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

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Abstract

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

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

Word count (main text) = 4811

Introduction

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

Like trees, urban shrubs can be exposed to a range of stress factors, undermining their functionality (Franco et al., 2006; Cassaniti et al., 2009; Paoletti et al., 2009). Damage to root systems is one such component. Shrubs can experience root severance from trenching and digging activities within the urban matrix due to maintenance of utilities such as underground cables and pipes. As shrubs tend to be smaller than trees, they can experience transplantation from one locality to another (e.g. within a garden), even as quite mature specimens – again potentially with traumatic loss of roots. Similarly, roots may be severed or damaged during commercial production, such as when lifted from a field situation, being potted-on or when delivered to customers via post (Mathers et al., 2007). Yet, little systematic research has identified the impact of such actions on shrub roots, and the capacity of the plants to recover. Indeed, whereas some trees seem to be highly susceptible to the effects of trenching (Hauer et al., 1994; Ghani et al., 2009; Benson et al., 2019), the situation with shrubs seems less clear; but as with trees they may be influenced by factors such as species choice and root architecture or growth patterns. Some species such as Daphne and Magnolia seem to be highly susceptible to root injury and transplanting established plants is rarely recommended (White, 2006; Anon, 2018a). Other species, such as Rosa (Anon 2018b), Rhododendron (American Rhododendron Society, 2019) and Viburnum (Clune, 2017), amongst many others, are thought to be able to be transplanted comparatively easily, but this is generally recommended to be done during winter when the plant is dormant, as moving a plant in summer may induce drought stress due to root injury impairing water absorption (Anon, 2018a; Spengler, 2018).

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

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

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

1. Methods

Plant species and approaches

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

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

Plants were re-potted between 24-26 May 2013 (See Supplementary Section, Fig. S1) using a ‘split pot’ system (Fig. S2). This involved carefully teasing apart the conventional root-ball into two equal sections and inserting these into two ‘cut-down’ clear polypropylene bottles which were stapled together and held in parallel; the dimension of each bottle being 260 x 100mm height x breadth (Fig. S2). The roots in each bottle were ‘backfilled’ with a 100% peat growing medium (graded as 15% of 0-5mm and 85% 0-10mm particle sizes, respectively) containing 5 g l^{-1} controlled release fertilizer granules (Osmocote 8-9M TE, ICL, Ipswich, Suffolk, UK) consisting 6.6% NO_3, 8.4% NH_4, 9% P_2O_5, 11% K_2O, 2% MgO and trace elements (TE) of micro-nutrients. Each section of the root-ball was arranged in such a manner that new roots would proliferate into the growing media of their respective bottles. For each plant, the two bottles themselves were labelled ‘right’ or ‘left’ and linked to the treatments imposed on each side of the root system. Black polythene was used to cover the clear bottle pots to avoid phototropism in root growth. Plants were placed back in the glasshouse until 27 Sep. 2013, by which point roots had grown down to the base of each container.

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

- Consistent light root-pruning (L+L) – the basal ⅓ of the roots were pruned off each side and the remaining root-balls placed back in their respective bottles with peat-based growing-media containing 1 g l^{-1} Osmocote 8-9M TE. (Figs. S3 and S4B).
- Consistent severe root-pruning both sides (S+S) – the basal ⅔ of the roots were pruned off each side and the remaining root-balls placed back in their respective bottles with peat-based growing-media containing 1 g l^{-1} Osmocote 8-9M TE. (Figs. S3 and S4C).
- Differential root-pruning (L+S) – the basal ⅓ of roots on one side (left, as viewed by the researcher) and ⅔ of roots on the alternative (right) side were pruned off and the remaining root-balls placed back in their respective bottles with peat-based growing-media containing 1 g l^{-1} Osmocote 8-9M TE. (Figs. S3 and S4D).

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

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

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

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

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

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

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

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

Data collection and handling

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

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

2. Results

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

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

Philadelphus 'Aureus'

Shoot biomass recorded in the spring showed no effect of root-pruning or nutrition treatments applied the previous autumn (Fig. 1, Table 2). Consistent severe root-pruning (S+S), however, had a negative effect on root biomass (e.g. significantly less biomass compared to the equivalent light root-pruned treatment L+L) (Fig. 1). In contrast, there was no difference in the number of new roots generated between the light (L+L) and severe (S+S) root-pruned treatments (Fig. 2). The differential treatment (L+S) had similar biomass levels to L+L, but reduced the number of new roots generated on the severely pruned side.; a value that was also less than the S+S treatment (Fig. 2).

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

Euonymus ‘Silver Queen’

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

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

Philadelphus ‘Aureus’

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

Euonymus 'Silver Queen'

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

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

Discussion

Survival and hypothesis testing

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

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

The greater impact on shoot biomass with root-pruning in July may relate to the plants being injured at a younger physiological stage. Thus, implying in this case, younger plants were less resilient than their marginally older peers. Alternatively, the loss of root in July may have impacted at a particularly critical period in the plants' development. Timing of root-pruning in relation to development phases in Malus has been shown to be important (Ferree and Knee, 1997); root pruning in spring prior to budbreak being less detrimental than during midsummer, when trees had a full canopy. This suggests that interference with resource capture and allocation may partly explain the more pronounced negative effect when plants are in active growth (Khan et al., 1998a; 1998b).

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

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

Root responses

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

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

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

Additional nutrient and root development

The provision of higher fertilizer rates seemed to have a beneficial effect on root development in some treatments, but not others. Additional fertilizer inhibited root-regeneration after consistent severe root-pruning of Philadelphus in September (i.e. compare S+SF to S+S, Fig. 2). Conversely, it helped new root generation in the differential treatments (both sides) (Fig. 2). High nutrient levels have been associated with decreasing the extension of existing roots and promoting axillary root formation in non-injured root systems (Trapeznikov et al., 2003). Something similar appears to have occurred here in terms of encouraging new root initials, but only when the root system as a whole was not overly-damaged. Under the consistent severe S+S root-pruning treatment, for example, a reduction in new roots generated (in the presence of higher fertilizer) may relate to a ‘feed-back system’ whereby those few roots that are initially generated are deemed to be acquiring sufficient nutrition to support the entire plant, and thus any further generation of de novo roots is not required. In essence when nutrient ions are freely available, and are being readily absorbed from the medium, the demand for further root generation is reduced. This was only noted however, under the consistent severe root-pruning treatments. In contrast, when roots systems were differentially damaged (L+S) the opposite was true. Indeed, it was interesting to observe that the extra nutrition seemed to re-instate the ability to generate new roots in the severe pruned side of the root-ball. Moreover, higher fertilizer rates in the summer root-pruned plants aided biomass accumulation and new root generation in the differential treatment, irrespective to whether the additional fertilizer was on the lightly- or severely-injured side of the root system (compare LF+S and L+SF to L+S in Figs 5 and 6). This suggests it is being readily translocated from either side of the root system and then distributed evenly across it, albeit perhaps via translocation to the stems and shoots first (Russell and Clarkson, 2016).

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

Limitations to the research

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

Conclusions

The data presented here re-enforces the argument that it is best to avoid moving shrubs when they are in active growth, thus broadly supporting practical advice on restricting transplanting of landscape shrubs to the autumn and winter seasons. The common assumption that severe, rather than light, root injury is more detrimental is challenged by our Philadelphus data, in that there was no negative effect on shoot growth, and severe pruning could stimulate new root generation. Adding supra-optima levels of fertilizer to any backfill soils or growing media was not warranted, however, by the data presented here. The fact that results were not always analogous to those found in trees, indicates that more research is justified for shrubs per se, and to understand better the impacts of root injury both in controlled experiments such as this, but also in in situ studies.

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Tables

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

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

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

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

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

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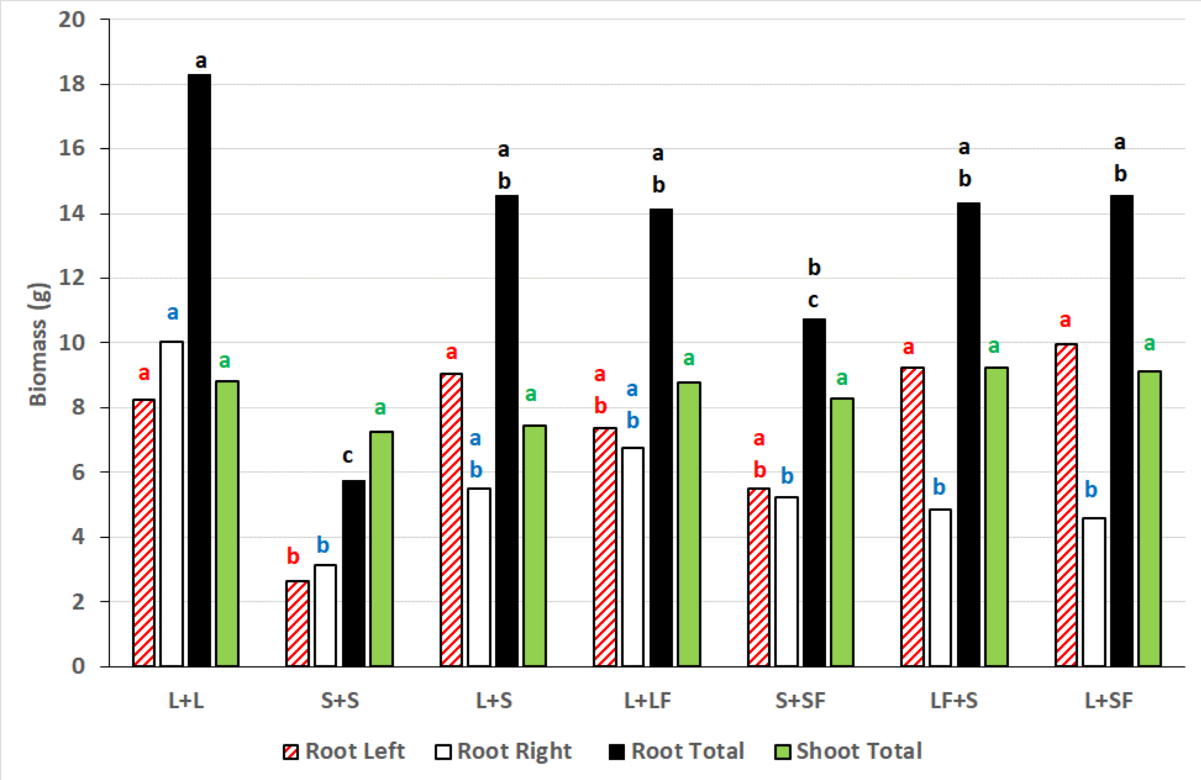

Biomass (g)
20
18
16
14
12
10
8
6
4
2
0
L+L
S+S
L+S
L+LF
S+SF
LF+S
L+SF
Root Left
Root Right
Root Total
Shoot Total

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

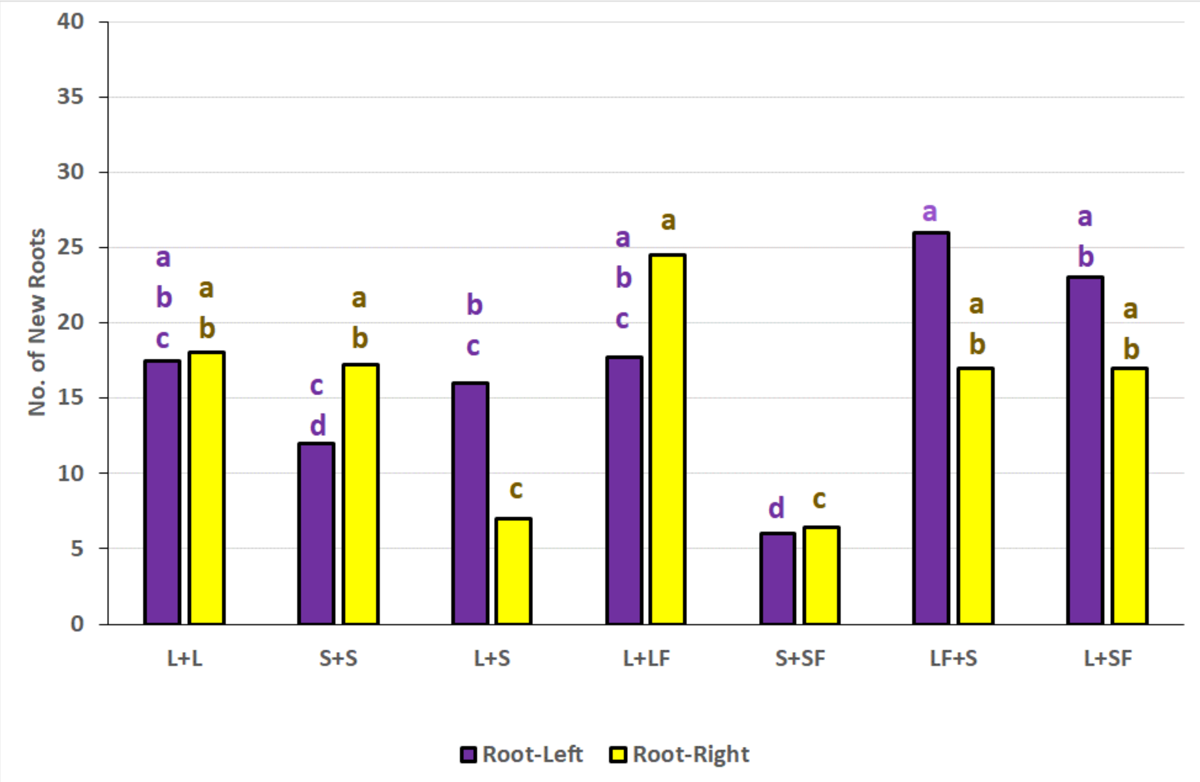


Figure 3. Euonymus 'Silver Queen'. Dry weight of roots (left bottle), roots (right bottle), total roots and total shoots in April following root-pruning when quiescent (September). L=light root-pruning, S=severe root-pruning, F=additional fertilizer. Letters denote differences for each parameter from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

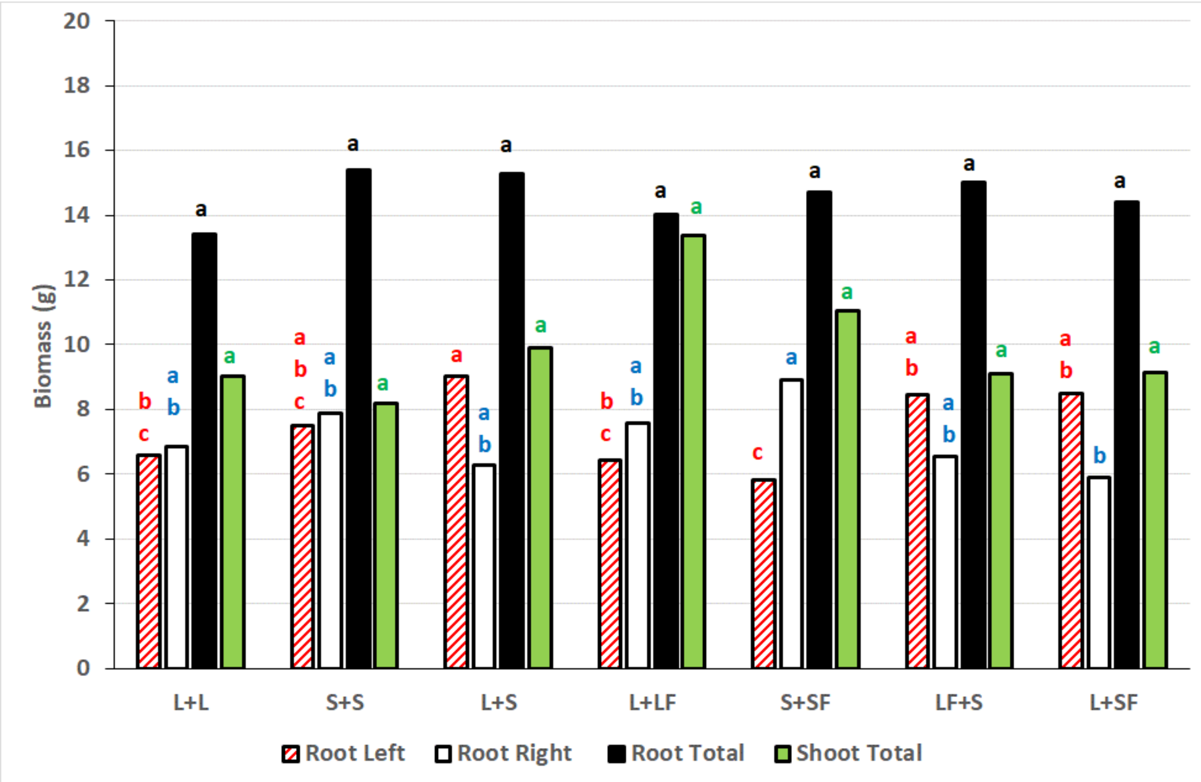


Figure 4. Euonymus 'Silver Queen'. Mean number of new roots observed on left side or right side of plants in April following root-pruning when quiescent (September). L=light root-pruning, S=severe root-pruning, F=additional fertilizer. Letters denote differences within each parameter from Sidak tests.

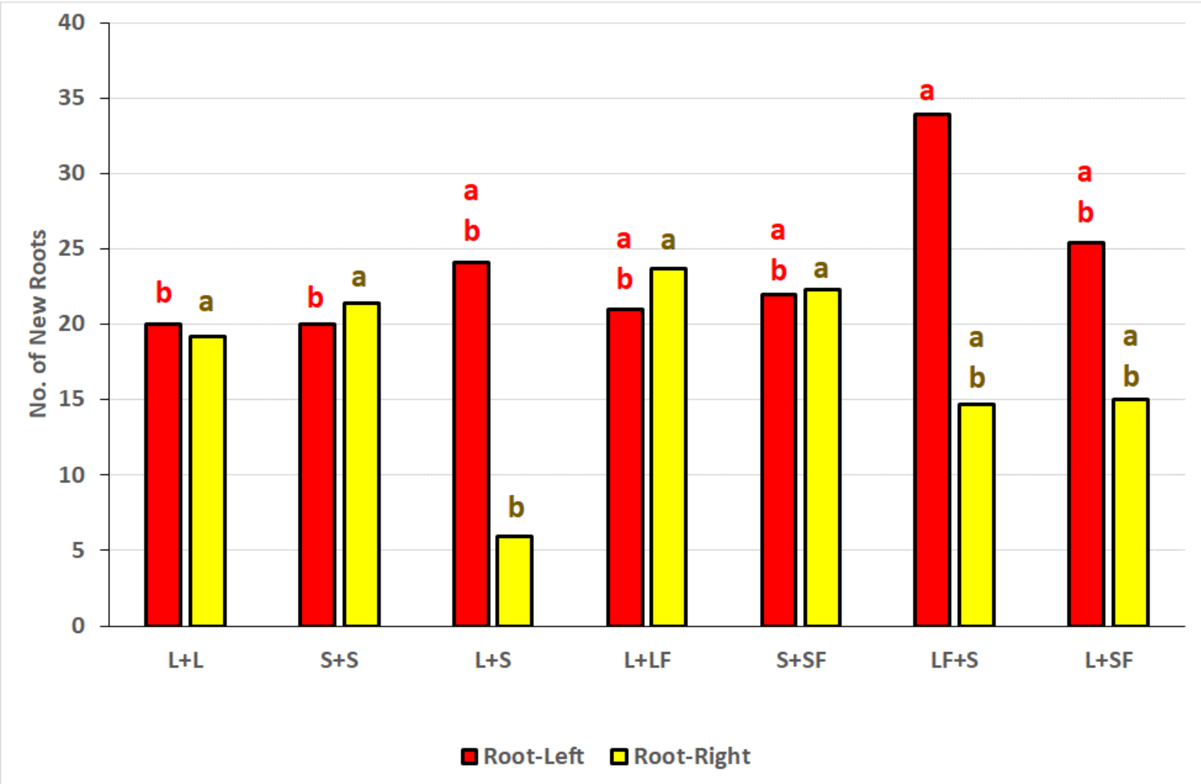


Figure 5. Philadelphus 'Aureus'. Dry weight of roots (left bottle), roots (right bottle), total roots and total shoots in September following root-pruning when active (July). L=light root-pruning, S=severe root-pruning, F=additional fertilizer. Letters denote differences for each parameter from Sidak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

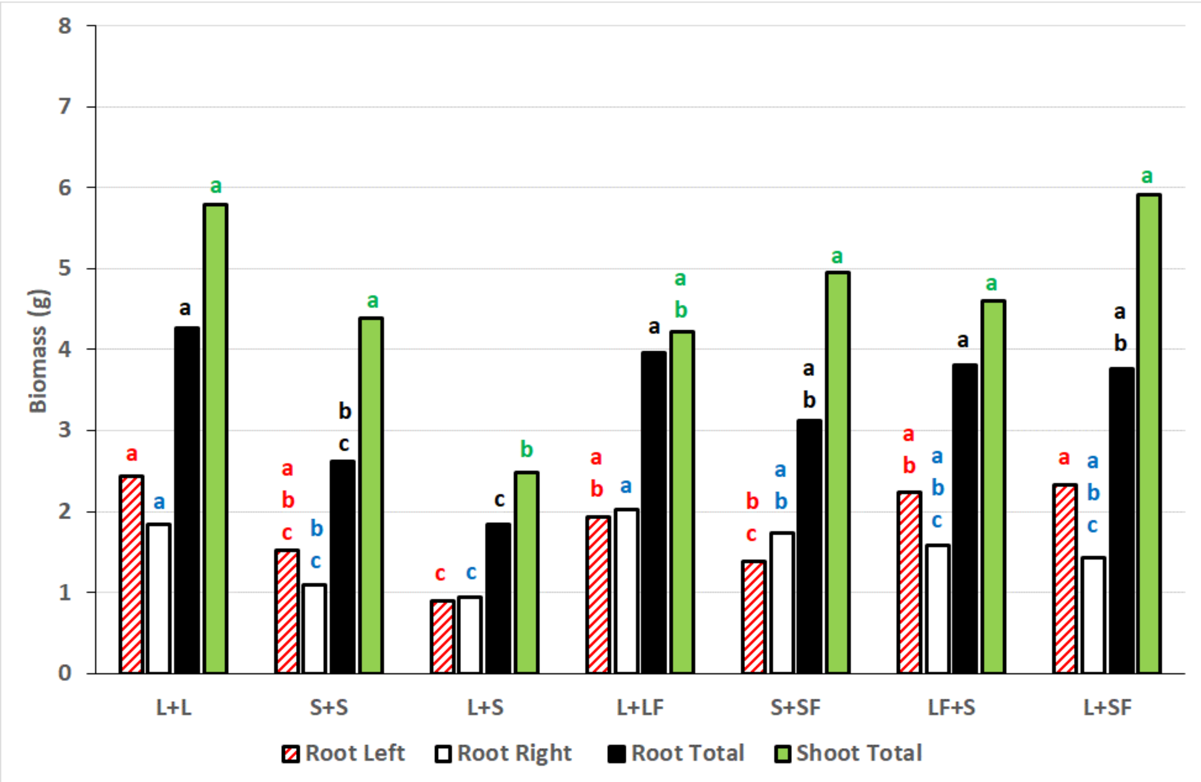


Figure 6. Philadelphus 'Aureus'. Mean number of new roots observed on left side or right side of plants in September following root-pruning when active (July). L=light root-pruning, S=severe root-pruning, F=additional fertilizer. Letters denote differences within each parameter from Sidak tests.

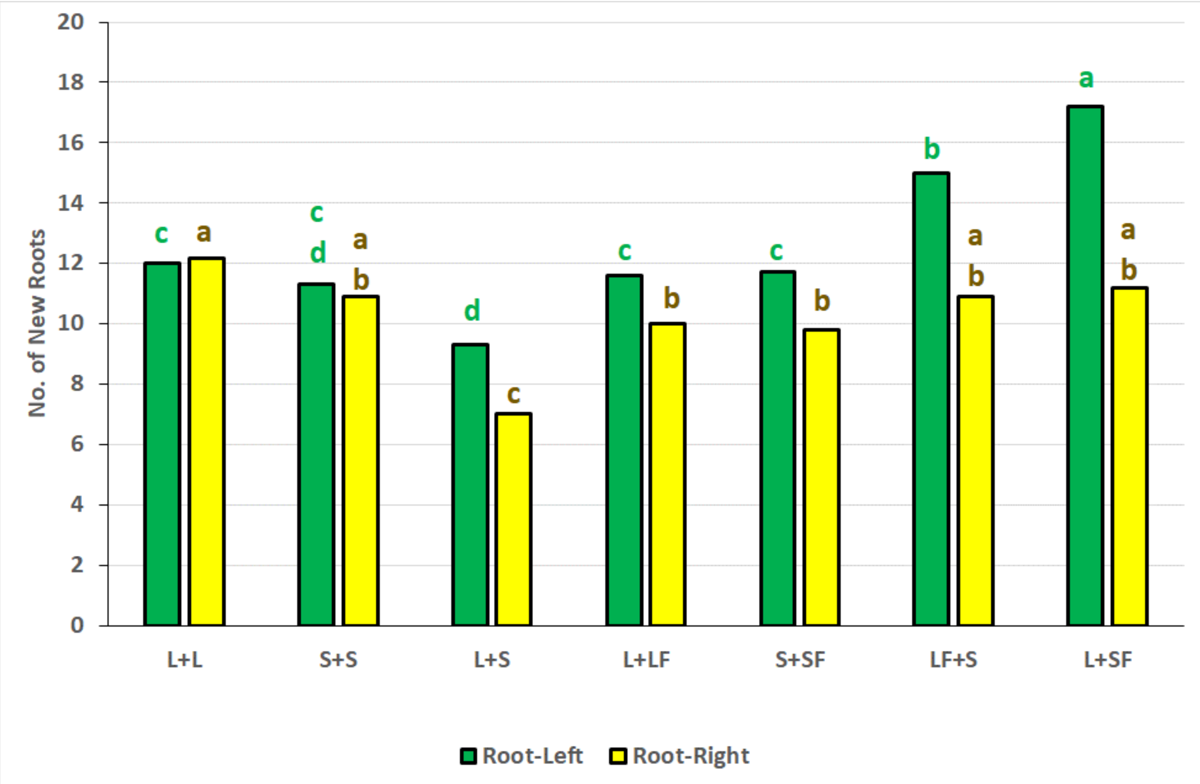


Figure 7. Euonymus ‘Silver Queen’. Dry weight of roots (left bottle), roots (right bottle), total roots and total shoots in September following root-pruning when active (July). L=light root-pruning, S=severe root-pruning, F=additional fertilizer. Letters denote differences for each parameter from Sidak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

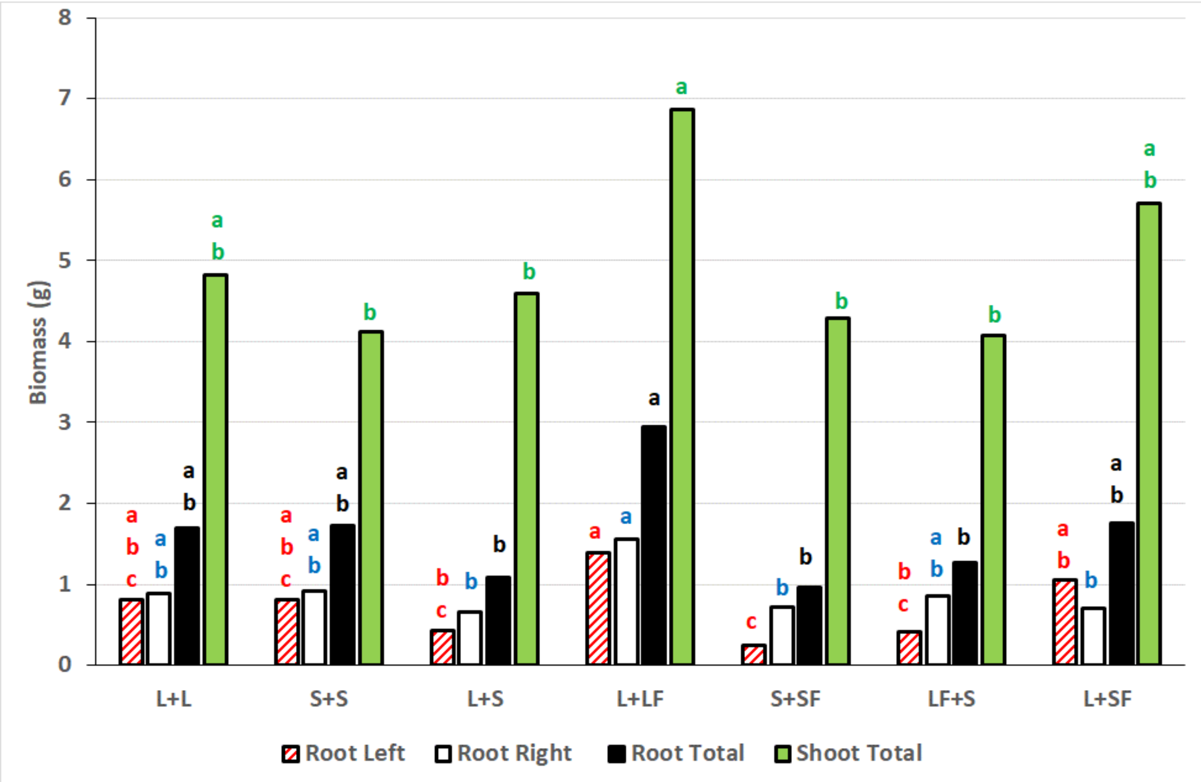
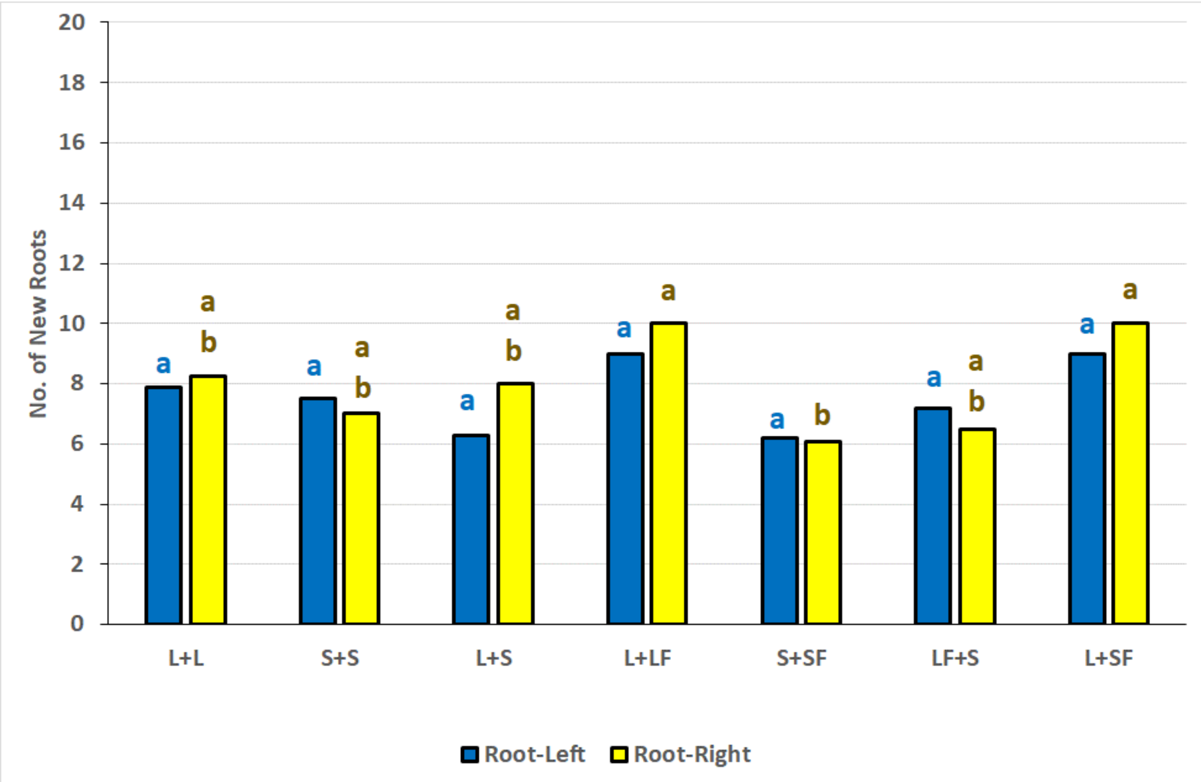


Figure 8. Euonymus 'Silver Queen'. Mean number of new roots observed on left side or right side of plants in September following root-pruning when active (July). L=light root-pruning, S=severe root-pruning, F=additional fertilizer. Letters denote differences within each parameter from Sidak tests.



Supplementary Figures

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

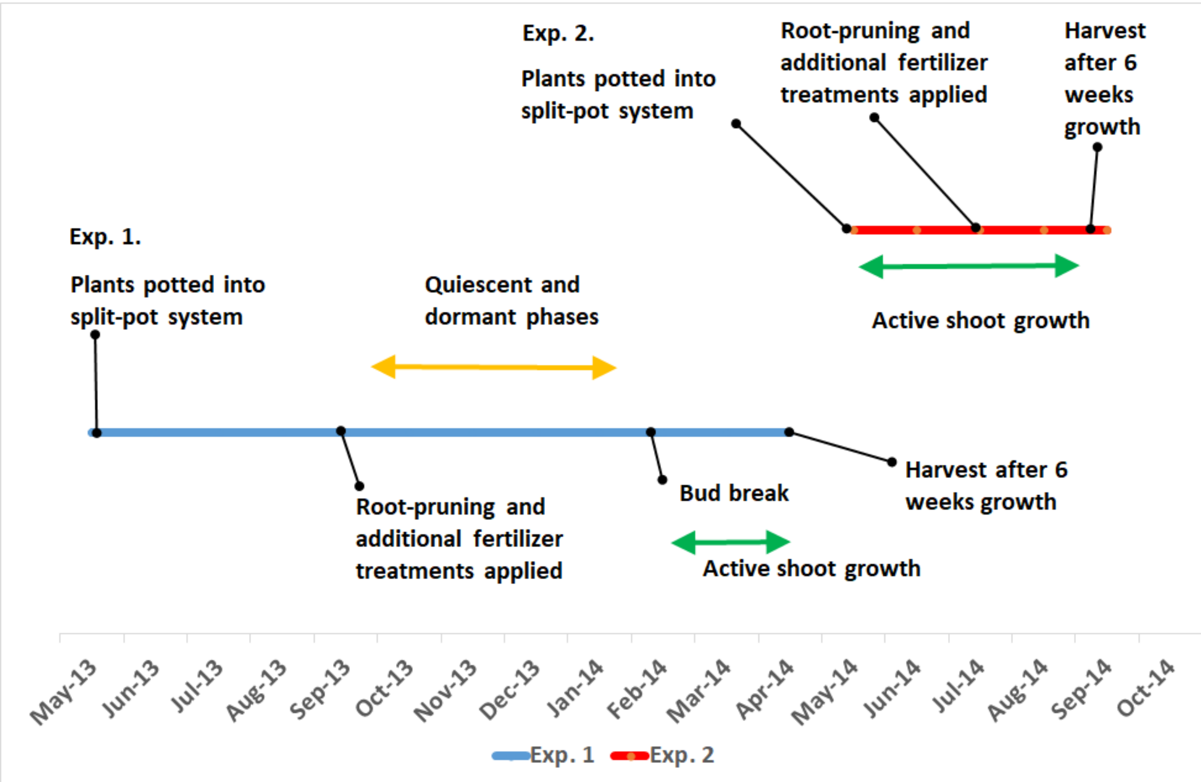
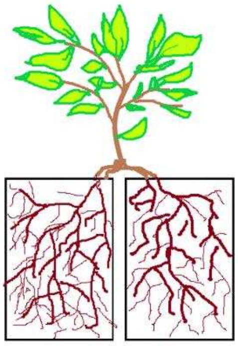


Figure S2. Two polypropylene cut down bottles as used as ‘pots’, with original roots of young plant carefully teased apart and encourage to grow in each side of the new pot system.

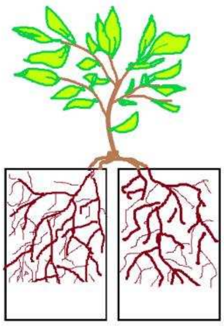
Figure S3. Diagram of typical root systems of plants before any root pruning; and consequently after the imposition of treatments L+L, S+S, L+S, L+LF, S+SF, LF+S, L+SF.



Plant before any root pruning

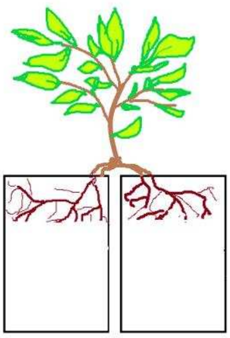
NB plants of this type were not assessed due to highly congested root systems

Treatments =



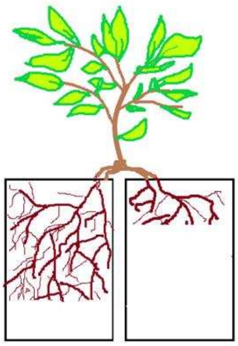
L+L

Lower 1/3 of roots removed from both sides



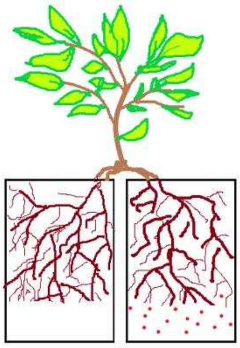
S+S

Lower 2/3 of roots removed from both sides



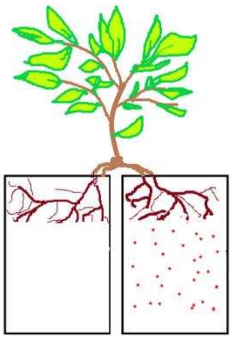
L+S

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



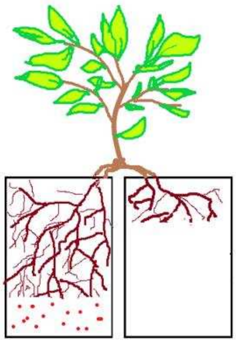
L+LF

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



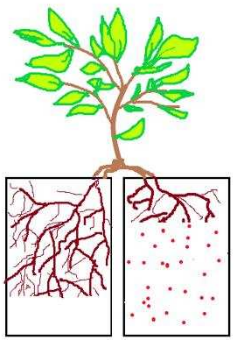
S+SF

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

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

A

B

C

D