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1 **Cut-off in their prime? Response of two landscape shrubs to**  
2 **different levels of root pruning, during active and quiescent**  
3 **growth phases.**

4  
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16  
17

18 **Abstract**

19 Shrubs have an important role in the future design of urban landscapes. Due to city-  
20 densification and pressure on space, shrubs are increasingly preferred over trees for urban  
21 amenity plantings. In contrast to trees, however, relatively little information exists on how  
22 shrubs adapt to urban stress. This includes their responses to physical root injury, that might  
23 occur through trenching or transplanting activities. Two shrub taxa, *Philadelphus coronarius*  
24 'Aureus' and *Euonymus fortunei* 'Silver Queen' were used to investigate the effects of severity  
25 and time of root injury on plant viability, and how additional fertilizer influenced recovery. A  
26 novel 'split-pot' system was developed to differentiate where root injury was induced. Results  
27 showed that both taxa were relatively resilient to root-pruning, although root injury was more  
28 detrimental during active growth than when plants were quiescent. This re-enforces the notion  
29 that transplanting of shrubs should be avoided in summer. Shoot development was not more  
30 detrimentally affected by severe root-pruning compared to light pruning. There was also  
31 evidence that uniform severe pruning across the root-ball stimulated stronger root-regeneration  
32 compared to root systems differentially injured. No consistent response to fertilizer was noted.  
33 Results have implications for the resilience and management of shrubs within the urban  
34 landscape.

35

36 **Keywords:** fertilizer; root loss; root injury; stress; transplanting; urban

37 **Word count (main text) = 4811**

## 38 **Introduction**

39 Shrubs are low-growing (0.5-6m) multi-stemmed, woody plants, frequently used in landscape  
40 design. Yet compared to trees their use, adaptability and function in urban landscapes tends to  
41 receive comparatively less research attention. This is surprising as they are widely used in  
42 urban landscapes, civic parks and private gardens and increasingly so in green walls and roof  
43 gardens (Cameron and Hitchmough, 2016). Moreover, as city densification increases and  
44 competition for urban space becomes more acute, it is feasible that the role of shrubs will  
45 become paramount in providing green infrastructure, as essentially they take up less space  
46 than trees.

47

48 Like trees, urban shrubs can be exposed to a range of stress factors, undermining their  
49 functionality (Franco et al., 2006; Cassaniti et al., 2009; Paoletti et al., 2009). Damage to root  
50 systems is one such component. Shrubs can experience root severance from trenching and  
51 digging activities within the urban matrix due to maintenance of utilities such as underground  
52 cables and pipes. As shrubs tend to be smaller than trees, they can experience transplantation  
53 from one locality to another (e.g. within a garden), even as quite mature specimens – again  
54 potentially with traumatic loss of roots. Similarly, roots may be severed or damaged during  
55 commercial production, such as when lifted from a field situation, being potted-on or when  
56 delivered to customers via post (Mathers et al., 2007). Yet, little systematic research has  
57 identified the impact of such actions on shrub roots, and the capacity of the plants to recover.  
58 Indeed, whereas some trees seem to be highly susceptible to the effects of trenching (Hauer et  
59 al., 1994; Ghani et al., 2009; Benson et al., 2019), the situation with shrubs seems less clear;  
60 but as with trees they may be influenced by factors such as species choice and root architecture  
61 or growth patterns. Some species such as *Daphne* and *Magnolia* seem to be highly susceptible  
62 to root injury and transplanting established plants is rarely recommended (White, 2006; Anon,

63 2018a). Other species, such as *Rosa* (Anon 2018b), *Rhododendron* (American Rhododendron  
64 Society, 2019) and *Viburnum* (Clune, 2017), amongst many others, are thought to be able to be  
65 transplanted comparatively easily, but this is generally recommended to be done during winter  
66 when the plant is dormant, as moving a plant in summer may induce drought stress due to root  
67 injury impairing water absorption (Anon, 2018a; Spengler, 2018).

68

69 Root injury may not be an entirely negative process though. Both young trees and shrubs can  
70 experience ‘undercutting’ in commercial field-production; a process which severs extending  
71 primary and secondary roots, and encourages lateral root development leading to a more  
72 fibrous root system that is deemed beneficial when plants are subsequently transplanted  
73 (Schultz and Thompson, 1997). Judicious root-pruning has been shown to reduce shoot vigour,  
74 promote side shoots, fruit quality and improve plant habit (Schupp and Ferree, 1990; Schupp  
75 et al., 1992; Thomas and Ravindra, 1997; Yang et al., 2010). In contrast, root-pruning can be  
76 detrimental to subsequent development, e.g. on *Magnolia* (Gilman and Kane, 1990) and  
77 *Quercus* (Larson, 1975; Andersen et al., 2000). Even within a single species, results can vary  
78 depending on timing or severity of root-pruning (Ferree, 1992) or water availability within the  
79 soil (Fini et al., 2013; Wang et al., 2014). Research in *Pseudotsuga menziesii* indicated that  
80 root regeneration differed, depending on severity, rooting condition and location of the pruning  
81 within the root-ball (Eis, 1968). Moreover, severe root-pruning in this species (pruning of both  
82 sides of the root) generated better root systems rather than just light root-pruning on one side  
83 only. Meanwhile, root-pruning of two ornamental shrubs *Buddleja davidii* 'Summer Beauty'  
84 and *Cistus* 'Snow Fire' at time of planting into the ground from pots, indicated better  
85 establishment through the promotion of new roots, and enhanced root development compared  
86 to other manipulation techniques such as teasing out roots or leaving the roots in their original  
87 root-ball (Blanusa et al., 2007). These points then raise questions such as does the extent, or

88 the time of root injury in shrubs affect the response of the plants in terms of shoot growth and  
89 subsequent redevelopment of the root system?

90

91 The aim of this research therefore was to determine how the severity and timing of root injury  
92 (root-pruning) affected shrub survival. We tested whether shrubs in a quiescent state (i.e. early  
93 autumn), but with a full leaf canopy still present, were more or less impaired by root injury  
94 compared to those where injury took place when they were in a period of active shoot growth  
95 (mid-summer). [The term ‘quiescent’ is used as we did not verify whether plants had entered  
96 endodormancy by this stage (Arora et al., 2003)]. We also wished to determine if additional  
97 fertilizer applied to the root system affected recovery and subsequent growth. Two medium-  
98 stature shrub taxa (final height approx. 2.5m) were selected for the study; the deciduous  
99 *Philadelphus coronarius* 'Aureus' and the evergreen *Euonymus fortunei* 'Silver Queen'. Both  
100 *P. coronarius* and *E. fortunei* are commonly used in urban landscapes due to a reputation for  
101 robustness and low maintenance requirements (HTA, 2017). The latter has less vigorous  
102 growth compared to the former, so was selected to provide a potential contrast within the study,  
103 in terms of speed of response. The study tested four hypotheses.

- 104 1. Severe root-pruning would be more detrimental than lighter root-pruning in terms of  
105 plant recovery and subsequent shoot growth.
- 106 2. Root-pruning during the quiescent phase would be more deleterious to subsequent  
107 shoot and root development than in the active growth phase.
- 108 3. The more vigorous *Philadelphus* would be the more resilient of the two taxa to root-  
109 pruning in terms of recovering root and shoot growth more rapidly.
- 110 4. The provision of additional fertilizer would accelerate recovery of the plants.

111

112

113 **1. Methods**

114 Plant species and approaches

115 Plants of *Philadelphus coronarius* ‘Aureus’ and *Euonymus fortunei* ‘Silver Queen’ were  
116 purchased from a commercial nursery (as 18-month-old, 150-200mm high plants in 90mm dia.,  
117  $\approx 0.35$  L pots) in both winter 2012-13 (Exp. 1) and winter 2013-14 (Exp. 2). These were grown  
118 on under (frost-free glass) at the University of Sheffield, Sheffield, UK, being exposed to  
119 natural photoperiods and without supplementary lighting.

120

121 Experiment 1. Root-pruning in the quiescent shoot phase (September)

122 Plants were re-potted between 24-26 May 2013 (See Supplementary Section, Fig. S1) using a  
123 ‘split pot’ system (Fig. S2). This involved carefully teasing apart the conventional root-ball  
124 into two equal sections and inserting these into two ‘cut-down’ clear polypropylene bottles  
125 which were stapled together and held in parallel; the dimension of each bottle being 260 x  
126 100mm height x breadth (Fig. S2). The roots in each bottle were ‘backfilled’ with a 100% peat  
127 growing medium (graded as 15% of 0-5mm and 85% 0-10mm particle sizes, respectively)  
128 containing 5 g l<sup>-1</sup> controlled release fertilizer granules (Osmocote 8-9M TE, ICL, Ipswich,  
129 Suffolk, UK) consisting 6.6% NO<sub>3</sub>, 8.4% NH<sub>4</sub>, 9% P<sub>2</sub>O<sub>5</sub>, 11% K<sub>2</sub>O, 2% MgO and trace  
130 elements (TE) of micro-nutrients. Each section of the root-ball was arranged in such a manner  
131 that new roots would proliferate into the growing media of their respective bottles. For each  
132 plant, the two bottles themselves were labelled ‘right’ or ‘left’ and linked to the treatments  
133 imposed on each side of the root system. Black polythene was used to cover the clear bottle  
134 pots to avoid phototropism in root growth. Plants were placed back in the glasshouse until 27  
135 Sep. 2013, by which point roots had grown down to the base of each container.

136

137 At this point, plants of each genotype were placed in a line on a glasshouse bench for visual  
138 comparison and any a-typical specimens removed. Remaining plants (56) were graded based  
139 on height, and then randomly allocated to one of the 7 treatment groups. Thus one treatment  
140 had a comparable 'population' of plants to another. Each treatment group (n=8 per taxon) were  
141 then subjected one of the following root manipulation treatments (Fig. S3). These were:

- 142 • Consistent light root-pruning (L+L) – the basal  $\frac{1}{3}$  of the roots were pruned off each side  
143 and the remaining root-balls placed back in their respective bottles with peat-based  
144 growing-media containing  $1 \text{ g l}^{-1}$  Osmocote 8-9M TE. (Figs. S3 and S4B).
- 145 • Consistent severe root-pruning both sides (S+S) – the basal  $\frac{2}{3}$  of the roots were pruned  
146 off each side and the remaining root-balls placed back in their respective bottles with  
147 peat-based growing-media containing  $1 \text{ g l}^{-1}$  Osmocote 8-9M TE. (Figs. S3 and S4C).
- 148 • Differential root-pruning (L+S) – the basal  $\frac{1}{3}$  of roots on one side (left, as viewed by  
149 the researcher) and  $\frac{2}{3}$  of roots on the alternative (right) side were pruned off and the  
150 remaining root-balls placed back in their respective bottles with peat-based growing-  
151 media containing  $1 \text{ g l}^{-1}$  Osmocote 8-9M TE. (Figs. S3 and S4D).

152

153 In these treatments a relatively low rate of fertilizer was used ( $1 \text{ g l}^{-1}$ ) so as not to provide a  
154 surplus of nutrients in the newly added media. Additional treatments, however, were provided  
155 where similar root manipulation took place, but where the growing media used to backfill one  
156 of the bottles (i.e. one side of the root system only) incorporated a higher rate of fertilizer i.e.  
157 ( $5 \text{ g l}^{-1}$  Osmocote 8-9M TE) to assess how this influenced root development. Additional rates  
158 of fertilizer were added to one side only to determine if a differential response was apparent,  
159 i.e. did the extra nutrition just promote/inhibit root development on the side it was added, or  
160 have an effect on both sides of the root system. Additional treatments were (Fig. S3):

- 161 • Consistent light root-pruning with additional fertilizer (L+LF).

- 162 • Consistent severe root-pruning with additional fertilizer (S+SF)
- 163 • Differential root-pruning with additional fertilizer added to the light pruned side only
- 164 (LF+S).
- 165 • Differential root-pruning with additional fertilizer added to the severe pruned side only
- 166 (L+SF).

167

168 A non root-pruned treatment i.e. ‘control’ was deemed not feasible. Pre-experiment  
169 assessments with the split-pot system, indicated that failure to remove the root-balls from the  
170 bottles, resulted in a highly congested root-ball, making accurate root counts impossible.  
171 Alternative systems of removing plants from the spit-pot system, refreshing the growing media  
172 at the base, and attempting to re-insert them to the respective bottles, frequently resulted in root  
173 damage. Thus it was considered that any such ‘control’ would, in reality, be similar to the light  
174 pruned (L+L) treatment.

175

176 Plants of each taxon were placed on separate benches within the one glasshouse. Plants were  
177 spaced 0.8 m apart in a grid pattern, with each row of this grid having one specimen of each  
178 treatment represented in it. The treatment position within the row was randomised. Irrigation  
179 was via watering-can with 1000ml applied daily to each of the split pots during active growth;  
180 holes in the bottles ensuring excess water drained freely. Over any 24 h period, plants were  
181 kept typically at 75-100% of container capacity. A subsection of plants (one rep, randomly  
182 chosen per treatment) were weighed every day, 1 h after watering (Mettler balance ICS226-  
183 QA15FCL-US, Mettler-Toledo, Leicester, UK) and all others assessed by hand-lifting to  
184 ensure weights (i.e. water contents) were approximately equivalent. Watering was less frequent  
185 during winter – usually once a week, due to limited evapo-transpirational demand, with  
186 weighing processes also taking place weekly. Root systems were monitored throughout winter

187 2013- spring 2014, by temporarily removing the black polythene covers and inspecting root  
188 development through the polypropylene bottles, with final destructive harvests being recorded  
189 6 weeks after first shoot budbreak in each plant. First budbreak in each plant ranged between  
190 2-7 Feb., thus. destructive harvests were conducted between 14-16, April 2014 (Fig. S1). The  
191 harvesting was carried out in a systematic manner (1 rep per treatment) to minimise bias due  
192 to interactions between treatment and harvest time. Harvesting took place after 6 weeks, thus  
193 allowing treatment differences to become manifest, whilst avoiding excessive congestion of  
194 roots at the base of the bottles and making root counting difficult.

195

196 Experiment 2. Root-pruning in the active shoot phase (July)

197 Similar procedures to Exp. 1 were followed except plants were moved to split pots on 12-13  
198 May 2014 and root-pruned on 29-30 July 2014 when shoots were still in active growth (Fig.  
199 S1). These plants were then assessed for new root and shoot development 6 weeks later on 14-  
200 16 Sep. 2014.

201

202 Data collection and handling

203 Root and shoot development was monitored every 2 weeks, with the number of new roots  
204 ('white' roots  $\geq 20\text{mm}$ ) at the surface of the root-ball counted and marked with indelible marker  
205 pens. At final harvest, the root-ball was carefully teased apart and peat gently brushed off. Any  
206 additional white roots identified within the middle of the root-ball were added to the numbers  
207 recorded on the surface, to give a final new root tally. This process, however, did not account  
208 for any new roots that may have stopped growing and lignified (turned pale brown, [Lipp and  
209 Andersen, 2003]) over the preceding 6 weeks, and which had been out of view, i.e. not on the  
210 surface. In reality at final harvest, we found no terminal roots without a white tip, suggesting  
211 those counted were a genuine indication of all the primary actively growing roots. White roots

212 < 20mm were not counted and so this data largely excludes the smaller secondary and tertiary  
213 roots present. Root mass was assessed by washing the roots under running water using a mesh  
214 and bucket system to catch and extract the roots from the growing medium. Roots were dried  
215 for 48 h at 80°C (Heratherm Protocol Oven, Thermo Fisher Scientific, Loughborough,  
216 Leicestershire, UK) and weight data derived from each bottle ('Root Left' and 'Root Right').  
217 These values were summed to give the total root mass per plant ('Root Total'). Shoot and stem  
218 tissue was also harvested and dried ('Shoot Total'). Effects of treatments were analysed by  
219 one-way ANOVA (Genstat 18 VSNi, Hemel Hempstead, Hertfordshire, UK), ensuring data  
220 was normally distributed and variance levels homogenous. Data are presented as mean values,  
221 with significant differences ( $P \leq 0.05$ ) between means verified by Sidak post-hoc, tests. The  
222 Sidak test was chosen as it was considered that each comparison was independent to any of the  
223 others.

224

## 225 **2. Results**

226 Experiment 1. Root-pruning in the quiescent shoot phase (September)

227 Pruning roots in the autumn, once plants had become quiescent resulted in few roots ( $\leq 3$  per  
228 plant) being observed at the interface of the rootball and the polypropylene pot over the winter  
229 in either *Philadelphus* or *Euonymus* (no significant differences due to treatment and data not  
230 shown). Shoot and more vigorous root development was noted in spring, however, and approx.  
231 6 weeks after budbreak (when plants had more than doubled in size), they were destructively  
232 harvested to assess development and biomass.

233

234 *Philadelphus* 'Aureus'

235 Shoot biomass recorded in the spring showed no effect of root-pruning or nutrition treatments  
236 applied the previous autumn (Fig. 1, Table 2). Consistent severe root-pruning (S+S), however,

237 had a negative effect on root biomass (e.g. significantly less biomass compared to the  
238 equivalent light root-pruned treatment L+L) (Fig. 1). In contrast, there was no difference in the  
239 number of new roots generated between the light (L+L) and severe (S+S) root-pruned  
240 treatments (Fig. 2). The differential treatment (L+S) had similar biomass levels to L+L, but  
241 reduced the number of new roots generated on the severely pruned side.; a value that was also  
242 less than the S+S treatment (Fig. 2).

243

244 Adding fertilizer to treatments did not alter root biomass significantly from equivalent plants  
245 not fertilised (Fig. 1), but did reduce the number of new roots on the fertilised side in S+SF  
246 (Fig. 2). In contrast, there were more roots generated when fertilizer was added to the lightly-  
247 pruned, left side of the differential treatment, i.e. LF+S (Fig. 2); and more on the severe pruned  
248 (right) side irrespective of where the fertilizer was placed (compare LF+S and L+SF to L+S).

249

250 *Euonymus* ‘Silver Queen’

251 There was no effect of treatment on shoot or total root biomass (Fig. 3). Root biomass within  
252 the left and right pots, however, could be affected by treatment. For example, relatively high  
253 biomass was recorded on the lightly root-pruned side of L+S, and low on the severely-pruned  
254 side of L+SF, and the non-fertilized side of S+SF (Fig. 3). There was no difference in the  
255 number of new roots generated between L+L and S+S (and indeed their fertilized equivalents,  
256 L+LF and S+SF) (Fig. 4). In the differential treatment (L+S) root numbers were suppressed on  
257 the severely pruned side. This suppression not being apparent on plants that received fertilizer  
258 (Fig. 4).

259

260 Experiment 2. Root-pruning in the active shoot phase (July)

261 *Philadelphus* ‘Aureus’

262 Harvested biomass was less than in Exp. 1 (note different scales on vertical axes, e.g. Figs. 1  
263 and 5), and plants generally had lower root to shoot ratios (Table 1). Summer root-pruning had  
264 a stronger influence on subsequent development compared to autumn root-pruning (especially  
265 in the absence of additional fertilizer), with a significant reduction in total root biomass in the  
266 S+S and L+S treatments compared to L+L (Fig. 5). Notably, shoot biomass was also  
267 significantly lower in the L+S treatment (Fig. 5, Table 2). Additionally, the number of new  
268 roots was significantly less in the L+S compared to the L+L (on both sides, Fig. 6). Growth  
269 performance was better in the differential treatment when fertilizer was added, with LF+S and  
270 L+SF having enhanced shoot and root biomass compared to L+S (Fig. 5) and many more  
271 developing roots (Fig. 6).

272

273 *Euonymus* ‘Silver Queen’

274 Biomass harvested after summer root-pruning (active-phase) was less than after autumn root-  
275 pruning (quiescent phase) (compare Fig. 7 to Fig. 3). Consistent severe root-pruning (S+S)  
276 conducted in summer, however, had no subsequent significant negative effect on plant biomass  
277 six weeks later, compared to L+L root-pruning (Fig. 7), i.e. plants had recovered from the  
278 severe treatment. There was no significant effect on the number of new roots generated in S+S  
279 compared to L+L (Fig. 8).

280

281 Adding additional fertilizer did not significantly improve biomass or root number over  
282 equivalent not fertilized treatments (Figs. 7 and 8). Effects of root-pruning and nutrition could  
283 combine, however, to influence plant responses; for example, the L+LF treatment had greater  
284 shoot and root biomass than S+SF (Fig. 7), and more new roots generated on the side with  
285 additional fertilizer (Fig. 8).

286

287 **Discussion**

288

289 Survival and hypothesis testing

290 All plants of both taxa survived the root-pruning treatments imposed. This was despite the loss  
291 of approximately two-thirds of total root mass in some treatments. Overall, plant biomass was  
292 greater after the September root-pruning compared to plants treated in July, but this may be  
293 partially due to different growing seasons (2013 vs 2014) as well as timing of root-pruning. As  
294 such comparisons here, focus on trends within each experiment rather than compare empirical  
295 data across the two experiments.

296

297 The most severe root-pruning treatment (S+S) had no effect on shoot biomass in *Philadelphus*,  
298 and only differential pruning (L+S) implemented in July, reduced shoot biomass. Timing of  
299 root-pruning had a stronger influence in *Euonymus*, with no effect on shoot biomass in the  
300 spring following a September root-pruning, but reductions in shoot biomass associated with a  
301 number of treatments involving severe root-pruning in July (Table 2). The data rejects our first  
302 hypothesis with respect to *Philadelphus*, i.e. that severe root pruning would be detrimental, but  
303 partially supports it for *Euonymus*, in that shoot growth was penalised after July root-pruning,  
304 even though no fatalities occurred. Data on shoot biomass also indicates that the second  
305 hypothesis should be rejected, i.e. root-pruning during the quiescent phase is more deleterious  
306 than that during active growth. In reality, plants of both taxa showed the opposite trend, namely  
307 greater setbacks in shoot development associated with a July root-pruning when plants were  
308 active (Table 2).

309

310 The greater impact on shoot biomass with root-pruning in July may relate to the plants being  
311 injured at a younger physiological stage. Thus, implying in this case, younger plants were less

312 resilient than their marginally older peers. Alternatively, the loss of root in July may have  
313 impacted at a particularly critical period in the plants' development. Timing of root-pruning in  
314 relation to development phases in *Malus* has been shown to be important (Ferree and Knee,  
315 1997); root pruning in spring prior to budbreak being less detrimental than during midsummer,  
316 when trees had a full canopy. This suggests that interference with resource capture and  
317 allocation may partly explain the more pronounced negative effect when plants are in active  
318 growth (Khan et al., 1998a; 1998b).

319

320 In terms of the third hypothesis, i.e. the more vigorous *Philadelphus* possessing greater  
321 resilience, results are more complex especially when root data is taken into consideration. As  
322 outlined above, root-pruning was detrimental to shoot development in the less vigorous  
323 *Euonymus* but only with July pruning. *Euonymus* plants root-pruned in September showed no  
324 adverse effects to either shoot or root biomass the following spring (Table 2). This was not the  
325 case for roots in *Philadelphus*, where severe root-pruning subsequently reduced root biomass  
326 in both July and September periods. As such, it could be argued (based on root growth alone)  
327 that the more vigorous species was actually the less resilient to severe-root pruning.

328

329 There was no consistent evidence that additional fertilizer helped plants recover (fourth  
330 hypothesis). Additional nutrition had a positive effect on a number of situations where  
331 differential root-pruning was employed (see below), but the influence was not universal.

332

333 Root responses

334 Consistent severe pruning treatment (S+S) negatively affected root biomass in *Philadelphus*,  
335 but interestingly, had less effect on total root biomass in *Euonymus* (Table 2). Localized effects  
336 however, i.e. in the sides where severe root-pruning was imposed was evident in both taxa.

337 Consistent severe pruning (S+S) did not inhibit new root generation (at least in the absence of  
338 additional fertilizer), and new root numbers were comparable with the equivalent light root-  
339 pruned treatment (L+L) (Figs. 2, 4, 6 and 8). Re-establishing a network of new roots rapidly  
340 after injury seemingly being a priority over, e.g. extension of remaining intact roots. Re-  
341 directing resources to new root development (at the expense of shoot growth) after root injury,  
342 has been observed in other species including *Pinus* (Stupendick and Shepherd, 1980), *Malus*  
343 (Ferree and Knee, 1997; Khan et al., 1998a; 1998b), *Vitis* (Thomas and Ravindra, 1997;  
344 McCartney and Ferree, 1999) and *Quercus* (Andersen et al., 2000).

345

346 In a number of situations differential root-pruning (L+S) inhibited root generation on the  
347 severely injured side, more so than consistent severe pruning (S+S), (i.e. Figs 2, 4 and 6). Why  
348 a greater ‘root-regeneration’ response was induced by the consistent severe root-pruning rather  
349 than just the partial severe pruning is not clear. Logically it might be assumed that L+S  
350 treatment would have been intermediate between L+L and S+S in terms of overall root damage  
351 incurred and the requirement for new roots to be generated after injury. However, it is possible  
352 that a more significant or consistent trauma (i.e. S+S) is required to fully-activate new root  
353 generation. For example, it may be that plants differentially pruned did not lose enough root  
354 mass overall, to stimulate the strength of wound responses required to elicit full root  
355 regeneration on the damaged side (León et al., 2001). Indeed, roots on the less injured, light-  
356 pruned side, may have been left sufficiently intact to maintain good hydraulic conductance  
357 (Davies and Zhang, 1991) or strong conventional hormonal signals (Francia et al., 2007; Huber  
358 and Bauerle, 2016) thus overriding any stimulus to initiate new roots coming from the more  
359 damaged, alternate side (Lipp and Andersen, 2003; Takahashi and Shinozaki, 2019). These  
360 results are in line with Blanus et al., (2007), who found similar responses in *Buddleja* and  
361 *Cistus*, i.e. severe root-injury encouraged more root growth than light-injury. The mechanisms

362 behind i. what determines the strength of, or ii. differential types of, wound responses remain  
363 to be further elucidated (Huber and Bauerle, 2016).

364

#### 365 Additional nutrient and root development

366 The provision of higher fertilizer rates seemed to have a beneficial effect on root development  
367 in some treatments, but not others. Additional fertilizer inhibited root-regeneration after  
368 consistent severe root-pruning of *Philadelphus* in September (i.e. compare S+SF to S+S, Fig.  
369 2). Conversely, it helped new root generation in the differential treatments (both sides) (Fig.  
370 2). High nutrient levels have been associated with decreasing the extension of existing roots  
371 and promoting axillary root formation in non-injured root systems (Trapeznikov et al., 2003).  
372 Something similar appears to have occurred here in terms of encouraging new root initials, but  
373 only when the root system as a whole was not overly-damaged. Under the consistent severe  
374 S+S root-pruning treatment, for example, a reduction in new roots generated (in the presence  
375 of higher fertilizer) may relate to a 'feed-back system' whereby those few roots that are initially  
376 generated are deemed to be acquiring sufficient nutrition to support the entire plant, and thus  
377 any further generation of de novo roots is not required. In essence when nutrient ions are freely  
378 available, and are being readily absorbed from the medium, the demand for further root  
379 generation is reduced. This was only noted however, under the consistent severe root-pruning  
380 treatments. In contrast, when roots systems were differentially damaged (L+S) the opposite  
381 was true. Indeed, it was interesting to observe that the extra nutrition seemed to re-instate the  
382 ability to generate new roots in the severe pruned side of the root-ball. Moreover, higher  
383 fertilizer rates in the summer root-pruned plants aided biomass accumulation and new root  
384 generation in the differential treatment, irrespective to whether the additional fertilizer was on  
385 the lightly- or severely-injured side of the root system (compare LF+S and L+SF to L+S in  
386 Figs 5 and 6). This suggests it is being readily translocated from either side of the root system

387 and then distributed evenly across it, albeit perhaps via translocation to the stems and shoots  
388 first (Russell and Clarkson, 2016).

389

390 In *Euonymus*, additional fertilizer did not alter any of the measured parameters compared to  
391 equivalent non-fertilized treatments (Figs 3 and 7). This is comparable to other studies in slow  
392 growing evergreen species e.g. *Ilex cornuta* 'Burfordii Nana'; (Gilman et al., 1996) and possibly  
393 slower growing species are less responsive in activating new shoot growth (Mooney and  
394 Rundel, 1979, Chapin, 1980). Inconsistent results in this research with respect to nutrient  
395 addition, resonate with other findings (Ferrini and Baietto, 2006). Despite being commonly  
396 practiced in landscape management, the actual benefits of adding additional fertilizer at the  
397 time of transplanting is still disputed (Harris et al., 2008).

398

399 Limitations to the research

400 These experiments were conducted under semi-controlled conditions thus allowing root  
401 development to be monitored carefully over time whilst avoiding disturbance to the root-  
402 systems. They do not necessarily though, fully represent field situations and further applied  
403 research is required to verify if results would be reproduced in situ within the landscape. Our  
404 data does not necessarily always explain cause and effect either, for example how specific  
405 nutrients are involved in regulating root and shoot development after root injury. Nevertheless,  
406 the research does much to understand key principles about how young shrubs respond to root  
407 injury.

408

409 Conclusions

410 The data presented here re-enforces the argument that it is best to avoid moving shrubs when  
411 they are in active growth, thus broadly supporting practical advice on restricting transplanting

412 of landscape shrubs to the autumn and winter seasons. The common assumption that severe,  
413 rather than light, root injury is more detrimental is challenged by our *Philadelphus* data, in that  
414 there was no negative effect on shoot growth, and severe pruning could stimulate new root  
415 generation. Adding supra-optima levels of fertilizer to any backfill soils or growing media was  
416 not warranted, however, by the data presented here. The fact that results were not always  
417 analogous to those found in trees, indicates that more research is justified for shrubs per se,  
418 and to understand better the impacts of root injury both in controlled experiments such as this,  
419 but also in in situ studies.

420

#### 421 Acknowledgments

422 The authors are grateful to the Ministry of Higher Education of Malaysia for providing funding  
423 for this research.

424

425

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583

584

585 **Tables**

586

587 Table 1. Root to shoot ratios in Philadelphus and Euonymus after both quiescent phase  
 588 (September) and active phase (July) root-pruning. Data recorded after 6 weeks of continued or  
 589 re-activated shoot activity. Letters denote differences within species and growth phase from  
 590 Sidak tests.

591

Treatment	Philadelphus Quiescent (Sept. prune)	Philadelphus Active (July prune)	Euonymus Quiescent (Sept. prune)	Euonymus Active (July prune)
L+L	2.07a	0.74a	1.48a	0.35a
S+S	0.79b	0.60a	1.89a	0.42a
L+S	1.96a	0.74a	1.54a	0.24a
L+LF	1.61ab	0.94a	1.05a	0.43a
S+SF	1.29ab	0.63a	1.33a	0.23a
LF+S	1.55ab	0.83a	1.65a	0.31a
L+SF	1.60ab	0.64a	1.57a	0.31a

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594

595 Table 2. Summary of treatments, where values for different parameters are significantly less  
 596 than one or more other treatments.

Parameter	Taxa / Time of Root-Pruning			
	Philadelphus	Philadelphus	Euonymus	Euonymus
	July	Sept	July	Sept
Shoot biomass	L+S	No Effect	S+S	No Effect
			L+S	
			S+SF	
			LF+S	
Total root biomass	S+S	S+S	L+S	No Effect
	L+S	S+SF	L+LF	
			LF+S	
Root biomass Left	L+S	S+S	L+S	L+L
	S+SF		S+SF	S+SF
			LF+S	
Root biomass Right	S+S	S+S	L+S	L+SF
	L+S	S+SF	S+SF	
		LF+S	L+SF	
		L+SF		

Root number Left	L+L	S+SF	No Effect	L+L
	S+S			S+S
	L+S			
	L+LF			
	S+SF			
	LF+S			
Root number Right	L+S	L+S	S+SF	L+S
	L+LF	S+SF		
	S+SF			

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597

598 **List of Figures**

599

600 Figure 1. Philadelphus ‘Aureus’. Dry weight of roots (left bottle), roots (right bottle),

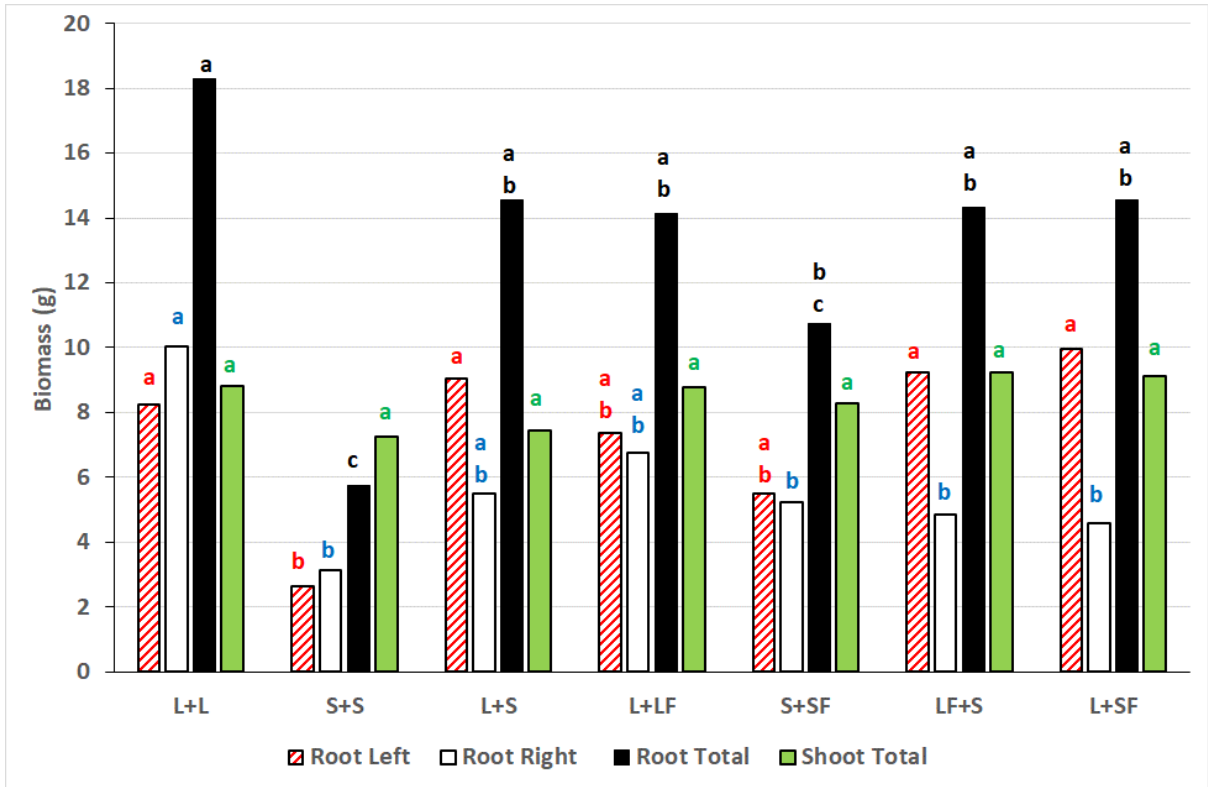
601 total roots and total shoots in April following root-pruning when quiescent

602 (September). L=light root-pruning, S=severe root-pruning, F=additional fertilizer. Letters

603 denote differences within each parameter from Sidak tests.

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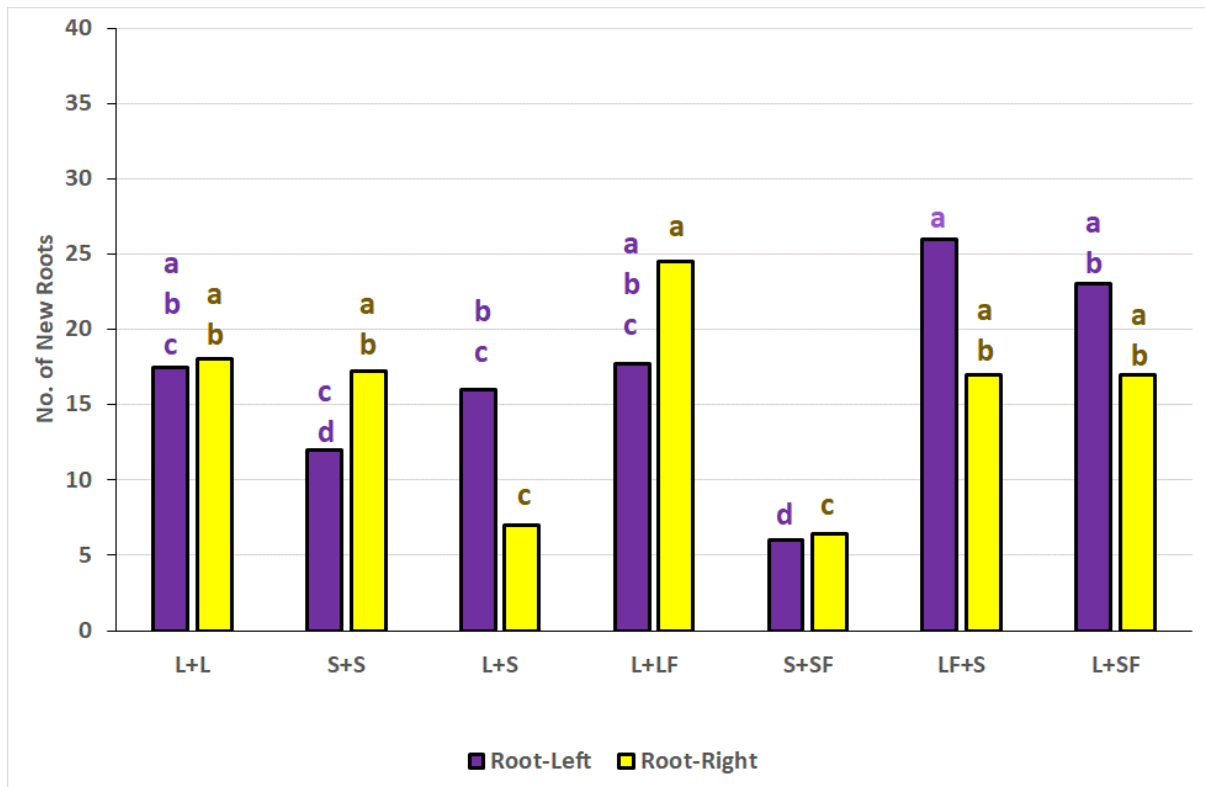
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611 Figure 2. Philadelphus ‘Aureus’. Mean number of new roots observed on left side or right  
 612 side of plants in April following root-pruning when quiescent (September). L=light root-  
 613 pruning, S=severe root-pruning, F=additional fertilizer. Letters denote differences within  
 614 each parameter from Sidak tests.

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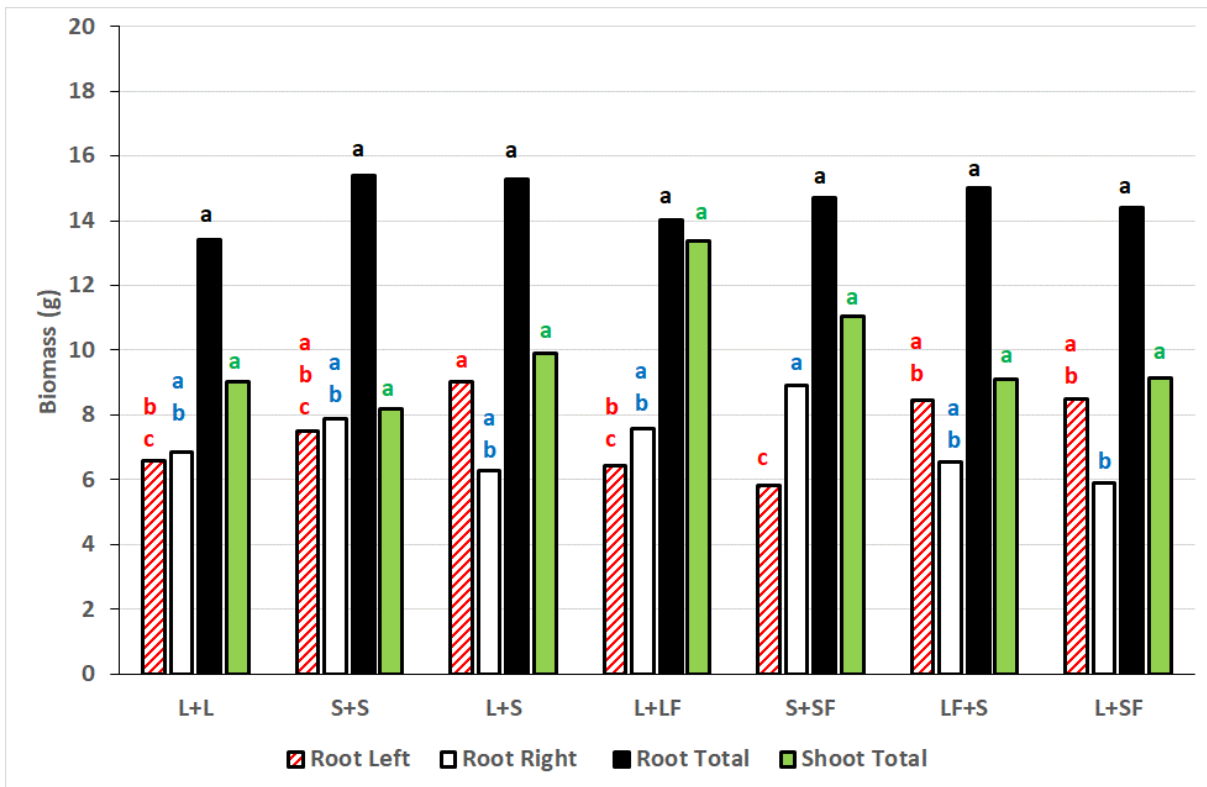
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623 Figure 3. *Euonymus* 'Silver Queen'. Dry weight of roots (left bottle), roots (right bottle),  
 624 total roots and total shoots in April following root-pruning when quiescent  
 625 (September). L=light root-pruning, S=severe root-pruning, F=additional fertilizer. Letters  
 626 denote differences for each parameter from Sidak tests.

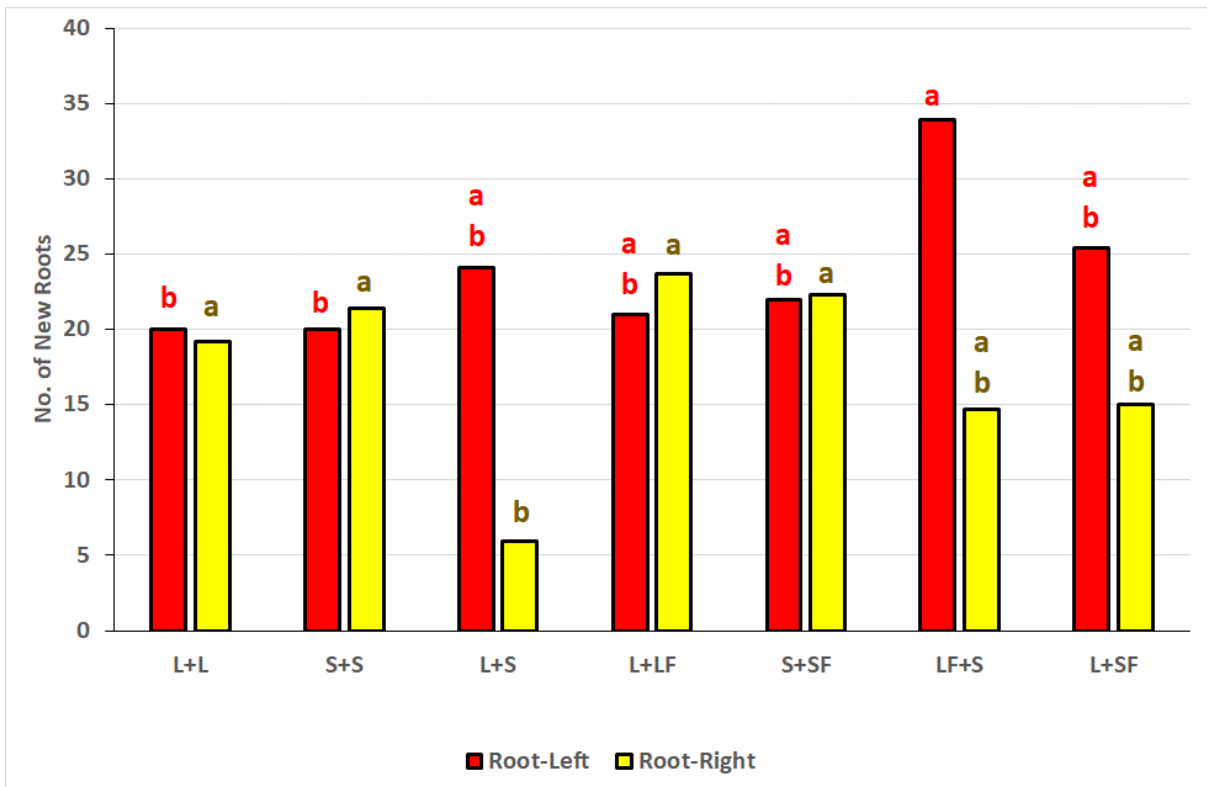
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630 Figure 4. *Euonymus* 'Silver Queen'. Mean number of new roots observed on left  
 631 side or right side of plants in April following root-pruning when quiescent (September).  
 632 L=light root-pruning, S=severe root-pruning, F=additional fertilizer. Letters denote  
 633 differences within each parameter from Sidak tests.

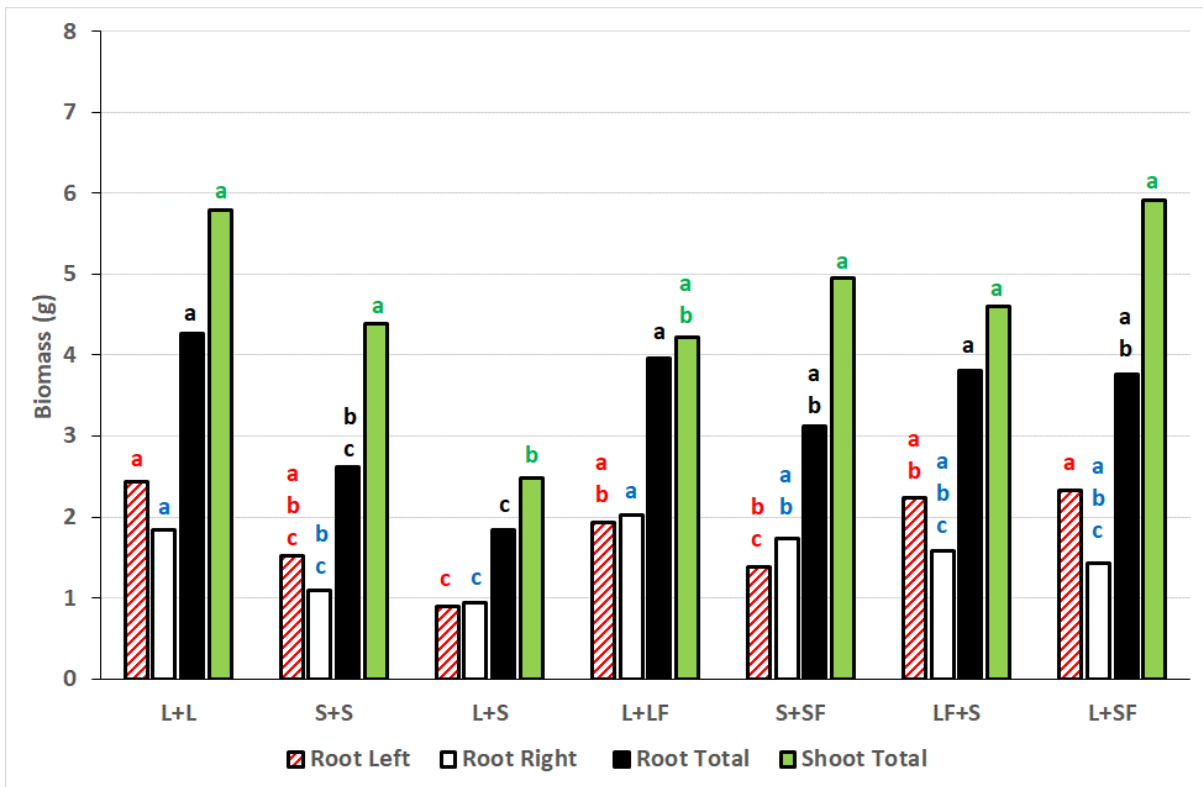
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642 Figure 5. *Philadelphus 'Aureus'*. Dry weight of roots (left bottle), roots (right bottle), total  
 643 roots and total shoots in September following root-pruning when active (July). L=light  
 644 root-pruning, S=severe root-pruning, F=additional fertilizer. Letters denote differences for  
 645 each parameter from Sidak tests.

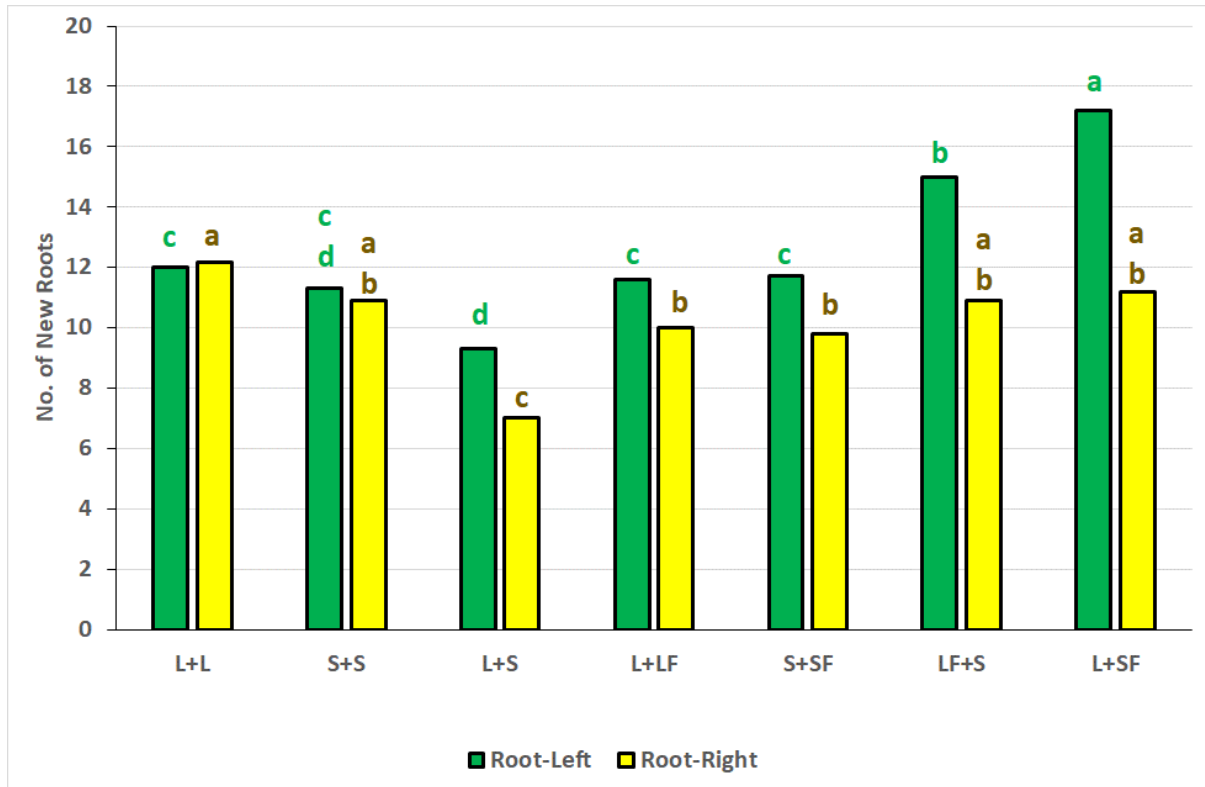
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651 Figure 6. *Philadelphus 'Aureus'*. Mean number of new roots observed on left side  
 652 or right side of plants in September following root-pruning when active (July). L=light root-  
 653 pruning, S=severe root-pruning, F=additional fertilizer. Letters denote differences within  
 654 each parameter from Sidak tests.

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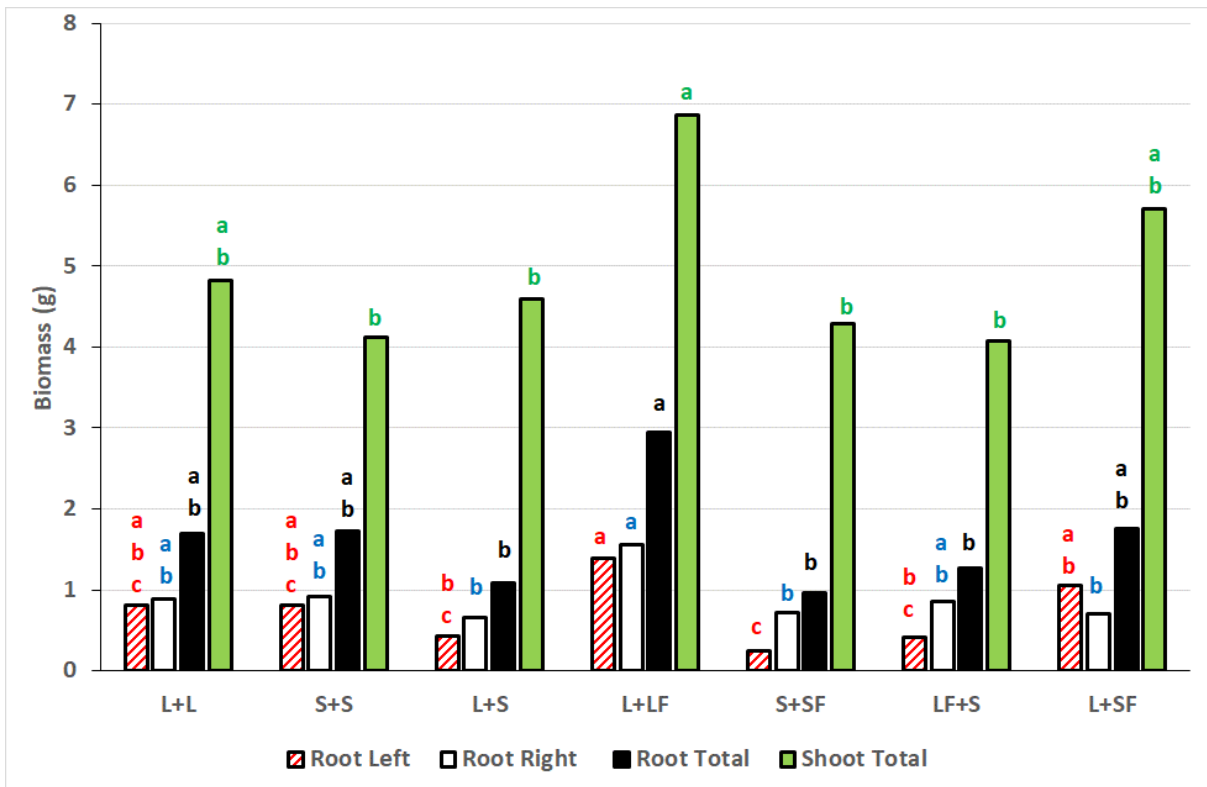
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659 Figure 7. *Euonymus* 'Silver Queen'. Dry weight of roots (left bottle), roots (right bottle),  
 660 total roots and total shoots in September following root-pruning when active (July).  
 661 L=light root-pruning, S=severe root-pruning, F=additional fertilizer. Letters denote  
 662 differences for each parameter from Sidak tests.

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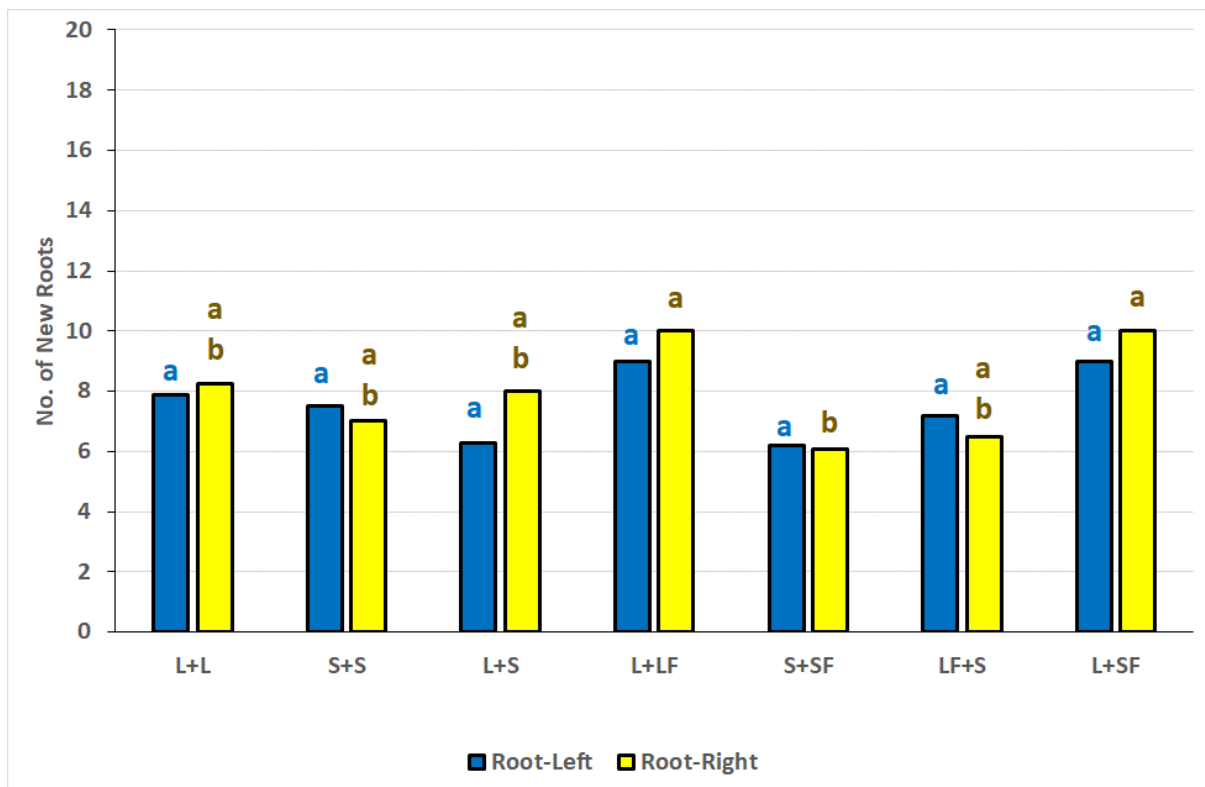


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668 Figure 8. *Euonymus* 'Silver Queen'. Mean number of new roots observed on left side or right  
669 side of plants in September following root-pruning when active (July). L=light root-pruning,  
670 S=severe root-pruning, F=additional fertilizer. Letters denote differences within each  
671 parameter from Sidak tests.

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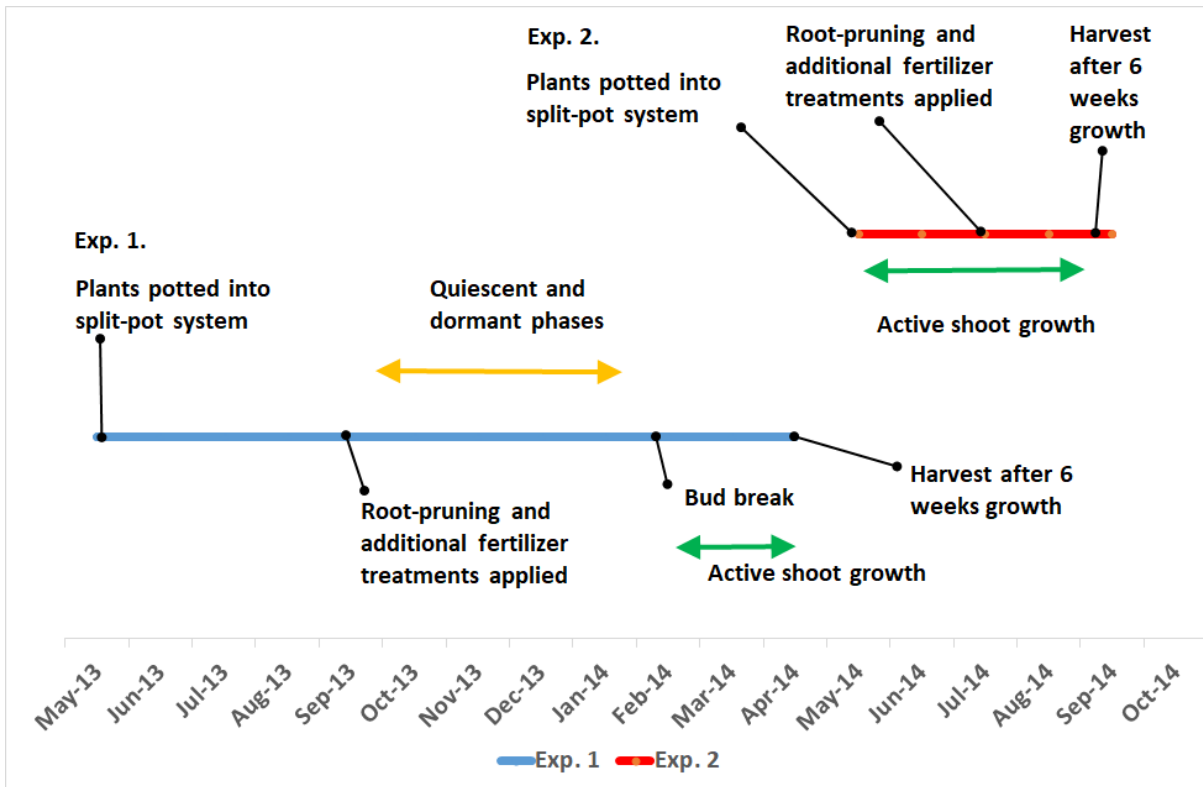
676 **Supplementary Figures**

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678 Figure S1. Timelines of the two experiments showing timing of root-pruning/  
679 additional fertilizer treatments and harvest periods.

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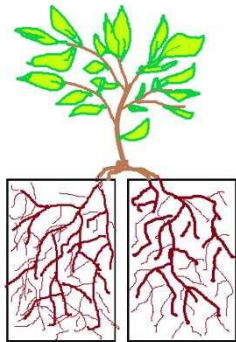
686 Figure S2. Two polypropylene cut down bottles as used as 'pots', with original roots of  
687 young plant carefully teased apart and encourage to grow in each side of the new pot system.

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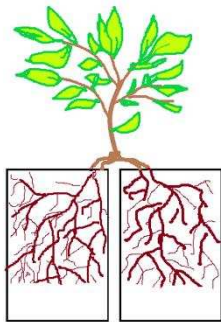
692 Figure S3. Diagram of typical root systems of plants before any root pruning; and  
693 consequently after the imposition of treatments L+L, S+S, L+S, L+LF, S+SF, LF+S, L+SF.  
694



Plant before any root pruning

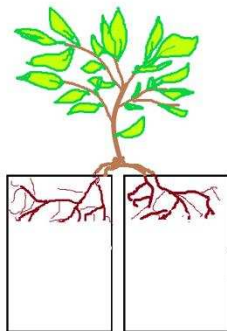
NB plants of this type were not assessed due to highly congested root systems

**Treatments =**



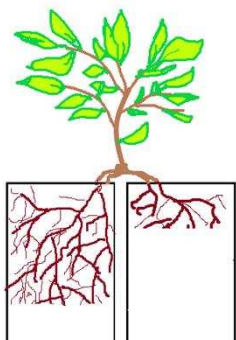
L+L

Lower 1/3 of roots removed from both sides



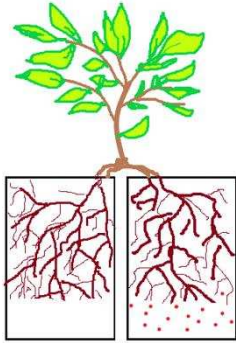
S+S

Lower 2/3 of roots removed from both sides



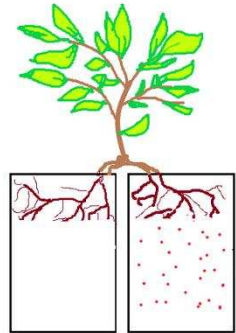
L+S

Differential pruning, 1/3 of roots removed on one side and 2/3 remove on the other



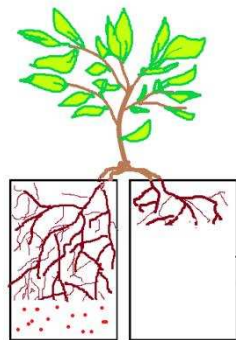
L+LF

Lower 1/3 of roots removed from both sides and additional fertilizer added to growing medium on one side



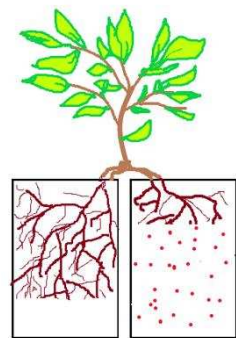
S+SF

Lower 2/3 of roots removed from both sides and additional fertilizer added to growing medium on one side



LF+S

Differential pruning, 1/3 removed on one side and 2/3 remove on the other, with additional fertilizer applied to the lightly pruned side



L+SF

Differential pruning, 1/3 removed on one side and 2/3 remove on the other, with additional fertilizer applied to severely pruned side

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699 Figure S4. Root-pruning treatments, showing A. established plant with divided root system,  
700 B. consistent light pruning on both sides of the root system (L+L), C. consistent severe  
701 pruning on both sides of root system (S+S) and D. differential pruning, light pruning on one  
702 side and severe on the other (L+S).

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**A**



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**B**



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**C**



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**D**



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