot dry mass increasing with % ET_A. Root dry mass was also affected by
359 the interaction of % ET_A with type of irrigation ($P = 0.02$, Fig. 7b). With overhead
360 irrigation, root dry mass increased with increasing % ET_A, but this response was less
361 clear with drip irrigation. Thus, when drip was used, compared to overhead irrigation,
362 root dry mass was not as reduced by the more severe deficit relative to full irrigation.
363 Root:shoot ratio was also affected by the interaction of % ET_A and type of irrigation
364 ($P < 0.001$, Fig. 7c). The root:shoot ratio decreased with increasing % ET_A under drip
365 irrigation, but this did not occur under overhead irrigation.

366 The following spring, number of flowers per unit shoot length was affected by the
367 % ET_A applied ($P < 0.001$, Fig. 8a). The plants receiving full irrigation had
368 approximately half the number of flowers per unit shoot length compared to those
369 receiving 50% ET_A. The increased number of flowers over a given length of shoot in
370 the deficit irrigation treatments was a result of an increased number of flowers per
371 node ($P = 0.018$, Fig. 8b) and shorter internode lengths ($P < 0.001$, Fig. 8c).

372

373 **4. Discussion**

374

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

387 Here we show that irrespective of type of irrigation system used (drip or overhead)
388 to apply deficit irrigation, reduced growth was apparent in response to a decline in

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

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

412 The increased root:shoot ratio apparent for *Forsythia* as a result of deficit irrigation
413 has important implications in the production of 'robust' plants which are able to
414 establish rapidly when transplanted. This is particularly true for better establishment
415 under semi-arid conditions (Franco et al., 2006). How this occurs, beyond
416 improvement in the plant's ability to capture water relative to that lost via
417 transpiration, is likely to be species-specific. In *Nerium oleander*, for example,
418 dehydration of the finer roots during transplanting is detrimental; deficit irrigation
419 induces thick roots, which increase the potential for water storage, leading to better
420 establishment of deficit irrigated plants (Bañón et al., 2006). In the current research
421 with *Forsythia*, however, it should be noted that an increased root:shoot ratio as a
422 result of deficit irrigation only occurred when irrigation was applied using a drip

423 system. The reduction in root biomass using overhead irrigation compared to drip
424 may have negative implications on transplanting and establishment. On the other
425 hand, drip irrigation can result in localised abundant root production in relation to the
426 dripper positioning in the container, where a high rooting density makes effective use
427 of applied water, but will limit the rate at which roots exploit the soil on transplanting.
428 The greater variation in volumetric moisture content within a layer shown here for
429 drip compared to overhead irrigation highlights the potential for localised root
430 formation under drip systems. Substrate types can also accentuate differences in water
431 distribution: coarse textured substrates lack small pore spaces to promote capillary
432 movement and water holding capacity (Klock-Moore and Broschat, 2001). Neither of
433 the substrates used in this study, however, accentuated variation in volumetric
434 moisture content compared to the other.

435 There was no interaction of irrigation quantity and substrate on final plant height,
436 implying that deficit irrigation can be used to control growth in a reduced peat
437 substrate, without any need to alter irrigation scheduling protocols developed for
438 100% peat. Reduced peat did not impact on root:shoot ratio, or variation within or
439 between pots in substrate volumetric moisture content. This may reflect limited
440 variation in water holding capacity between substrates with peat substitution from 40
441 to 70% (Caron et al., 1998). Yu and Zinati (2006) found that increasing the
442 percentage of bark from 40% to 90% in parallel with a decreasing percentage of peat
443 led to decreased substrate water holding capacity, from 63% to 49%. This difference
444 is small and would be easily managed within a deficit irrigation strategy and would
445 have little impact on its effectiveness with respect to growth control. The substrate-
446 derived differences in growth seen here with Forsythia are likely to relate to
447 nutritional differences. To compensate for an expected reduction in nitrogen
448 availability when peat is partially substituted with bark (Wright et al., 1999),
449 ammonium nitrate was added initially. This apparently overcompensated, with
450 enhanced growth in the reduced peat substrate – which was seen under full as well as
451 deficit irrigation. Variation in growth when using a diverse range of growing media is
452 well documented (Guérin et al., 2001).

453 Currently it is not possible to predict exact % ET_A deficits to induce well-defined
454 levels of growth control or increases in production quality across the wide range of
455 species and cultivars in hardy nursery stock production. That innate differences in
456 response to limited water availability exist between species is well known, and this

457 variability interacts with factors such as variation in the growing environment (Evans
458 and Sadler, 2008). Another challenge is how to easily determine the actual water input
459 corresponding to the desired % ET_A (Feres and Soriano, 2006): if entire crops are
460 being deficit irrigated, fully irrigated plants may not be available for gravimetric
461 calibration, as used in this current study. One solution would be through adjustment of
462 scheduling coefficients on the basis of plant size (canopy area and hence transpiring
463 area). Where the Evaposensor has been used to schedule (full) irrigation, this
464 approach has been shown to be effective for diverse species (Grant et al., 2012).
465 Alternatively, coefficients (K_c) can be estimated from variables such as plant height,
466 to use with reference evapotranspiration (ET_o) calculated from meteorological
467 variables (Incrocci et al., 2014).

468

469 **5. Conclusions**

470

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

480

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482

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488

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619

620 **Figure captions**

621

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

630

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

636

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

643

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

651

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

657

658 **Fig. 6.** Volumetric substrate moisture content (θ) at the top (a), middle (b) and bottom
659 (c) of pots filled with 100% peat (top) or a reduced peat substrate (bottom), and in
660 which Forsythia × intermedia ‘Lynwood’ was grown under full or deficit (70% or
661 50% ET_A) irrigation, applied via drip (closed columns) or overhead (open columns),
662 measured in August, $n = 5$ pots. Asterisks denote significant differences between drip
663 and overhead irrigation, as indicated by post-hoc tests (LSD) following ANOVA, $P <$
664 0.05.

665

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

673

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

681

682

683

684 **Tables**

685

686 **Table 1**

687 Final plant canopy width of *Cornus alba* ‘Elegantissima’ following eight weeks of
688 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

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

692

693

694 **Table 2**

695 Coefficients of variation (%)^a of volumetric substrate moisture content in different
 696 layers of two types of substrate (100% peat or reduced peat) under two irrigation
 697 systems (drip or overhead) and three different quantities of irrigation (full or deficit –
 698 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

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

701

702

1 | **Application of deficit irrigation to container-grown hardy**
2 | **ornamental nursery stock via overhead irrigation, compared to drip**
3 | **irrigation**

4

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17

18 | Keywords:

19 | Container production

20 | Hardy nursery stock (HNS)

21 | Irrigation management

22 | Irrigation scheduling

23 | Irrigation systems

24 | Peat alternatives

25 | Plant growth management

26 | Resource use efficiency

27

28 ABSTRACT

29

30 | Growth control of container-grown hardy nursery stock generally requires substantial
31 | labour investment. Therefore the possibility of alternative growth control using deficit
32 | irrigation is appealing. Increasing water costs and limited availability of abstraction
33 | licences have added further incentives for nursery stock producers to use deficit
34 | irrigation. There are still, however, concerns that inherent non-uniformity of water
35 | uptake under commonly used overhead irrigation, and differing irrigation
36 | requirements of diverse crops and substrates, may limit the commercial relevance of a
37 | protocol developed for single crops growing in 100% peat and irrigated with a high
38 | precision drip system. The aim of this research was to determine whether growth
39 | control of hardy nursery stock is possible using deficit irrigation applied with
40 | conventional overhead irrigation. Over two years, crop growth under an overhead
41 | irrigation system was compared under full irrigation and two severities of deficit
42 | irrigation. Initially, two crops of contrasting canopy structure i.e. *Cornus* alba and
43 | *Lonicera* periclymenum were grown. In a subsequent experiment one crop (*Forsythia*
44 | × intermedia) was grown in two substrates with contrasting quantities of peat (60 and
45 | 100%). Deficit irrigation was found to be highly effective in controlling vegetative
46 | growth when applied using overhead irrigation – with similar results as when drip
47 | irrigation was used. This comparable response suggests that deficit irrigation can be
48 | applied without precision drip irrigation. Scheduling two very different crops with
49 | respect to their water use and uptake potential, however, highlighted challenges with
50 | respect to application of appropriate deficits for very different crops under one
51 | system; responses to deficit irrigation will be more consistent where nursery
52 | management allows for scheduling of crops with very different architecture and water
53 | use under different regimes. The effectiveness of deficit irrigation in controlling the
54 | growth of *Forsythia* was similar when a reduced peat based substrate was compared
55 | with pure peat; additionally, flowering was enhanced.

56

57

58 **1. Introduction**

59

60 Future global irrigation management will require users to look for methods of
61 application which are efficient (Bacci et al., 2008; Kim et al., 2011; Majsztrik et al.,
62 2011; Lea-Cox et al., 2013). For example, metrics such as water use and water
63 productivity (Fereres and Soriano, 2006) may be required to justify irrigation
64 practices. The use of deficit irrigation not only provides the means by which water use
65 can be reduced and its use efficiency enhanced, but also enables crop growth and
66 quality to be controlled (Jensen et al., 2010; Cirillo et al., 2014). Deficit irrigation is
67 the application of less water than a crop would lose by evapotranspiration if water
68 availability was not limiting (Fereres et al., 2003). However, for deficit irrigation to
69 be effective requires understanding crop growth patterns, and some commentators
70 suggest that use of advanced irrigations systems is also essential (Evans and Sadler,
71 2008; O'Meara et al., 2013). Deficit irrigation is applied either as sustained deficit
72 irrigation i.e. by systematically applying water at a constant fraction of potential
73 evapotranspiration through the season, or as regulated deficit irrigation, in which case
74 soil moisture deficits are imposed only at certain plant developmental stages (Costa et
75 al., 2007).

76 The primary challenges in the development of effective application of deficit
77 irrigation to control growth and quality in container grown crops, such as hardy
78 nursery stock, are a multitude of species and cultivars with different water
79 requirements, and sensitivities to deficit irrigation, combined with a general absence
80 of economic justification for the use of sophisticated precision irrigation systems
81 (Kim et al., 2011; Majsztrik et al., 2011). There are examples, however, where
82 economic assessment reveals apparently good initial savings and returns from
83 investment in irrigation automation (Majsztrik et al., 2011; Belayneh et al., 2013).
84 The successful application of deficit irrigation in hardy nursery stock production
85 offers environmental and economic benefits, such as reduced container leaching of
86 nutrients and pesticides and a reduction in fertiliser and pesticide costs associated with
87 wastage (Caron et al., 1998). This combination of economic with environmental
88 benefits has been recently highlighted (Levidow et al., 2014) as critical if producers
89 are to take up opportunities for improved water management. Other benefits may arise
90 from nursery production of more robust plants when subjected to environmental
91 stresses, such as drought (Cameron et al. 2008). Some studies have now begun to

92 elucidate the mechanisms by which deficit irrigation approaches achieve these ‘carry-
93 over’ effects in the container crop production cycle (Sanchez-Blanco et al., 2004;
94 Bañón et al., 2006; Cameron et al., 2006; Franco et al., 2006).

95 HNS production approaches are economically constricted by the need for mass
96 production to consistently high crop quality (Warsaw et al., 2009). Despite retailer
97 requirements for producers to meet precise crop-specific quality criteria (Álvarez et
98 al., 2009; Majsztzik et al., 2011), retail margins often mean that investment in
99 sophisticated irrigation approaches is not easily justified. Despite the high labour costs
100 in nurseries’ budgets, at least in UK, Dutch, and Irish production (Thorne et al.,
101 2002), and the potential for deficit irrigation to remove or reduce the need for costly
102 operations such as manual pruning (Cameron et al., 1999), there is still a lack of
103 commercial confidence in the application of the approach (Kim et al., 2011). There
104 are a number of questions which need answering before widespread uptake of deficit
105 irrigation for container production is likely (Belayneh et al., 2013).

106 One of the concerns with respect to commercial application of deficit irrigation is
107 whether approaches developed for high precision drip irrigation can be adapted for
108 extensive commercial practice, which still relies heavily on overhead irrigation
109 (Briercliffe et al., 2000; Pettitt 2014). The drawbacks of overhead irrigation are well
110 described and for hardy nursery stock focus on a lack of spatial uniformity of
111 irrigation supply meeting crop water ‘demand’; this may have considerable
112 implications for crop uniformity when deficit irrigation reduces container substrate
113 water availability (Beeson and Knox, 1991; Beeson and Yeager, 2003; Grant et al.,
114 2011). Related to the use of overhead irrigation is the tendency to grow several crops
115 under one system. Differences in water use and uptake amongst species may mean
116 that a deficit appropriate for one crop is detrimental for another.

117 The capacity of the container substrate to sustain the applied deficit irrigation
118 regime must also be considered. Most commercial experience lies with the use of pure
119 peat, but continued reliance on pure peat production is not sustainable (Barkham,
120 1993; Chapman et al., 2003; Alexander et al., 2008). Substrate producers are therefore
121 looking into alternative media, at least to reduce, if not completely replace, peat
122 consumption (Alexander et al., 2008). Changing the constituents in growing media,
123 however, frequently alters the water holding capacity of the substrate (Yu and Zinati,
124 2006).

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

130

131 2. Materials and methods

132

133 2.1. Plant material and the growing environment

134

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

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

152

153 2.2. Irrigation systems and scheduling

154

155 Irrigation was scheduled to replace a predetermined percentage of the potential
156 crop evapotranspiration (i.e. the actual evapotranspiration, ET_A , if water availability
157 was not limiting). Two different deficit irrigation treatments were applied each year,

158 in comparison with a full irrigation treatment, with two bays used for each treatment;
159 treatments were allocated randomly to the different bays. In the case of full irrigation,
160 150% ET_A was applied to ensure that even if irrigation delivery was non-uniform, all
161 plants would receive at least 100% ET_A . Excess water ran through the pot bases, and
162 drained freely through the MyPex and the gravel beneath, showing no signs of ground
163 surface accumulation. High quality mains supply water was used for irrigation.

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

181 ET_A was determined every two weeks by weighing plants in the full irrigation
182 treatments after irrigation (after allowing for pot gravity draining, and water
183 intercepted by the canopy to run off) and again a day later. Wet leaf temperature
184 depression was determined simultaneously with a sensor (Evaposensor, Skye, Powys,
185 UK) located in the crop. The sensor continuously measures temperature differences
186 between wet and dry artificial leaves (Harrison-Murray, 1991), with the accumulated
187 difference recorded and logged via a dedicated meter (Evapometer, Skye), as °C h,
188 where 1°C h equates to a difference of 1°C for a duration of 1 h. Thus, for example, if
189 a plant uses 100 mL water during an accumulation of 100°C h, this plant will require
190 1 mL of irrigation for every 1°C h accumulated, if the intention is to apply 100% of

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

200

201 2.3. A single species scheduling approach applied to crops of contrasting canopy
202 structure

203

204 Lonicera and Cornus growing in 100% sphagnum peat (Shamrock Premium
205 Grade, Bord na Móna, Newbridge, Co. Kildare, Ireland) were compared in year 1
206 (2006). This peat consists of particles up to 14 mm, including 50% in the range 6-12
207 mm, and has an approximate air filled porosity of 12% and electrical conductivity < 1
208 mS cm⁻¹. Plants were arranged in five rows per bay, with Lonicera on one half of the
209 bed and Cornus on the other, providing 21 experimental plants of each species, which
210 were fully guarded. The deficit irrigation treatments applied were 50% ET_A and 25%
211 ET_A i.e. crops were irrigated to replace 50% or 25% of water used by the fully
212 irrigated plants. These two deficit irrigation treatments were selected to represent a
213 deficit of sufficient severity to have a noticeable impact on growth (50%), and a very
214 severe deficit that might risk reducing plant quality (25%). Results from the two
215 different severities would thus be expected to provide a guideline for a range
216 appropriate for use on nurseries. Irrigation for both the crops was scheduled on the
217 basis of crop factors obtained for Lonicera. The reasoning for this is that different
218 crops are often grown together on single beds, and with overhead irrigation will
219 inevitably be irrigated by the same amount. Treatments were applied from the start of
220 August, for eight weeks. During this time, daily mean air temperature in the tunnel
221 was on average 21.4 $^{\circ}C$, ranging from 16.3 $^{\circ}C$ to 24.9 $^{\circ}C$. Relative humidity was on
222 average 82.9%. Average mean and maximum daytime global radiation were 188 and
223 455 W m⁻², respectively, with the maximum global radiation reached equalling 655

224 | W m⁻². Meteorological data were recorded from sensors integrated with a data-logger
225 | (Datahog, Skye Instruments Ltd., Powys, UK).

227 | 2.4. Comparison of substrates

229 | 100% peat (as above) was compared with a reduced peat mix [60% peat: 40% bark
230 | (Melcourt Potting bark, Melcourt Industries Ltd., Tetbury, Gloucestershire, UK)].

231 | Particles in the selected bark are predominantly in the range 3-15 mm, and its air
232 | filled porosity is approximately 62%, with an electrical conductivity of about 0.1 mS
233 | cm⁻¹. For the reduced peat mix, 1 g ammonium nitrate per L of bark was incorporated

234 | to compensate for the low nitrogen availability in bark (see recommendation by
235 | Wright et al., 1999). The two substrate treatments were replicated randomly in each
236 | bay. Plants of Forsythia were arranged in four rows per bay and DI treatments of 70%
237 | and 50% ET_A applied. These treatments were selected following analysis of the first
238 | experiment, with the 70% ET_A representing a mild deficit – potentially the smallest
239 | reduction in water supply likely to show a significant reduction in growth. Crop
240 | evapotranspiration of Forsythia in 100% peat and in the reduced peat mix was similar,
241 | and therefore crop factors for irrigation scheduling were based on average crop ET_A
242 | (measured by pot weighing as above) across both substrates.

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

257

258 2.5. Substrate moisture content

259

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

273

274 2.6. Plant growth, biomass allocation, and flowering

275

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

286

287 2.7. Statistical analysis

288

289 The significance of treatment differences was assessed by analysis of variance
290 (ANOVA), followed by LSD tests where appropriate, in Genstat software (Genstat
291 9.1, Rothamsted Experimental Station, UK). A repeated measures ANOVA was used
292 where variables were measured repeatedly on the same individual plants or pots.

293

294 **3. Results**

295

296 3.1. A single species scheduling approach applied to crops of contrasting canopy
297 structure

298

299 The overhead sprinkler arrangement achieved a Christiansen's coefficient of
300 uniformity of 91%, a scheduling coefficient of 1.2, and a mean application rate of 7.7
301 mm per hour. Drip irrigation resulted in a Christiansen's coefficient of uniformity of
302 96-98% and a scheduling coefficient of 1.0 to 1.1. While there was evidence during
303 irrigation that pot weight gain was less homogenous under overhead compared to drip
304 irrigation (example in Fig. 24a), variation in substrate volumetric moisture content
305 was not consistently greater under overhead irrigation (example in Fig. 24b).
306 Measurements of water uptake indicated that Cornus under overhead irrigation took
307 up less water than Lonicera (Fig. 24a), while water uptake with drip was similar for
308 both crops.

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

319 Over the course of the experiment, deficit irrigation significantly (P < 0.05)
320 reduced substrate volumetric moisture content (Fig. 32a), on average, across all pots,
321 and resulted in reduced growth (Fig. 32b). For both Lonicera and Cornus, there was

322 an interaction between irrigation quantity (% ET_A) and method of application on
323 substrate volumetric moisture content ($P < 0.001$). For *Lonicera*, there was no
324 difference between drip and overhead irrigation with respect to plant growth over the
325 experiment (Fig. 32b). For *Cornus*, there was an interaction of irrigation system and
326 % ET_A applied ($P = 0.003$) over the experiment, resulting in final plant heights being
327 reduced under overhead compared to drip irrigation when full irrigation was applied,
328 but not when deficit irrigation was applied. *Cornus* plants showed wider leaf canopy
329 diameters at the end of the experiment when drip irrigated compared to overhead, and
330 reduced canopy diameters under deficit compared to full irrigation (both $P < 0.001$;
331 Table 1).

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

349

350 3.2. Comparison of substrates

351

352 During the second experiment, evapotranspiration of the fully irrigated crop was
353 on average 3.2 mm day⁻¹, accumulating to 445 mm over the whole season. Thus daily
354 averages of 4.9, 2.3, and 1.6 mm day⁻¹ irrigation was applied to the full (150% ET_A).

355 70% ET_A and 50% ET_A treatments, respectively. As a result, over the entire growing
356 season, 667 mm irrigation was applied to the fully irrigated crop, and 311 and 222
357 mm to the milder and more severe deficit treatments, respectively. Substrate
358 volumetric moisture content was reduced by deficit irrigation throughout this ~~second~~
359 experiment ($P < 0.001$) (Fig. 54a). A frequent but less consistent effect of irrigation
360 system also occurred, but only occasionally were differences in substrate volumetric
361 moisture content seen between the two types of substrate. Growth slowed in the 50%
362 ET_A DI treatment from 14 days after treatments started ($P \leq 0.012$; Fig. 54b). Five
363 weeks from the start of the experiment, an interaction with respect to cumulative plant
364 height increment was seen between irrigation quantity and system ($P = 0.013$).
365 Differences between treatments in shoot growth were reflected in the average mass of
366 shoot material per plant obtained during pruning: 10–12 g for 50% ET_A, 12–18 g for
367 70% ET_A, and 22–24 g for full irrigation. Post-pruning bud break was significantly
368 lower ($P < 0.001$) in the deficit irrigation treatments (around 7–9 bud breaks per
369 plant) than in the full irrigation treatment (around 16 bud breaks per plant). After
370 pruning, rapid growth was seen under full irrigation, with growth much reduced under
371 deficit irrigation (Fig. 54b). From pruning onwards, there was no interaction between
372 substrate and irrigation quantity or system, and no interaction between irrigation
373 quantity and system i.e. reduced growth occurred with deficit irrigation using both
374 drip and overhead and with both 100% peat and the reduced peat substrates. The
375 combination of fewer bud breaks and reduced shoot elongation under deficit irrigation
376 led to more compact plants. Growth was greater in the reduced peat substrate ($P <$
377 0.001).

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

384 Early in August, Forsythia plants were removed from their pots and variation in
385 substrate volumetric moisture content determined. Coefficients of variation ($100\% \times$
386 standard deviation/mean) between the four measurements per layer (top, middle, or
387 bottom) of the substrate showed that greatest variation most frequently occurred at the

388 top (Table 2). Variation within a substrate layer was generally much greater when DI
389 was applied using drip irrigation rather than overhead. Variation was also generally
390 greater for the more severe deficit. Generally across all pots, independently of
391 whether full or deficit irrigation was applied, the substrate was drier in the top layer
392 with both substrate types and both irrigation systems ($P < 0.001$, Fig. 6). Substrate
393 volumetric moisture content tended to be greater using overhead irrigation compared
394 to drip.

395 In autumn, shoot dry mass was affected only by % ET_A applied ($P < 0.001$, Fig.
396 7a), with shoot dry mass increasing with % ET_A . Root dry mass was also affected by
397 the interaction of % ET_A with type of irrigation ($P = 0.02$, Fig. 7b). With overhead
398 irrigation, root dry mass increased with increasing % ET_A , but this response was less
399 clear with drip irrigation. Thus, when drip was used, compared to overhead irrigation,
400 root dry mass was not as reduced by the more severe deficit relative to full irrigation.
401 Root:shoot ratio was also affected by the interaction of % ET_A and type of irrigation
402 ($P < 0.001$, Fig. 7c). The root:shoot ratio decreased with increasing % ET_A under drip
403 irrigation, but this did not occur under overhead irrigation.

404 The following spring, number of flowers per unit shoot length was affected by the
405 % ET_A applied ($P < 0.001$, Fig. 8a). The plants receiving full irrigation had
406 approximately half the number of flowers per unit shoot length compared to those
407 receiving 50% ET_A . The increased number of flowers over a given length of shoot in
408 the deficit irrigation treatments was a result of an increased number of flowers per
409 node ($P = 0.018$, Fig. 8b) and shorter internode lengths ($P < 0.001$, Fig. 8c).

410

411 **4. Discussion**

412

413 A reduction of substrate volumetric moisture content, in response to deficit
414 irrigation, led to a reduction in the shoot growth of all the species used here, as it does
415 with other species ([Beeson 1992](#); Cameron et al. 1999; Grant et al. 2004; Chaves et al.
416 2007). This reduction is also known to influence a number of different growth
417 variables, both above and below ground (Franco et al., 2006). In most previous
418 research, however, deficit irrigation has been applied using a high-precision drip
419 irrigation system. Our novel approach was to validate the potential of deficit irrigation
420 to control growth through the utilisation of overhead irrigation – which is still an

421 important and much used system in commercial ornamental plant production.
422 Different irrigation systems are known to impact on plant dry matter production even
423 when full irrigation is applied (Klock-Moore and Broschat, 2001), and deficit
424 irrigation might accentuate such effects.

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

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

450 The increased root:shoot ratio apparent for *Forsythia* as a result of deficit irrigation
451 has important implications in the production of 'robust' plants which are able to
452 establish rapidly when transplanted. This is particularly true for better establishment
453 under semi-arid conditions (Franco et al., 2006). How this occurs, beyond
454 improvement in the plant's ability to capture water relative to that lost via

455 transpiration, is likely to be species-specific. In *Nerium oleander*, for example,
456 dehydration of the finer roots during transplanting is detrimental; deficit irrigation
457 induces thick roots, which increase the potential for water storage, leading to better
458 establishment of deficit irrigated plants (Bañón et al., 2006). In the current research
459 with *Forsythia*, however, it should be noted that an increased root:shoot ratio as a
460 result of deficit irrigation only occurred when irrigation was applied using a drip
461 system. The reduction in root biomass using overhead irrigation compared to drip
462 may have negative implications on transplanting and establishment. On the other
463 hand, drip irrigation can result in localised abundant root production in relation to the
464 dripper positioning in the container, where a high rooting density makes effective use
465 of applied water, but will limit the rate at which roots exploit the soil on transplanting.
466 The greater variation in volumetric moisture content within a layer shown here for
467 drip compared to overhead irrigation highlights the potential for localised root
468 formation under drip systems. Substrate types can also accentuate differences in water
469 distribution: coarse textured substrates lack small pore spaces to promote capillary
470 movement and water holding capacity (Klock-Moore and Broschat, 2001). Neither of
471 the substrates used in this study, however, accentuated variation in volumetric
472 moisture content compared to the other.

473 There was no interaction of irrigation quantity and substrate on final plant height,
474 implying that deficit irrigation can be used to control growth in a reduced peat
475 substrate, without any need to alter irrigation scheduling protocols developed for
476 100% peat. Reduced peat did not impact on root:shoot ratio, or variation within or
477 between pots in substrate volumetric moisture content. This may reflect limited
478 variation in water holding capacity between substrates with peat substitution from 40
479 to 70% (Caron et al., 1998). Yu and Zinati (2006) found that increasing the
480 percentage of bark from 40% to 90% in parallel with a decreasing percentage of peat
481 led to decreased substrate water holding capacity, from 63% to 49%. This difference
482 is small and would be easily managed within a deficit irrigation strategy and would
483 have little impact on its effectiveness with respect to growth control. Comparing two
484 peat-sand mixes, at 10% volumetric substrate moisture content, Bunt (1976) reported
485 a decrease in water tension of over 0.3 MPa for the 50:50 mix compared to the 75:25
486 mix, falling to a difference of only about 0.1 MPa at 20% volumetric moisture
487 content. Walczak et al. (2002) found substantial reductions in water retention only
488 when the peat content was far lower than in the current mixed substrate. Nonetheless,

489 hydraulic conductivity should be determined for different substrates. Londra (2010)
490 found considerable increases in hydraulic conductivity with the addition of perlite or
491 coir over pure peat (1.32 cm min⁻¹). Hydraulic conductivity has been frequently
492 assessed for pure peat (e.g. Walczak et al., 2002; Naasz et al., 2005; Londra, 2010),
493 but given the wide range of alternative substrates, used in different proportions with
494 peat, uncertainty remains regarding the hydraulic properties of specific substrate
495 mixes.

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

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

519 **5. Conclusions**

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

530

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532

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538

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684

685 **Figure captions**

686

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

689

690 **Fig. 21.** Variation between pots in water delivery, measured as weight gain of pots
691 during an irrigation event (a), and in volumetric substrate moisture content (θ , b)
692 during an experiment with deficit-irrigated *Lonicera periclymenum* ‘Graham Thomas’
693 (top) and *Cornus alba* ‘Elegantissima’ (bottom) under drip (shaded symbols) and
694 overhead (open symbols) irrigation. Boxes indicate the 25th to 75th percentile range,
695 whiskers extend another 15% either way, and outliers are represented by circles, n =
696 20. Application of 100% ET_A in (a) on that date would have equalled 165 mL
697 irrigation. Data in (b) were obtained following 7 weeks of irrigation treatments.

698

699 **Fig. 32.** Volumetric substrate moisture content (θ) in pots (a) and plant height (b) of
700 *Lonicera periclymenum* ‘Graham Thomas’ (top) and *Cornus alba* ‘Elegantissima’
701 (bottom) measured at intervals in an experiment comparing full irrigation (circles) and
702 deficit irrigation (50% ET_A – triangles – or 25% ET_A – squares), imposed via drip
703 (closed symbols) or overhead (open symbols) irrigation. Data are means \pm s.e., n = 10.

704

705 **Fig. 43.** Volumetric substrate moisture content (θ) at the top (a) and bottom (b) of
706 pots, and shoot (c) and root (d) dry mass of *Lonicera periclymenum* ‘Graham
707 Thomas’ (top) and *Cornus alba* ‘Elegantissima’ (bottom) following 8 weeks of full or
708 deficit irrigation (50% or 25% ET_A), applied via drip (closed symbols) or overhead
709 (open symbols). Bars represent means \pm s.e., n = 10. Within a single graph, different
710 letters represent significant differences between means (LSD) at P < 0.05.

711

712 **Fig. 54.** Volumetric substrate moisture content (θ , a) and increase in plant height
713 (shown as the cumulative increase from the start of the experiment or after pruning)
714 (b) during application of full (circles) or deficit (70% ET_A – triangles – or 50% ET_A –
715 squares) irrigation, applied via drip (closed symbols) or overhead (open symbols) to
716 *Forsythia × intermedia* ‘Lynwood’ grown in 100% peat (top) or a reduced peat
717 substrate (bottom). Symbols represent means \pm s.e., n = 16 before pruning and n = 10

718 following pruning.

719

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

725

726 **Fig. 6.** Volumetric substrate moisture content (θ) at the top (a), middle (b) and bottom
727 (c) of pots filled with 100% peat (top) or a reduced peat substrate (bottom), and in
728 which Forsythia × intermedia ‘Lynwood’ was grown under full or deficit (70% or
729 50% ET_A) irrigation, applied via drip (closed columns) or overhead (open columns),
730 measured in August, n = 5 pots. Asterisks denote significant differences between drip
731 and overhead irrigation, as indicated by post-hoc tests (LSD) following ANOVA, P <
732 0.05.

733

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

741

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

749

750

751

752 **Tables**

753

754 **Table 1**

755 Final plant canopy width of *Cornus alba* ‘Elegantissima’ following eight weeks of
756 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

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

760

761

762 **Table 2**

763 Coefficients of variation (%)^a of volumetric substrate moisture content in different
 764 layers of two types of substrate (100% peat or reduced peat) under two irrigation
 765 systems (drip or overhead) and three different quantities of irrigation (full or deficit –
 766 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

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

769

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771

772

Figure 1
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Figure 2

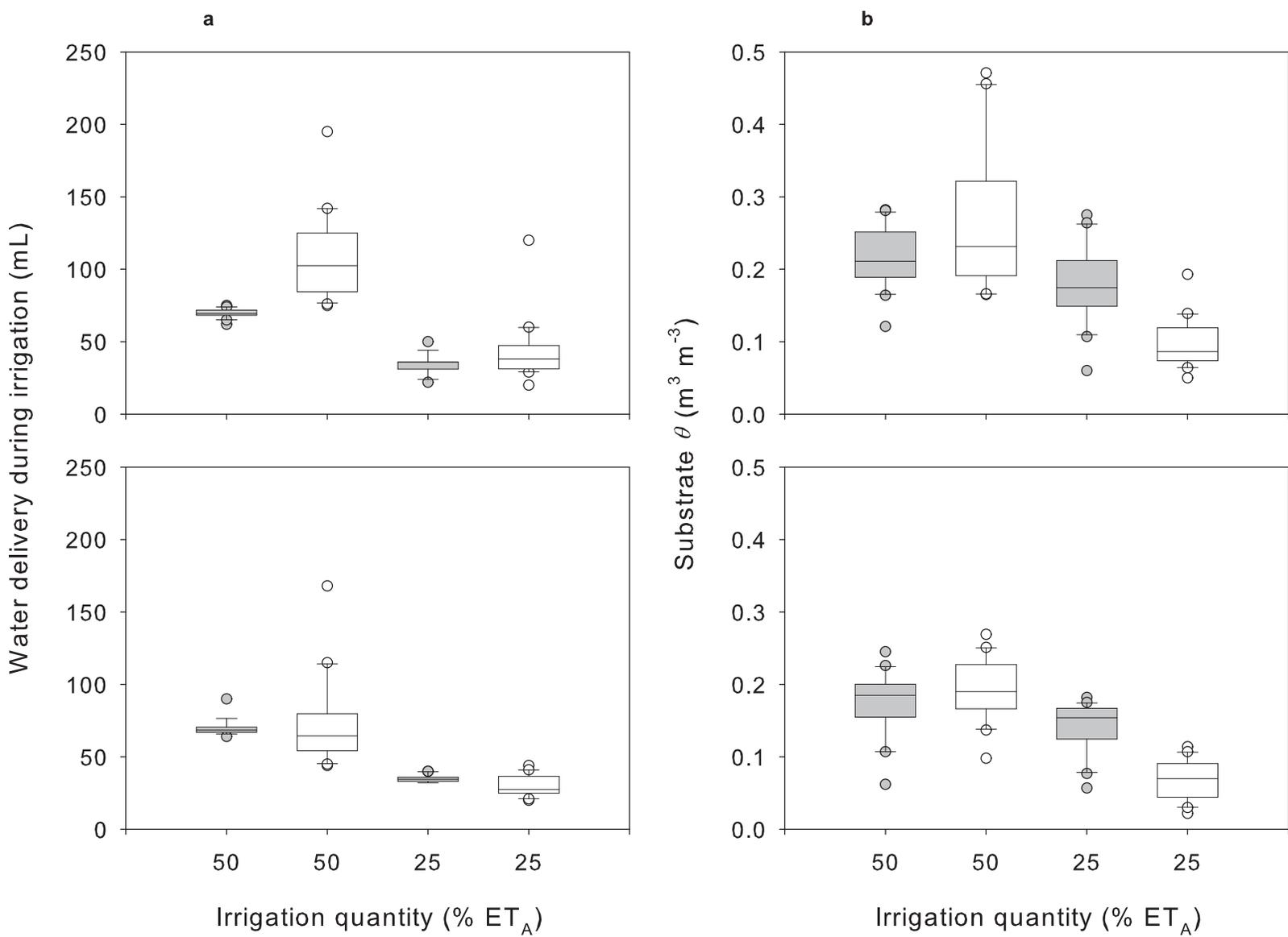


Figure 3

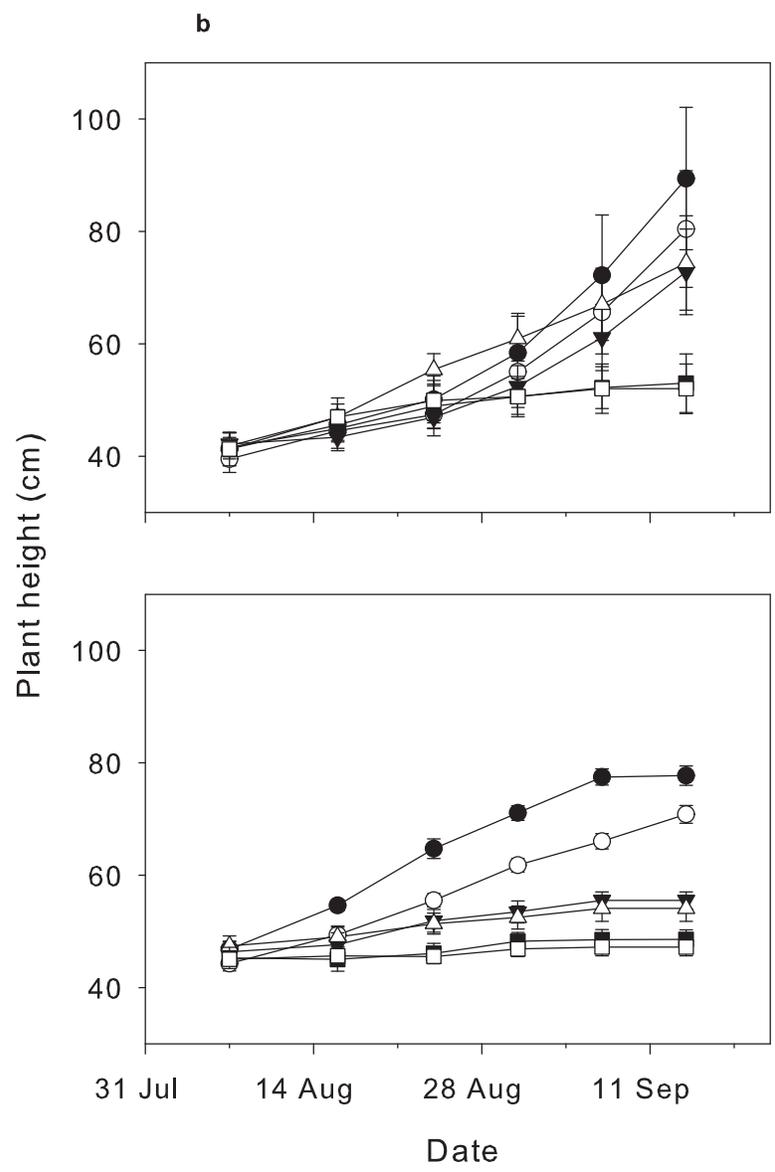
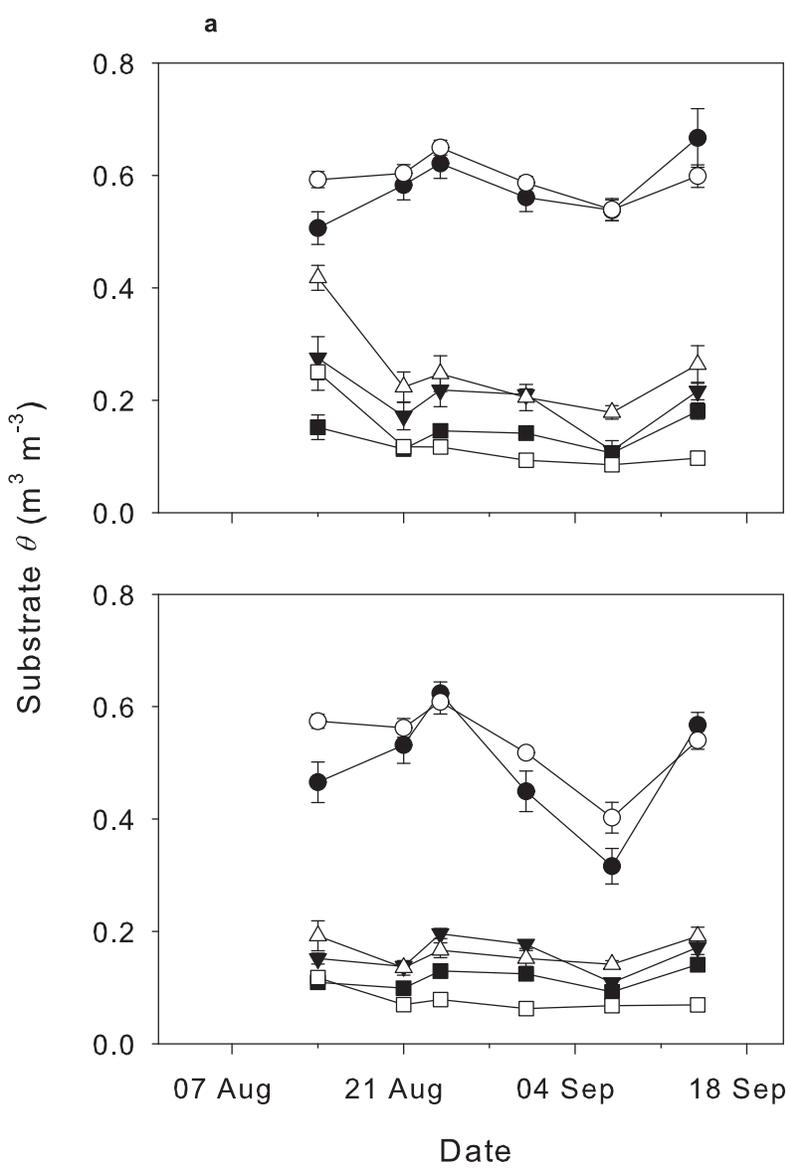


Figure 4

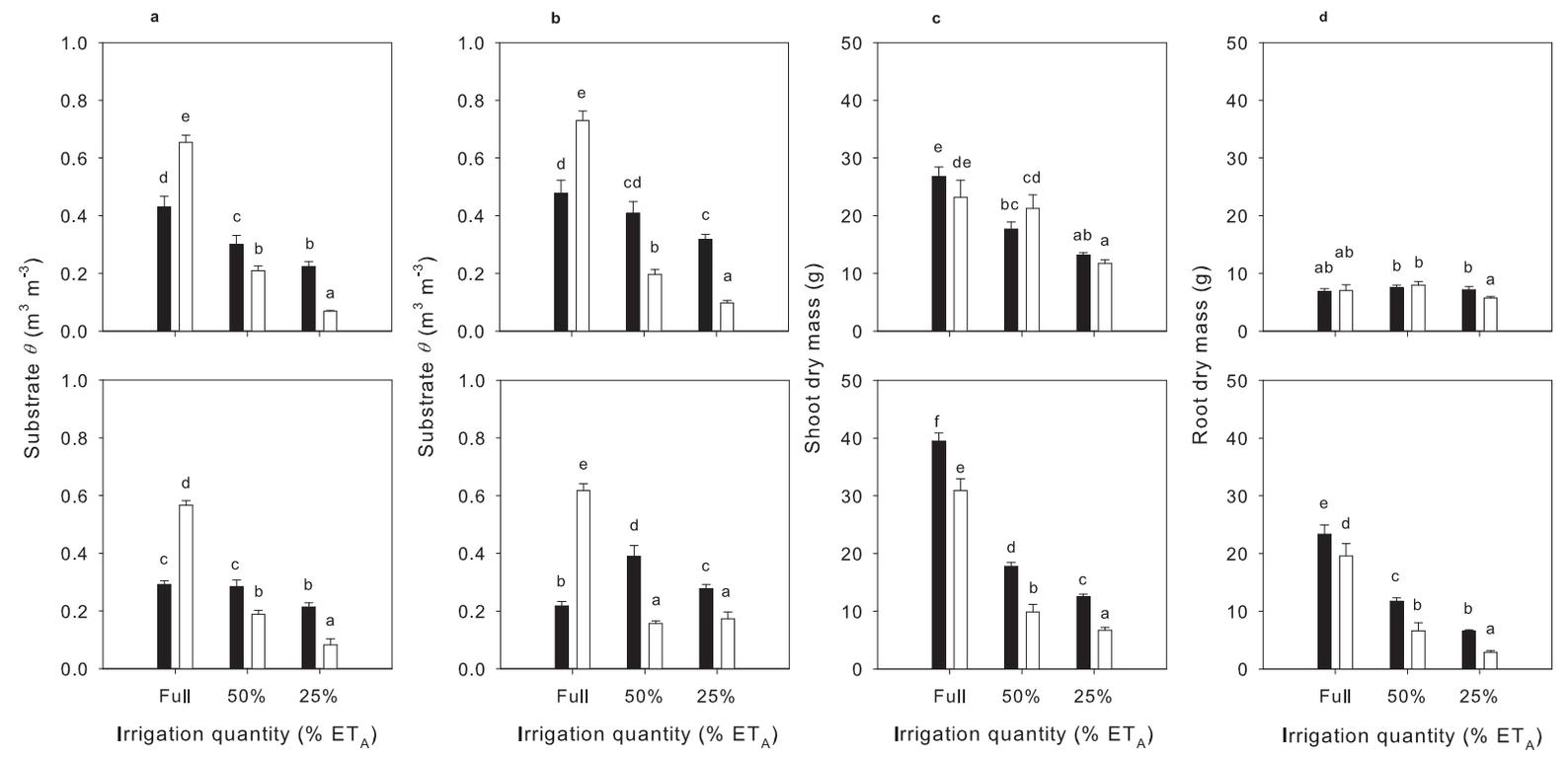


Figure 5

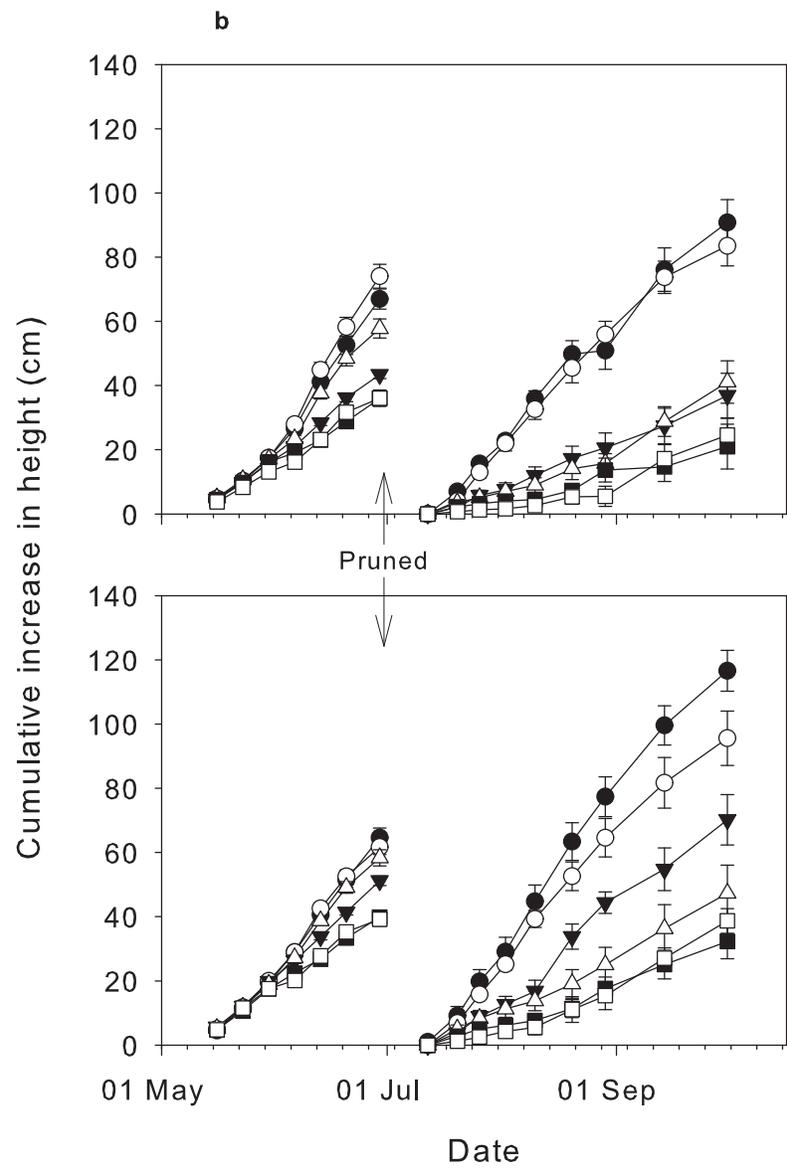
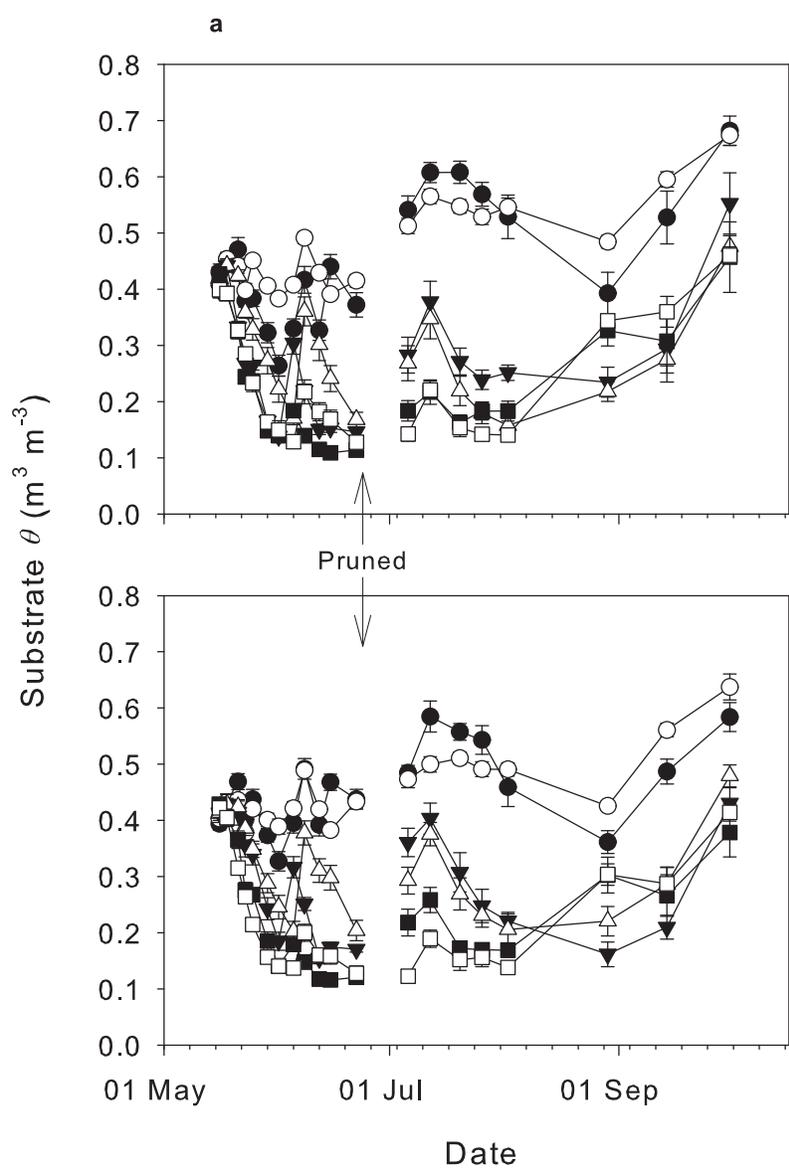


Figure 6

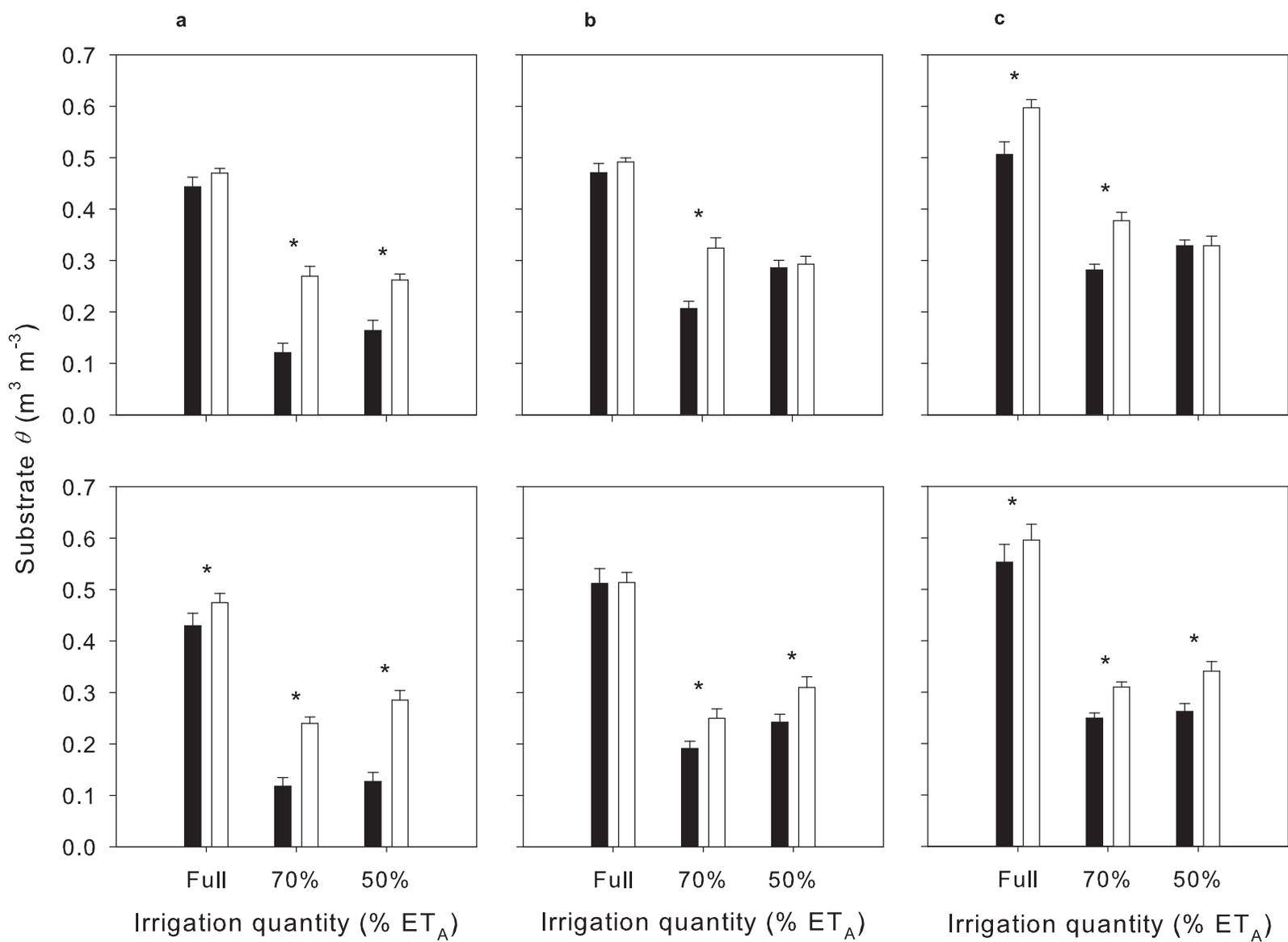


Figure 7

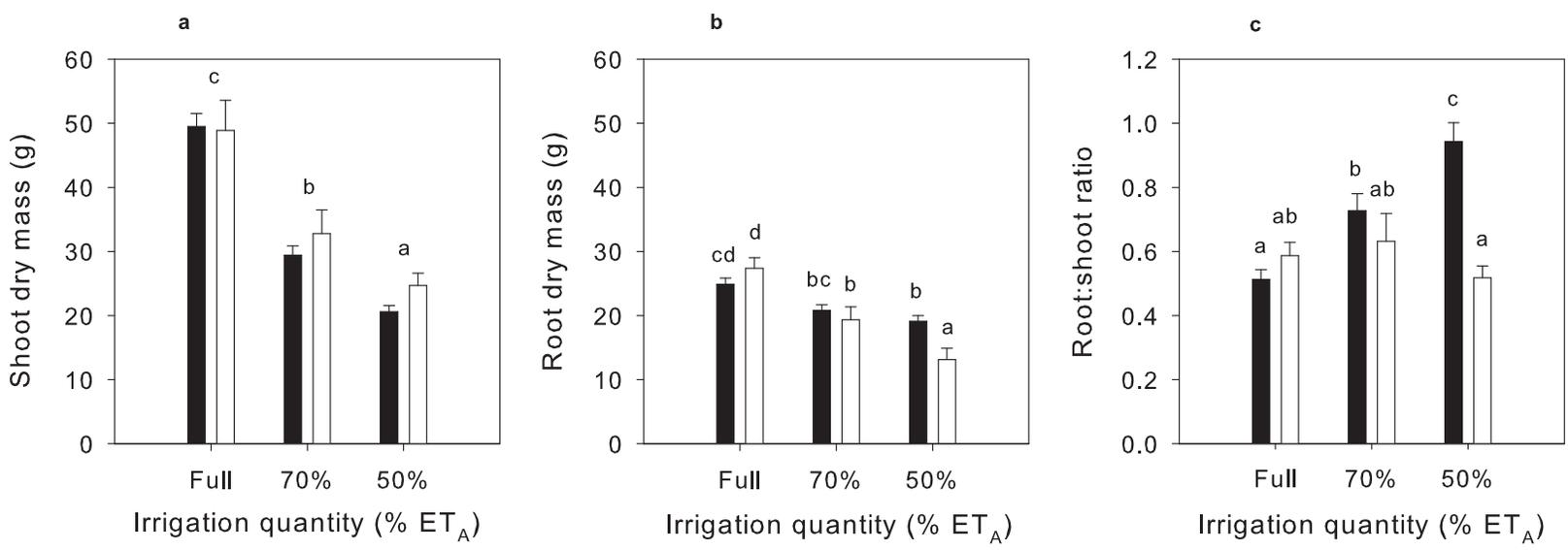


Figure 8

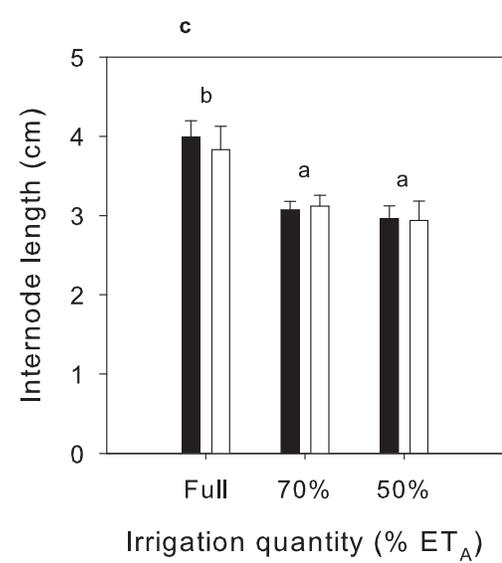
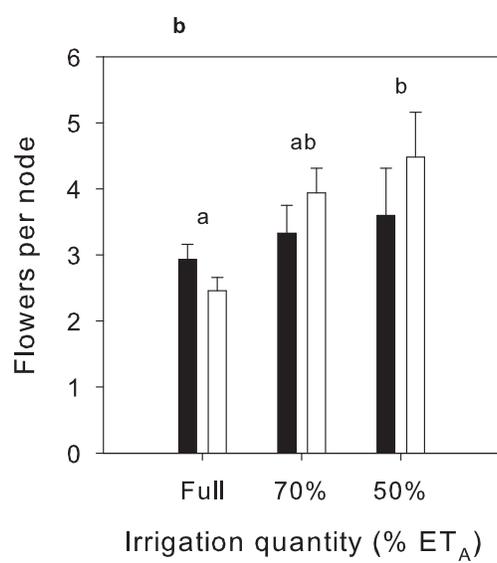
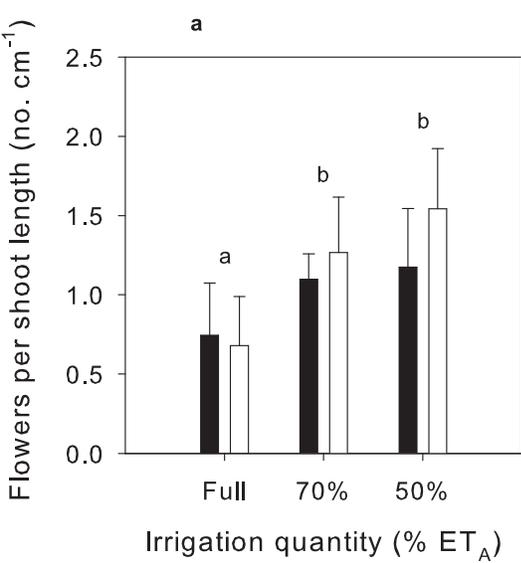


Figure 1

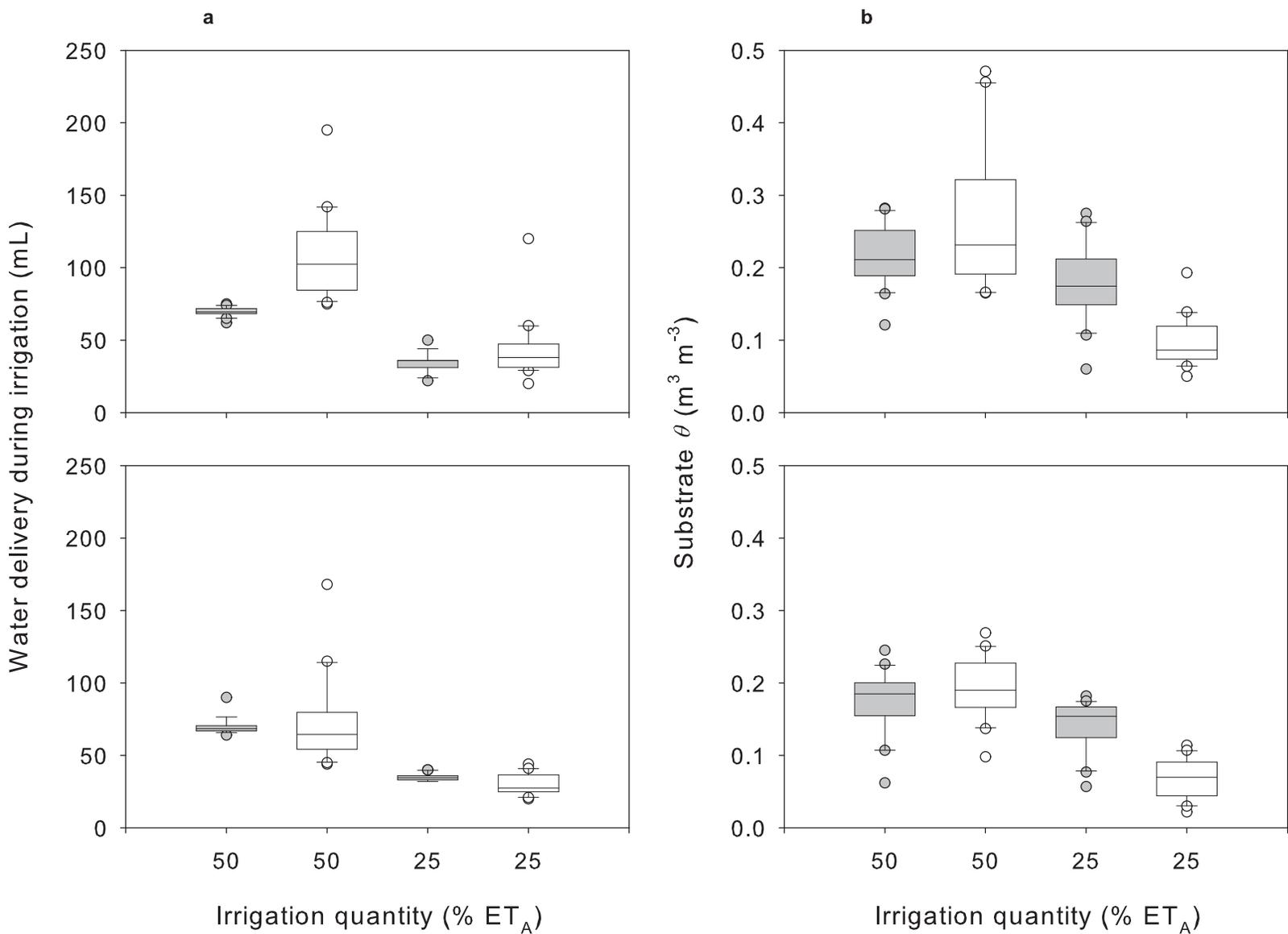


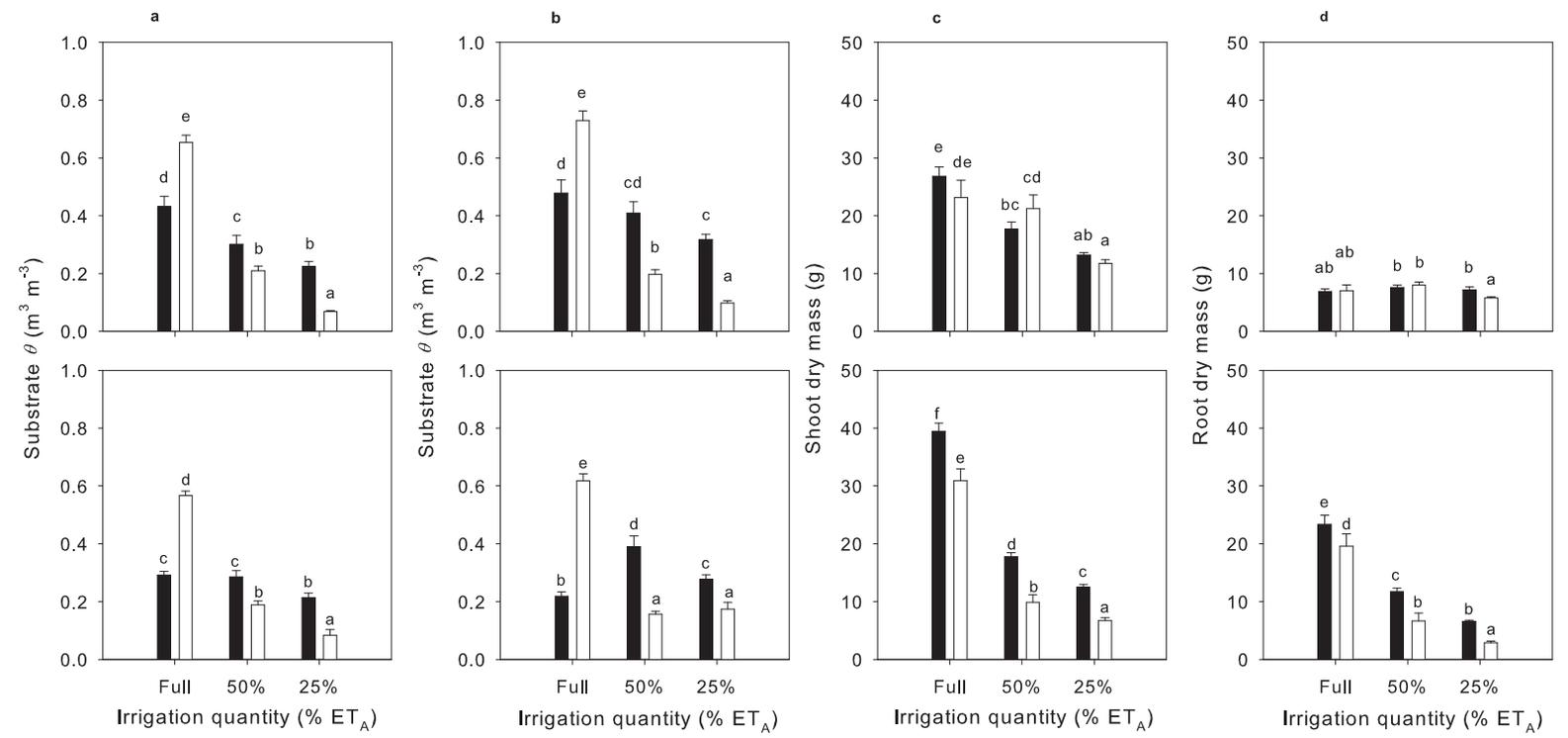
Figure 3

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

4

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17

18 Keywords:

19 Container production

20 Irrigation scheduling

21 Irrigation systems

22 Peat alternatives

23 Plant growth management

24 Resource use efficiency

25

26 ABSTRACT

27

28 Growth control of container-grown hardy nursery stock generally requires substantial
29 labour investment. Therefore the possibility of alternative growth control using deficit
30 irrigation is appealing. Increasing water costs and limited availability of abstraction
31 licences have added further incentives for nursery stock producers to use deficit
32 irrigation. There are still, however, concerns that inherent non-uniformity of water
33 uptake under commonly used overhead irrigation, and differing irrigation
34 requirements of diverse crops and substrates, may limit the commercial relevance of a
35 protocol developed for single crops growing in 100% peat and irrigated with a high
36 precision drip system. The aim of this research was to determine whether growth
37 control of hardy nursery stock is possible using deficit irrigation applied with
38 conventional overhead irrigation. Over two years, crop growth under an overhead
39 irrigation system was compared under full irrigation and two severities of deficit
40 irrigation. Initially, two crops of contrasting canopy structure i.e. *Cornus alba* and
41 *Lonicera periclymenum* were grown. In a subsequent experiment one crop (*Forsythia*
42 \times *intermedia*) was grown in two substrates with contrasting quantities of peat (60 and
43 100%). Deficit irrigation was found to be highly effective in controlling vegetative
44 growth when applied using overhead irrigation – with similar results as when drip
45 irrigation was used. This comparable response suggests that deficit irrigation can be
46 applied without precision drip irrigation. Scheduling two very different crops with
47 respect to their water use and uptake potential, however, highlighted challenges with
48 respect to application of appropriate deficits for very different crops under one
49 system; responses to deficit irrigation will be more consistent where nursery
50 management allows for scheduling of crops with very different architecture and water
51 use under different regimes. The effectiveness of deficit irrigation in controlling the
52 growth of *Forsythia* was similar when a reduced peat based substrate was compared
53 with pure peat; additionally, flowering was enhanced.

54

55

56 **1. Introduction**

57

58 Future global irrigation management will require users to look for methods of
59 application which are efficient (Bacci et al., 2008; Kim et al., 2011; Majsztrik et al.,
60 2011; Lea-Cox et al., 2013). For example, metrics such as water use and water
61 productivity (Fereres and Soriano, 2006) may be required to justify irrigation
62 practices. The use of deficit irrigation not only provides the means by which water use
63 can be reduced and its use efficiency enhanced, but also enables crop growth and
64 quality to be controlled (Jensen et al., 2010; Cirillo et al., 2014). Deficit irrigation is
65 the application of less water than a crop would lose by evapotranspiration if water
66 availability was not limiting (Fereres et al., 2003). However, for deficit irrigation to
67 be effective requires understanding crop growth patterns, and some commentators
68 suggest that use of advanced irrigations systems is also essential (Evans and Sadler,
69 2008; O'Meara et al., 2013). Deficit irrigation is applied either as sustained deficit
70 irrigation i.e. by systematically applying water at a constant fraction of potential
71 evapotranspiration through the season, or as regulated deficit irrigation, in which case
72 soil moisture deficits are imposed only at certain plant developmental stages (Costa et
73 al., 2007).

74 The primary challenges in the development of effective application of deficit
75 irrigation to control growth and quality in container grown crops, such as hardy
76 nursery stock, are a multitude of species and cultivars with different water
77 requirements, and sensitivities to deficit irrigation, combined with a general absence
78 of economic justification for the use of sophisticated precision irrigation systems
79 (Kim et al., 2011; Majsztrik et al., 2011). There are examples, however, where
80 economic assessment reveals apparently good initial savings and returns from
81 investment in irrigation automation (Majsztrik et al., 2011; Belayneh et al., 2013).
82 The successful application of deficit irrigation in hardy nursery stock production
83 offers environmental and economic benefits, such as reduced container leaching of
84 nutrients and pesticides and a reduction in fertiliser and pesticide costs associated with
85 wastage (Caron et al., 1998). This combination of economic with environmental
86 benefits has been recently highlighted (Levidow et al., 2014) as critical if producers
87 are to take up opportunities for improved water management. Other benefits may arise
88 from nursery production of more robust plants when subjected to environmental
89 stresses, such as drought (Cameron et al. 2008). Some studies have now begun to

90 elucidate the mechanisms by which deficit irrigation approaches achieve these ‘carry-
91 over’ effects in the container crop production cycle (Sanchez-Blanco et al., 2004;
92 Bañón et al., 2006; Cameron et al., 2006; Franco et al., 2006).

93 HNS production approaches are economically constricted by the need for mass
94 production to consistently high crop quality (Warsaw et al., 2009). Despite retailer
95 requirements for producers to meet precise crop-specific quality criteria (Álvarez et
96 al., 2009; Majsztrik et al., 2011), retail margins often mean that investment in
97 sophisticated irrigation approaches is not easily justified. Despite the high labour costs
98 in nurseries’ budgets, at least in UK, Dutch, and Irish production (Thorne et al.,
99 2002), and the potential for deficit irrigation to remove or reduce the need for costly
100 operations such as manual pruning (Cameron et al., 1999), there is still a lack of
101 commercial confidence in the application of the approach (Kim et al., 2011). There
102 are a number of questions which need answering before widespread uptake of deficit
103 irrigation for container production is likely (Belayneh et al., 2013).

104 One of the concerns with respect to commercial application of deficit irrigation is
105 whether approaches developed for high precision drip irrigation can be adapted for
106 extensive commercial practice, which still relies heavily on overhead irrigation
107 (Briercliffe et al., 2000; Pettitt 2014). The drawbacks of overhead irrigation are well
108 described and for hardy nursery stock focus on a lack of spatial uniformity of
109 irrigation supply meeting crop water ‘demand’; this may have considerable
110 implications for crop uniformity when deficit irrigation reduces container substrate
111 water availability (Beeson and Knox, 1991; Beeson and Yeager, 2003; Grant et al.,
112 2011). Related to the use of overhead irrigation is the tendency to grow several crops
113 under one system. Differences in water use and uptake amongst species may mean
114 that a deficit appropriate for one crop is detrimental for another.

115 The capacity of the container substrate to sustain the applied deficit irrigation
116 regime must also be considered. Most commercial experience lies with the use of pure
117 peat, but continued reliance on pure peat production is not sustainable (Barkham,
118 1993; Chapman et al., 2003; Alexander et al., 2008). Substrate producers are therefore
119 looking into alternative media, at least to reduce, if not completely replace, peat
120 consumption (Alexander et al., 2008). Changing the constituents in growing media,
121 however, frequently alters the water holding capacity of the substrate (Yu and Zinati,
122 2006).

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

127

128 **2. Materials and methods**

129

130 2.1. Plant material and the growing environment

131

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

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

149

150 2.2. Irrigation systems and scheduling

151

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

156 treatments were allocated randomly to the different bays. In the case of full irrigation,
157 150% ET_A was applied to ensure that even if irrigation delivery was non-uniform, all
158 plants would receive at least 100% ET_A . Excess water ran through the pot bases, and
159 drained freely through the MyPex and the gravel beneath, showing no signs of ground
160 surface accumulation. High quality mains supply water was used for irrigation.

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

178 ET_A was determined every two weeks by weighing plants in the full irrigation
179 treatments after irrigation (after allowing for pot gravity draining, and water
180 intercepted by the canopy to run off) and again a day later. Wet leaf temperature
181 depression was determined simultaneously with a sensor (Evaposensor, Skye, Powys,
182 UK) located in the crop. The sensor continuously measures temperature differences
183 between wet and dry artificial leaves (Harrison-Murray, 1991), with the accumulated
184 difference recorded and logged via a dedicated meter (Evapometer, Skye), as °C h,
185 where 1°C h equates to a difference of 1°C for a duration of 1 h. Thus, for example, if
186 a plant uses 100 mL water during an accumulation of 100°C h, this plant will require
187 1 mL of irrigation for every 1°C h accumulated, if the intention is to apply 100% of
188 ET_A . Combining water use per °C h with the time required to apply the determined

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

197

198 2.3. A single species scheduling approach applied to crops of contrasting canopy
199 structure

200

201 Lonicera and Cornus growing in 100% sphagnum peat (Shamrock Premium
202 Grade, Bord na Móna, Newbridge, Co. Kildare, Ireland) were compared in year 1
203 (2006). This peat consists of particles up to 14 mm, including 50% in the range 6-12
204 mm, and has an approximate air filled porosity of 12% and electrical conductivity < 1
205 $mS\ cm^{-1}$. Plants were arranged in five rows per bay, with Lonicera on one half of the
206 bed and Cornus on the other, providing 21 experimental plants of each species, which
207 were fully guarded. The deficit irrigation treatments applied were 50% ET_A and 25%
208 ET_A i.e. crops were irrigated to replace 50% or 25% of water used by the fully
209 irrigated plants. These two deficit irrigation treatments were selected to represent a
210 deficit of sufficient severity to have a noticeable impact on growth (50%), and a very
211 severe deficit that might risk reducing plant quality (25%). Results from the two
212 different severities would thus be expected to provide a guideline for a range
213 appropriate for use on nurseries. Irrigation for both the crops was scheduled on the
214 basis of crop factors obtained for Lonicera. The reasoning for this is that different
215 crops are often grown together on single beds, and with overhead irrigation will
216 inevitably be irrigated by the same amount. Treatments were applied from the start of
217 August, for eight weeks. During this time, daily mean air temperature in the tunnel
218 was on average 21.4°C, ranging from 16.3°C to 24.9°C. Relative humidity was on
219 average 82.9%. Average mean and maximum daytime global radiation were 188 and
220 $455\ W\ m^{-2}$, respectively, with the maximum global radiation reached equalling 655

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

223

224 2.4. Comparison of substrates

225

226 100% peat (as above) was compared with a reduced peat mix [60% peat: 40% bark
227 (Melcourt Potting bark, Melcourt Industries Ltd., Tetbury, Gloucestershire, UK)].
228 Particles in the selected bark are predominantly in the range 3-15 mm, and its air
229 filled porosity is approximately 62%, with an electrical conductivity of about 0.1 mS
230 cm^{-1} . For the reduced peat mix, 1 g ammonium nitrate per L of bark was incorporated
231 to compensate for the low nitrogen availability in bark (see recommendation by
232 Wright et al., 1999). The two substrate treatments were replicated randomly in each
233 bay. Plants of Forsythia were arranged in four rows per bay and DI treatments of 70%
234 and 50% ET_A applied. These treatments were selected following analysis of the first
235 experiment, with the 70% ET_A representing a mild deficit – potentially the smallest
236 reduction in water supply likely to show a significant reduction in growth. Crop
237 evapotranspiration of Forsythia in 100% peat and in the reduced peat mix was similar,
238 and therefore crop factors for irrigation scheduling were based on average crop ET_A
239 (measured by pot weighing as above) across both substrates.

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

254

255 2.5. Substrate moisture content

256

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

270

271 2.6. Plant growth, biomass allocation, and flowering

272

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

283

284 2.7. Statistical analysis

285

286 The significance of treatment differences was assessed by analysis of variance
287 (ANOVA), followed by LSD tests where appropriate, in Genstat software (Genstat
288 9.1, Rothamsted Experimental Station, UK). A repeated measures ANOVA was used
289 where variables were measured repeatedly on the same individual plants or pots.

290

291 **3. Results**

292

293 3.1. A single species scheduling approach applied to crops of contrasting canopy
294 structure

295

296 The overhead sprinkler arrangement achieved a Christiansen's coefficient of
297 uniformity of 91%, a scheduling coefficient of 1.2, and a mean application rate of 7.7
298 mm per hour. Drip irrigation resulted in a Christiansen's coefficient of uniformity of
299 96-98% and a scheduling coefficient of 1.0 to 1.1. While there was evidence during
300 irrigation that pot weight gain was less homogenous under overhead compared to drip
301 irrigation (example in Fig. 2a), variation in substrate volumetric moisture content was
302 not consistently greater under overhead irrigation (example in Fig. 2b). Measurements
303 of water uptake indicated that Cornus under overhead irrigation took up less water
304 than Lonicera (Fig. 2a), while water uptake with drip was similar for both crops.

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

315 Over the course of the experiment, deficit irrigation significantly ($P < 0.05$)
316 reduced substrate volumetric moisture content (Fig. 3a), on average, across all pots,
317 and resulted in reduced growth (Fig. 3b). For both Lonicera and Cornus, there was an
318 interaction between irrigation quantity (% ET_A) and method of application on

319 substrate volumetric moisture content ($P < 0.001$). For *Lonicera*, there was no
320 difference between drip and overhead irrigation with respect to plant growth over the
321 experiment (Fig. 3b). For *Cornus*, there was an interaction of irrigation system and %
322 ET_A applied ($P = 0.003$) over the experiment, resulting in final plant heights being
323 reduced under overhead compared to drip irrigation when full irrigation was applied,
324 but not when deficit irrigation was applied. *Cornus* plants showed wider leaf canopy
325 diameters at the end of the experiment when drip irrigated compared to overhead, and
326 reduced canopy diameters under deficit compared to full irrigation (both $P < 0.001$;
327 Table 1).

328 At the end of the experiment, an interaction between irrigation system and % ET_A
329 ($P < 0.001$) was detected on mean substrate volumetric moisture content, both at the
330 top and at the bottom of the pot, for both species. Substrate volumetric moisture
331 content was lower under overhead than drip irrigation for both deficit irrigation
332 treatments. On the other hand, it was higher under overhead than drip irrigation when
333 full irrigation was applied (Fig. 4a, b). For *Lonicera*, shoot dry mass was not
334 significantly affected by the type of irrigation (drip vs. overhead) within a given %
335 ET_A . However, there was a significant effect of % ET_A on plant mass ($P < 0.001$ for
336 shoots and $P = 0.025$ for roots). Under drip irrigation both deficit treatments showed
337 reduced shoot, but not root, dry mass, whereas under overhead irrigation only the
338 more severe deficit reduced shoot dry mass (Fig. 4c, d). Root:shoot ratio decreased as
339 % ET_A increased ($P < 0.001$, data not shown). For *Cornus*, both shoot dry mass and
340 root dry mass were affected by % ET_A ($P < 0.001$), with increasing dry mass at the
341 higher % ET_A (Fig. 4c, d). Both shoot and root mass was greater under drip irrigation
342 compared to overhead ($P < 0.001$). Root:shoot ratio was affected by % ET_A ($P <$
343 0.001), with a lower root: shoot ratio under 25% ET_A than under the other two
344 treatments (data not shown).

345

346 3.2. Comparison of substrates

347

348 During the second experiment, evapotranspiration of the fully irrigated crop was
349 on average 3.2 mm day^{-1} , accumulating to 445 mm over the whole season. Thus daily
350 averages of 4.9, 2.3, and 1.6 mm day^{-1} irrigation was applied to the full (150% ET_A),
351 70% ET_A and 50% ET_A treatments, respectively. As a result, over the entire growing

352 season, 667 mm irrigation was applied to the fully irrigated crop, and 311 and 222
353 mm to the milder and more severe deficit treatments, respectively. Substrate
354 volumetric moisture content was reduced by deficit irrigation throughout this
355 experiment ($P < 0.001$) (Fig. 5a). A frequent but less consistent effect of irrigation
356 system also occurred, but only occasionally were differences in substrate volumetric
357 moisture content seen between the two types of substrate. Growth slowed in the 50%
358 ET_A DI treatment from 14 days after treatments started ($P \leq 0.012$; Fig. 5b). Five
359 weeks from the start of the experiment, an interaction with respect to cumulative plant
360 height increment was seen between irrigation quantity and system ($P = 0.013$).
361 Differences between treatments in shoot growth were reflected in the average mass of
362 shoot material per plant obtained during pruning: 10–12 g for 50% ET_A , 12–18 g for
363 70% ET_A , and 22–24 g for full irrigation. Post-pruning bud break was significantly
364 lower ($P < 0.001$) in the deficit irrigation treatments (around 7–9 bud breaks per
365 plant) than in the full irrigation treatment (around 16 bud breaks per plant). After
366 pruning, rapid growth was seen under full irrigation, with growth much reduced under
367 deficit irrigation (Fig. 5b). From pruning onwards, there was no interaction between
368 substrate and irrigation quantity or system, and no interaction between irrigation
369 quantity and system i.e. reduced growth occurred with deficit irrigation using both
370 drip and overhead and with both 100% peat and the reduced peat substrates. The
371 combination of fewer bud breaks and reduced shoot elongation under deficit irrigation
372 led to more compact plants. Growth was greater in the reduced peat substrate ($P <$
373 0.001).

374 Early in August, Forsythia plants were removed from their pots and variation in
375 substrate volumetric moisture content determined. Coefficients of variation ($100\% \times$
376 $\text{standard deviation/mean}$) between the four measurements per layer (top, middle, or
377 bottom) of the substrate showed that greatest variation most frequently occurred at the
378 top (Table 2). Variation within a substrate layer was generally much greater when DI
379 was applied using drip irrigation rather than overhead. Variation was also generally
380 greater for the more severe deficit. Generally across all pots, independently of
381 whether full or deficit irrigation was applied, the substrate was drier in the top layer
382 with both substrate types and both irrigation systems ($P < 0.001$, Fig. 6). Substrate
383 volumetric moisture content tended to be greater using overhead irrigation compared
384 to drip.

385 In autumn, shoot dry mass was affected only by % ET_A applied ($P < 0.001$, Fig.
386 7a), with shoot dry mass increasing with % ET_A. Root dry mass was also affected by
387 the interaction of % ET_A with type of irrigation ($P = 0.02$, Fig. 7b). With overhead
388 irrigation, root dry mass increased with increasing % ET_A, but this response was less
389 clear with drip irrigation. Thus, when drip was used, compared to overhead irrigation,
390 root dry mass was not as reduced by the more severe deficit relative to full irrigation.
391 Root:shoot ratio was also affected by the interaction of % ET_A and type of irrigation
392 ($P < 0.001$, Fig. 7c). The root:shoot ratio decreased with increasing % ET_A under drip
393 irrigation, but this did not occur under overhead irrigation.

394 The following spring, number of flowers per unit shoot length was affected by the
395 % ET_A applied ($P < 0.001$, Fig. 8a). The plants receiving full irrigation had
396 approximately half the number of flowers per unit shoot length compared to those
397 receiving 50% ET_A. The increased number of flowers over a given length of shoot in
398 the deficit irrigation treatments was a result of an increased number of flowers per
399 node ($P = 0.018$, Fig. 8b) and shorter internode lengths ($P < 0.001$, Fig. 8c).

400

401 **4. Discussion**

402

403 A reduction of substrate volumetric moisture content, in response to deficit
404 irrigation, led to a reduction in the shoot growth of all the species used here, as it does
405 with other species (Beeson 1992; Cameron et al. 1999; Grant et al. 2004; Chaves et al.
406 2007). This reduction is also known to influence a number of different growth
407 variables, both above and below ground (Franco et al., 2006). In most previous
408 research, however, deficit irrigation has been applied using a high-precision drip
409 irrigation system. Our novel approach was to validate the potential of deficit irrigation
410 to control growth through the utilisation of overhead irrigation – which is still an
411 important and much used system in commercial ornamental plant production.
412 Different irrigation systems are known to impact on plant dry matter production even
413 when full irrigation is applied (Klock-Moore and Broschat, 2001), and deficit
414 irrigation might accentuate such effects.

415 Here we show that irrespective of type of irrigation system used (drip or overhead)
416 to apply deficit irrigation, reduced growth was apparent in response to a decline in
417 substrate volumetric moisture content. The experiment with *Cornus*, however, showed

418 that plant size was dependent on the irrigation system used, with reduced canopy
419 diameter and biomass with overhead irrigation compared to drip. The reason *Cornus*
420 grew less with overhead irrigation relates to this crop taking up less water than
421 *Lonicera*. This response was visually apparent during irrigation events, where applied
422 water was deflected by the *Cornus* canopy while the supported upright structure of
423 *Lonicera* promoted water funnelling into the pots. *Cornus* growth was excessively
424 reduced by the application of the severe deficit, highlighting the difficulty of
425 scheduling deficit irrigation for different species using the same irrigation system. We
426 strongly recommend that users grow crops together which have similar canopy
427 architectural and structural attributes along with similar water uptake. Several factors
428 not included here are known to exacerbate non-uniformity of overhead irrigation
429 delivery (Li 1998; Grant 2012).

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

440 The increased root:shoot ratio apparent for *Forsythia* as a result of deficit irrigation
441 has important implications in the production of 'robust' plants which are able to
442 establish rapidly when transplanted. This is particularly true for better establishment
443 under semi-arid conditions (Franco et al., 2006). How this occurs, beyond
444 improvement in the plant's ability to capture water relative to that lost via
445 transpiration, is likely to be species-specific. In *Nerium oleander*, for example,
446 dehydration of the finer roots during transplanting is detrimental; deficit irrigation
447 induces thick roots, which increase the potential for water storage, leading to better
448 establishment of deficit irrigated plants (Bañón et al., 2006). In the current research
449 with *Forsythia*, however, it should be noted that an increased root:shoot ratio as a
450 result of deficit irrigation only occurred when irrigation was applied using a drip
451 system. The reduction in root biomass using overhead irrigation compared to drip

452 may have negative implications on transplanting and establishment. On the other
453 hand, drip irrigation can result in localised abundant root production in relation to the
454 dripper positioning in the container, where a high rooting density makes effective use
455 of applied water, but will limit the rate at which roots exploit the soil on transplanting.
456 The greater variation in volumetric moisture content within a layer shown here for
457 drip compared to overhead irrigation highlights the potential for localised root
458 formation under drip systems. Substrate types can also accentuate differences in water
459 distribution: coarse textured substrates lack small pore spaces to promote capillary
460 movement and water holding capacity (Klock-Moore and Broschat, 2001). Neither of
461 the substrates used in this study, however, accentuated variation in volumetric
462 moisture content compared to the other.

463 There was no interaction of irrigation quantity and substrate on final plant height,
464 implying that deficit irrigation can be used to control growth in a reduced peat
465 substrate, without any need to alter irrigation scheduling protocols developed for
466 100% peat. Reduced peat did not impact on root:shoot ratio, or variation within or
467 between pots in substrate volumetric moisture content. This may reflect limited
468 variation in water holding capacity between substrates with peat substitution from 40
469 to 70% (Caron et al., 1998). Yu and Zinati (2006) found that increasing the
470 percentage of bark from 40% to 90% in parallel with a decreasing percentage of peat
471 led to decreased substrate water holding capacity, from 63% to 49%. This difference
472 is small and would be easily managed within a deficit irrigation strategy and would
473 have little impact on its effectiveness with respect to growth control. Comparing two
474 peat-sand mixes, at 10% volumetric substrate moisture content, Bunt (1976) reported
475 a decrease in water tension of over 0.3 MPa for the 50:50 mix compared to the 75:25
476 mix, falling to a difference of only about 0.1 MPa at 20% volumetric moisture
477 content. Walczak et al. (2002) found substantial reductions in water retention only
478 when the peat content was far lower than in the current mixed substrate. Nonetheless,
479 hydraulic conductivity should be determined for different substrates. Londra (2010)
480 found considerable increases in hydraulic conductivity with the addition of perlite or
481 coir over pure peat (1.32 cm min^{-1}). Hydraulic conductivity has been frequently
482 assessed for pure peat (e.g. Walczak et al., 2002; Naasz et al., 2005; Londra, 2010),
483 but given the wide range of alternative substrates, used in different proportions with

484 peat, uncertainty remains regarding the hydraulic properties of specific substrate
485 mixes.

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

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

508

509 **5. Conclusions**

510

511 Deficit irrigation applied by overhead irrigation can be used to control growth and
512 quality of container grown crops as effectively as when applied by drip irrigation.
513 Therefore effective deficit does not rely solely on more expensive and less frequently
514 used drip irrigation. This conclusion should encourage commercial uptake of deficit
515 irrigation. Addressing the challenge of identifying a deficit irrigation regime that is
516 appropriate for specific cultivars and level of growth control will require more
517 experimentation. Additionally, approaches to scheduling that can be easily applied

518 commercially (e.g. monitoring evapotranspiration or substrate volumetric moisture
519 content) merit further consideration.

520

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522

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528

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674

675 **Figure captions**

676

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

679

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

688

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

694

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

701

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

708 following pruning.

709

710 **Fig. 6.** Volumetric substrate moisture content (θ) at the top (a), middle (b) and bottom
711 (c) of pots filled with 100% peat (top) or a reduced peat substrate (bottom), and in
712 which Forsythia \times intermedia ‘Lynwood’ was grown under full or deficit (70% or
713 50% ET_A) irrigation, applied via drip (closed columns) or overhead (open columns),
714 measured in August, n = 5 pots. Asterisks denote significant differences between drip
715 and overhead irrigation, as indicated by post-hoc tests (LSD) following ANOVA, P <
716 0.05.

717

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

725

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

733

734

735

736 **Tables**

737

738 **Table 1**

739 Final plant canopy width of *Cornus alba* ‘Elegantissima’ following eight weeks of
 740 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

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

744

745

746 **Table 2**
 747 Coefficients of variation (%)^a of volumetric substrate moisture content in different
 748 layers of two types of substrate (100% peat or reduced peat) under two irrigation
 749 systems (drip or overhead) and three different quantities of irrigation (full or deficit –
 750 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

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

753

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