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Optimizing Reduction Pruning of Trees Under Electrical Lines: The Influence of Intensity and Season of Pruning on Epicormic Branch Growth and Wound Compartmentalization

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Abstract. Reduction pruning of the main stem is commonly used during the maintenance of power lines to encourage the establishment and development of scaffold limbs away from wires. Understanding the physiology of epicormic branch initiation and growth as well as wound compartmentalization following reduction pruning are important for optimizing the pruning cycle and maintaining healthy and safe trees. In this study, the influence of both intensity and time of year of pruning on epicormic branch response and wound compartmentalization was investigated on 56 11-year-old Pennsylvania ash trees (*Fraxinus pennsylvanica* Marsh.) about 5 to 7 m in height within a controlled nursery environment. During the second growing season following reduction of the main stem, the number, height, and volume of epicormic branches, as well as tallest epicormic branches and the area of discolored wood, increased with pruning intensity. Pruning during the leaf-on season compared to the leaf-off season limited the establishment and development of epicormic branches without affecting wound-closure rate or the area of wood discoloration at the cutting point. Results are consistent with the known seasonal fluctuation of carbohydrates reserves. In the context of the electrical distribution network, where trees are subjected to pruning throughout the year, trees pruned in summer during a maintenance cycle could be pruned during the next cycle, in winter, and so on, to optimize the return interval of the pruning cycle.

Keywords. CODIT; Electricity Distribution Networks; Pruning Return Cycle; Sucker Growth; Utility Arboriculture; Vegetation Management.

INTRODUCTION

In urban areas, trees actively contribute to the improvement of human health and quality of life by providing numerous ecosystem services (Bolund and Hunhammar 1999; Nowak et al. 2018). However, trees are subjected to several pruning operations during their life spans to secure urban infrastructure (Gilman 2011). Good or better pruning practices will guarantee the safety and service benefits of urban trees (Raimbault and Tanguy 1993; Raimbault et al. 1995; Drénou 1999; Gilman 2011; Dujesiefken et al. 2016).

Electricity distribution networks are one of the major utilities in a city that requires continuous pruning maintenance of the tree crown to enhance cohabitation and ensure the safe functioning of the power lines (Dupras et al. 2016). During the mature phase of the tree life span (Dujesiefken et al. 2016), tree-crown architecture depends on the planting distance to utility wires and the height and types of utility wires (Millet and Bouchard 2003; Gilman 2011). When trees are planted directly under the wire, reduction pruning of the main stem during tree training is commonly used to encourage the occurrence and establishment of scaffold limbs near the cutting point (Millet and Bouchard 2003; Gilman 2011). Afterwards, scaffold limbs are directed away from the wire by directional pruning to obtain a "V" bilateral crown form (Millet and Bouchard 2003; Gilman 2011; Lecigne et al. 2018). Generally, the first scaffold limb is located between 2 m and 4 m from the ground for wires running about 7 m to 9 m above the ground (Millet and Bouchard 2003), because reduction pruning of the main stem is often performed when the annual growth of the terminal shoot comes into contact with the wire (Gilman 2011). Current knowledge on reduction pruning of the tree main stem suggests that the cut should be made just beyond a scaffold branch, and that the diameter of the removed part should comprise between one-half and two-thirds of the scaffold branch to stimulate the recovery of the apical dominance by this scaffold branch (Gilman and Lilly 2002; see Figure 1 in Grabosky and Gilman 2007). Nonetheless, a few years after reduction pruning, the space created within the internal tree structure is usually filled with epicormic branch recolonization (Goodfellow et al. 1987; Millet and Bouchard 2003; Follett et al. 2016). The epicormic branch initiation process, originating from proventitious or adventitious buds (Meier et al. 2012), occurs primarily to rebuild the leaf area loss of the crown (Deal et al. 2003) and restore the energy balance between both the above- and belowground systems following an injury (Valentine 1985). It is necessary to plan cyclical tree pruning to remove these epicormic branches entering the security corridor beneath the power lines (Millet and Bouchard 2003; Follett et al. 2016; Lecigne et al. 2018).

Each year, more than 800 million dollars are spent for line clearance pruning in the United States (Goodfellow et al. 1987) compared with 60 million in the province of Québec, Canada (Millet 2012). These costs of tree maintenance depend on the length of the return interval, the time a tree is pruned, and the amount of biomass removed (Nowak 1990; Browning and Wiant 1997). In Montreal, the return time for tree maintenance can vary from 3 or more years (Millet and Bouchard 2003; Millet 2012; Lecigne et al. 2018), depending on the growth rate of the tallest epicormic branch (Follett et al. 2016), although 5 to 6 years is the optimum length of time based on economics (Browning and Wiant 1997). Therefore, as higher expenses are incurred with shorter intervals, a better understanding of epicormic branch growth rate is needed in order to increase the return time interval and optimize maintenance of the distribution network.

On the other hand, pruning creates wounds and dysfunctional wood at the cutting point and may provide an entry for microorganisms of decay that, over time, can induce cavity formation and alter the health, mechanical strength, and safety of the tree (Dujesiefken and Stobbe 2002; Dujesiefken et al. 2016). The wound compartmentalization process has been well defined ever since the CODIT (compartmentalization of decay in trees) model was established by Shigo and Marx (1977). Following an injury in functional sapwood, trees react by surrounding it with 4 walls laid down in the wood (Shigo and Marx 1977; Gilman 2011). Although walls 1 to 3 prevent the spread of discoloration and decay in the internal wood structure by forming a reaction zone around the wound site, wall 4 closes the exposed wound area over time by forming a protective barrier zone. An increasing number of studies on the compartmentalization process that occurs when a branch is removed have been carried out (Dujesiefken and Stobbe 2002; Gilman and Grabosky 2006; Dănescu et al. 2015). However, few studies have focused on tree response to branch (Grabosky and Gilman 2007) or main-stem reduction (Gilman and Grabosky 2006).

This study was undertaken to specifically investigate the predominant factors that control the growth-rate response of epicormic branches following a main-stem reduction and their influence on wound compartmentalization. Epicormic branch establishment and development have been extensively investigated in forestry management for stand regeneration after harvesting or for pruning of the lower primary branches in order to improve bole value (Meier et al. 2012). As it is well documented that higher stand basal area prior to harvesting (Kays and Canham 1991; Babeux and Mauffette 1994; Perrette et al. 2014) and higher pruning intensity (O'Hara et al. 2008; DesRochers et al. 2015) produce a greater number, length, and biomass of epicormic branches, our first objective was to determine the magnitude of this effect at the tree main stem reduction scale. As the timing of silvicultural operations can also influence the epicormic branch response (Kays and Canham 1991; Babeux and Mauffette 1994; O'Hara et al. 2008; DesRochers et al. 2015), our second objective was to evaluate the benefits of main-stem reduction during the leaf-on season versus the leaf-off season. Our final objective was to investigate the influence of the intensity of reduction pruning and time of year on the closure rate and the area of wood discoloration of the pruning wound. To avoid urban environmental conditions that could affect tree growth (Jutras et al. 2010), this study was carried out within a controlled nursery environment.

MATERIALS AND METHODS

Study Site

The study was conducted 40 km northeast of Montréal at the Montréal Municipal Nursery in Assomption, Québec, Canada (45° 48' N, 73° 25' W). In this area, the climate is continental and humid, with hot summers and cold winters. The mean annual temperature is 5.3 °C, and the mean annual precipitation is 1018.7 mm, with a mean annual snow cover of 208.9 cm

(Environment Canada 2018, Assomption weather station). The soil is clay and clay mixed with fine sand subsoil.

Experimental Design and Reduction Pruning Treatments

The experiment took place in 2015 in an existing plantation composed of 2 cultivars of Pennsylvania ash trees (*Fraxinus pennsylvanica* Marsh.) from field-grown seedlings propagated in 2004 and transplanted in 2009. A total of 21 and 35 trees from 'Prairie Spire' and 'Patmore' cultivars, respectively, devoid of stress were selected among 22 and 39 individuals, respectively (see explanation below for selection). Trees from 'Prairie Spire' were 6 m to 6.6 m in height and 7.7 cm to 9.4 cm in DBH, whereas the 'Patmore' attains a height of 5.6 m to 7.3 m and a DBH of 5.7 cm to 9.7 cm.

The experiment consisted of 7 treatments, arranged in a random block design, with 3 and 5 blocks (replicates) for 'Prairie Spire' and 'Patmore' cultivars, respectively, and 7 trees per block. In addition to a control with no reduction pruning treatment, 2 main-stem reduction pruning treatments were performed between 2 m and 2.5 m, as well as between 3 m and 3.5 m above the ground (hereafter referred to as high and low intensity of reduction pruning, respectively) to simulate a prescribed corridor zone of 2.5 m around a fictitious power distribution network located 7 m above the ground during 3 distinctive season periods: early July, early September, and early December (hereafter referred to as summer, late summer, and winter, respectively). As the retained scaffold branch diameter relative to the parent axis diameter (aspect ratio) affects the surface area of decay after pruning (Eisner et al. 2002; Gilman and Grabosky 2006), we tried to keep the aspect ratio of the main-stem reduction pruning across trees within a small range (from 0.38 to 0.46). Although control trees were not pruned, they had one similar aspect ratio between the trunk and a scaffold branch in each part located between 2 m and 2.5 m as well as between 3 m and 3.5 m above the ground. To obtain the range of aspect ratio between trunk and scaffold branch in pruned and control trees, similar unions were first selected on each tree for both intensities of reduction pruning and prior to assigning random block treatment. For each branch union selected, the trunk and scaffold branch diameters were measured 10 mm above the scaffold branch bark ridge with a 2-m Lufkin tape measure to determine the aspect ratio of the main-stem reduction pruning. Trees with no aspect ratio that ranged from 0.38 to 0.46 for both intensities of reduction pruning treatments were excluded from the study. Trees with aspect ratios for both intensities of reduction pruning treatments were conserved as controls and not pruned, whereas season treatments were randomly assigned to trees on which only one intensity of reduction pruning was applied. For each reduction pruning treatment of the main stem, only one reduction pruning cut was made using a hand saw, so as to comply with the American National Standards Institute (ANSI 2008). Pruning wound diameters ranged from 5 cm to 7.5 cm and from 4.2 cm to 6.6 cm for high and low intensity of reduction pruning treatments, respectively. The amount of biomass removed was visually estimated by 2 assessors and ranged from 60% to 72% for the high intensity of reduction pruning treatment and from 35% to 52% for the low intensity of reduction pruning treatment. Including the retained scaffold branch of the main-stem reduction pruning, 4 to 6 and 10 to 15 lateral branches remained on the trunk for high and low intensity of reduction pruning treatments, respectively. No reduction pruning treatment of the main stem was made on a scaffold branch with included bark or codominant aspect, and no heartwood was visually present on any reduction pruning cut.

Data Collection

Epicormic Branch Inventory

Live epicormic branches from each tree were counted and measured during late summer from 2015 to 2017. As defined by Bégin and Filion (1999), all deferred or proleptic epicormic branches on the trunk and branches were counted. Additionally, all immediate or sylleptic epicormic branches on branches were counted (except in 2015) if their annual growth length was greater than the annual growth length of the retained scaffold branch of the main-stem reduction pruning. Each inventoried epicormic branch was first labeled using a tapener, measured for initiation height, and classified relative to the year of its establishment, i.e., 2015, 2016, or 2017. All the growth units of each epicormic branch were classified per branching order (Barthelemy and Caraglio 2007). The length was recorded with a ruler, and the median diameter was recorded with calipers at the widest part and at right angles for an average rounded to the nearest millimeter. To obtain the total height and volume per epicormic branch, growth units of primary order lengths and growth unit volume of all branch orders were added. Growth unit volume (V) was calculated according to the formula:

$$V = \frac{\pi \times {d_m}^2}{4} \times L$$

where L and d_m^2 are the length and median diameter of the growth unit, and π is equal to 3.1416. An epicormic branch was considered above the reduction pruning cut when epicormic branch initiation or growth reached beyond the height of the reduction pruning cut. To be considered a problematic epicormic branch, part of the growth unit had to be in contact with the virtual wire corridor zone located 5.5 m above the ground. The mean number, volume, and tallest epicormic branch per reduction pruning treatment were obtained by averaging the number, sum, and length results of each tree, whereas mean height was obtained by averaging epicormic branch height per tree prior to averaging per reduction pruning treatment.

Reduction Pruning and Wound-Closure Rate

Immediately after reduction pruning of the main stem in 2015 and at the end of the growing season in 2016 and 2017, the vertical length (parallel to the retained scaffold branch of the main-stem reduction pruning) and horizontal width of the pruning wound, both crossing the pith, were measured with a caliper to the nearest centimeter to determine the rate of pruning-wound closure. Each year, the surface area of the wound (S) not fully closed by the callus tissue was calculated as an ellipse according to the formula:

$$S = \frac{(L \times l) \times \pi}{4}$$

where L and l are vertical length and horizontal width, respectively. The pruning wound-closure rate was expressed as a percentage of the immediate surface wound area after pruning reduction.

Discolored Wood Area Following Reduction Pruning

At the time of harvest in 2017, a 1-m trunk section containing wound-reduction pruning treatments and two 0.5-m trunk sections containing both selected aspect ratios of controls were removed from trees with a chain saw. Lateral branches originating within these sections were removed close to the union with the trunk, with the exception of the retained scaffold branch of the main-stem reduction pruning, where a length of 5 cm was preserved. All trunk sections were dissected with a sliding table saw along a radial longitudinal plane of 30 cm, bisecting both centers of the reduction pruning wound and the scaffold branch. Dissected sections were progressively polished with up to 400-grit sandpaper and scanned at 2400 dpi. The area of discolored wood on each scan was delineated, and its surface area was calculated based on pixel counts using Adobe Photoshop CC 2018 (Adobe Systems, Inc., San Jose, CA, USA). All areas of discoloration were normalized by dividing by the length of the cross-sectional pruning cut area. The final area of discolored wood per reduction pruning wound was computed as the average of the 2 halves.

Statistical Analysis

Linear mixed effect models were used to predict epicormic branch (height, number, volume, tallest, and problematic) and wound (closure rate and discolored area) responses as a function of reduction pruning intensity and season. Sampling blocks were included in the models as a random effect. Differences between cultivars were first tested, and because they were found similar (Figure 1), models were rerun with both cultivars pooled. As no interaction between reduction pruning intensity and season was found in any model, these results are not presented. To examine the effects of reduction pruning treatment over time on the density and volume of epicormic branches in the 2015, 2016, and 2017 cohorts, a multivariate analysis of variance (MANOVA) was performed. Main effects were treatments and years. All statistical analyses were conducted using JMP software, version 13.0.0 (SAS Institute, Cary, NC, USA).

RESULTS

Physiological Tree Response After Reduction Pruning Treatments

In 2017, 2 years after reduction of the main stem, the dynamics of epicormic branch initiation and development through treatments above the pruning cut were similar to the epicormic branch dynamics of the whole tree (Figure 2). All reduction pruning treatments had greater effects on the epicormic branch initiation and development than control trees (Figure 2; results not shown). For all season treatments, a higher intensity of reduction pruning of the main stem significantly increased the number ($F_{1,7}$ = 106.71,

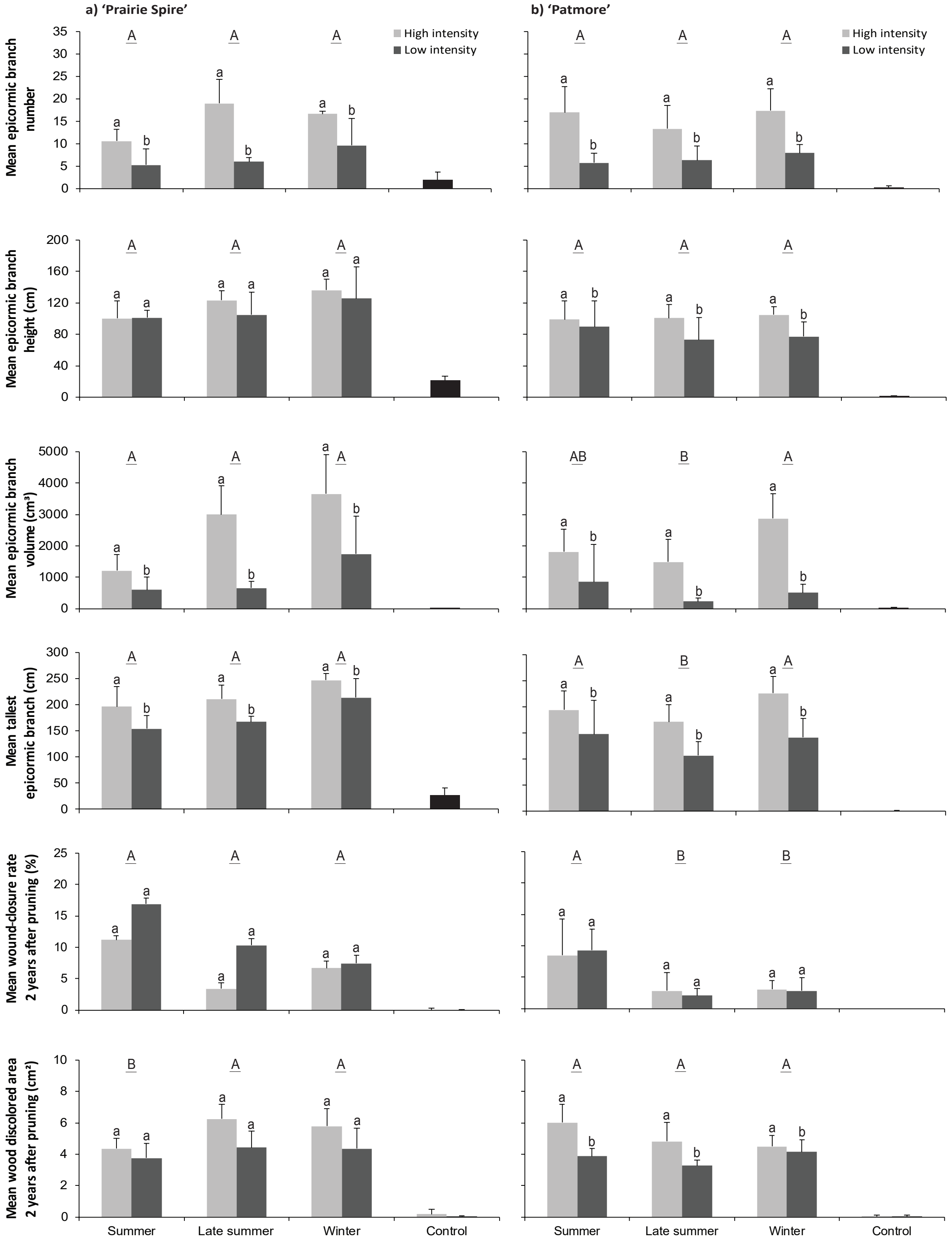

Figure 1. Mean (± SD) number, height, volume, and tallest epicormic branch, as well as wound-closure rate and area of discolored wood, 2 years after pruning reduction by pruning intensity and by season: (a) *Fraxinus pennsylvanica* Marsh. 'Prairie Spire' (left panel); and (b) *Fraxinus pennsylvanica* Marsh. 'Patmore' (right panel). Differences between intensities within seasons: different letters above the bars indicate significant differences based on paired *t*-tests. Differences between seasons within intensities: capital letters above the bar pairs indicate significant differences based on Tukey's HSD post-hoc tests ($p > 0.05$). Despite having been excluded from the analyses, controls are shown in the graph.

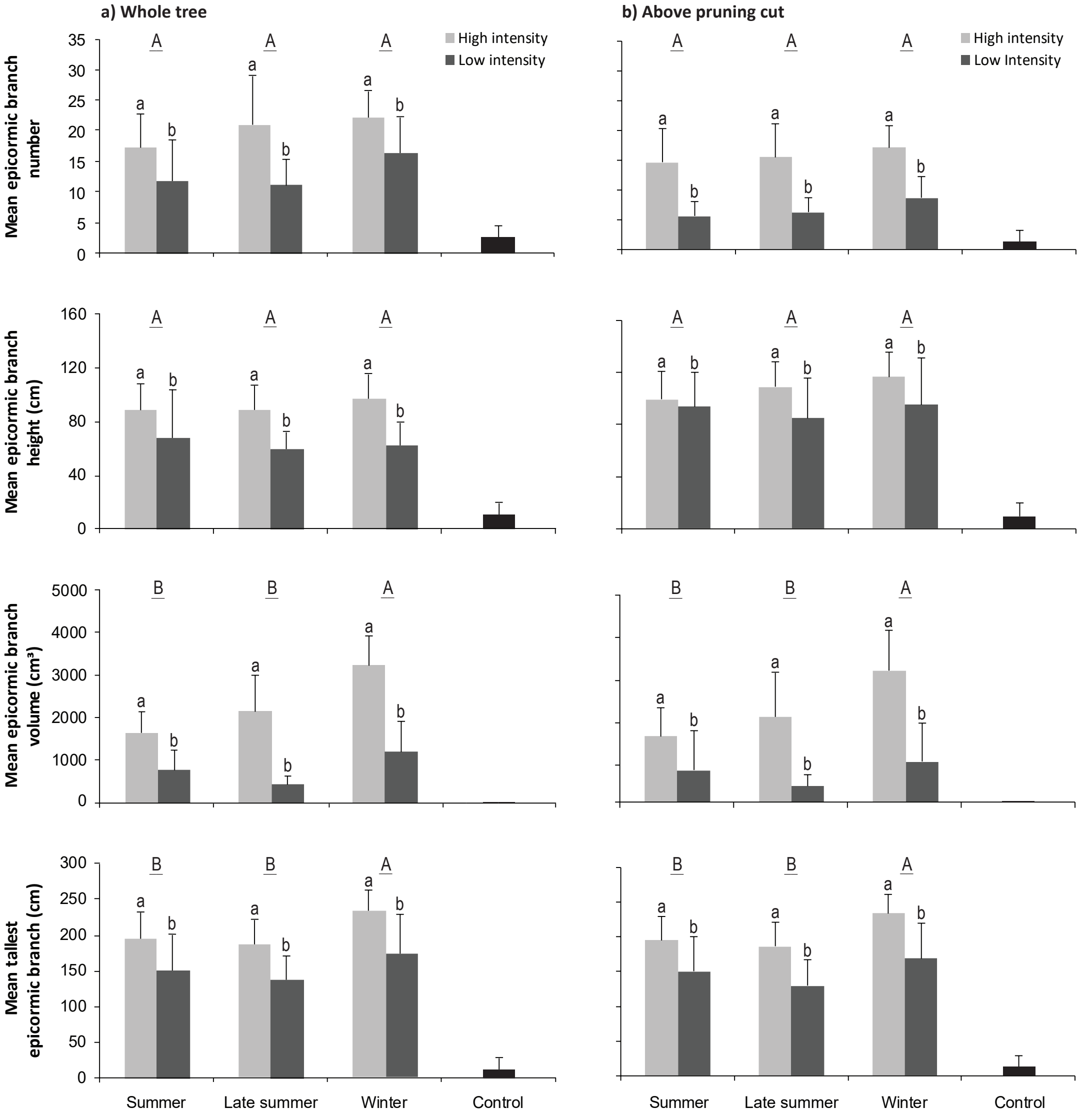

Figure 2. Mean (± SD) number, height, volume, and tallest epicormic branch after reduction of the main stem and 2 growing seasons by pruning intensity and by season: (a) on the whole tree (left panel); and (b) above the pruning cut (right panel). Differences between intensities within seasons: different letters above the bars indicate significant differences based on paired *t*-tests. Differences between seasons within intensities: capital letters above the bar pairs indicate significant differences based on Tukey's HSD post-hoc tests ($p > 0.05$). Despite having been excluded from analyses, controls are shown in the graph.

$p < 0.0001$), height ($F_{1,7} = 8.74$, $p = 0.0212$), and volume ($F_{1,7} = 70.19$, $p = 0.0002$) of epicormic branches located above the pruning cut. The pruning season had no effect on the number ($F_{2,14} = 1.69$, $p = 0.2195$) or height ($F_{2,14} = 0.82$, $p = 0.4612$) of epicormic branches for any intensity of reduction pruning treatment; however, reduction pruning during winter increased epicormic branch volume ($F_{2,14} = 4.73$, $p = 0.0270$) and the height of the tallest epicormic branch ($F_{2,14} = 8.3$, $p = 0.0042$) at the end of the second growing season.

Epicormic Branch Cohort Establishment and Survival Dynamics

Between 2015 and 2017, total epicormic branch density above the reduction pruning cut varied over time, reaching a maximum in 2017, i.e., 2 years after reduction of the main stem (Figure 3; MANOVA, $F_{2,41} = 162.95$, $p < 0.0001$). The 2015 epicormic branch cohort was influenced by treatments of pruning intensities and seasons (MANOVA, $F_{5,42} = 6.55$, $p < 0.0001$), but not by years (MANOVA, $F_{2,41} = 2.97$, $p = 0.0623$) or the

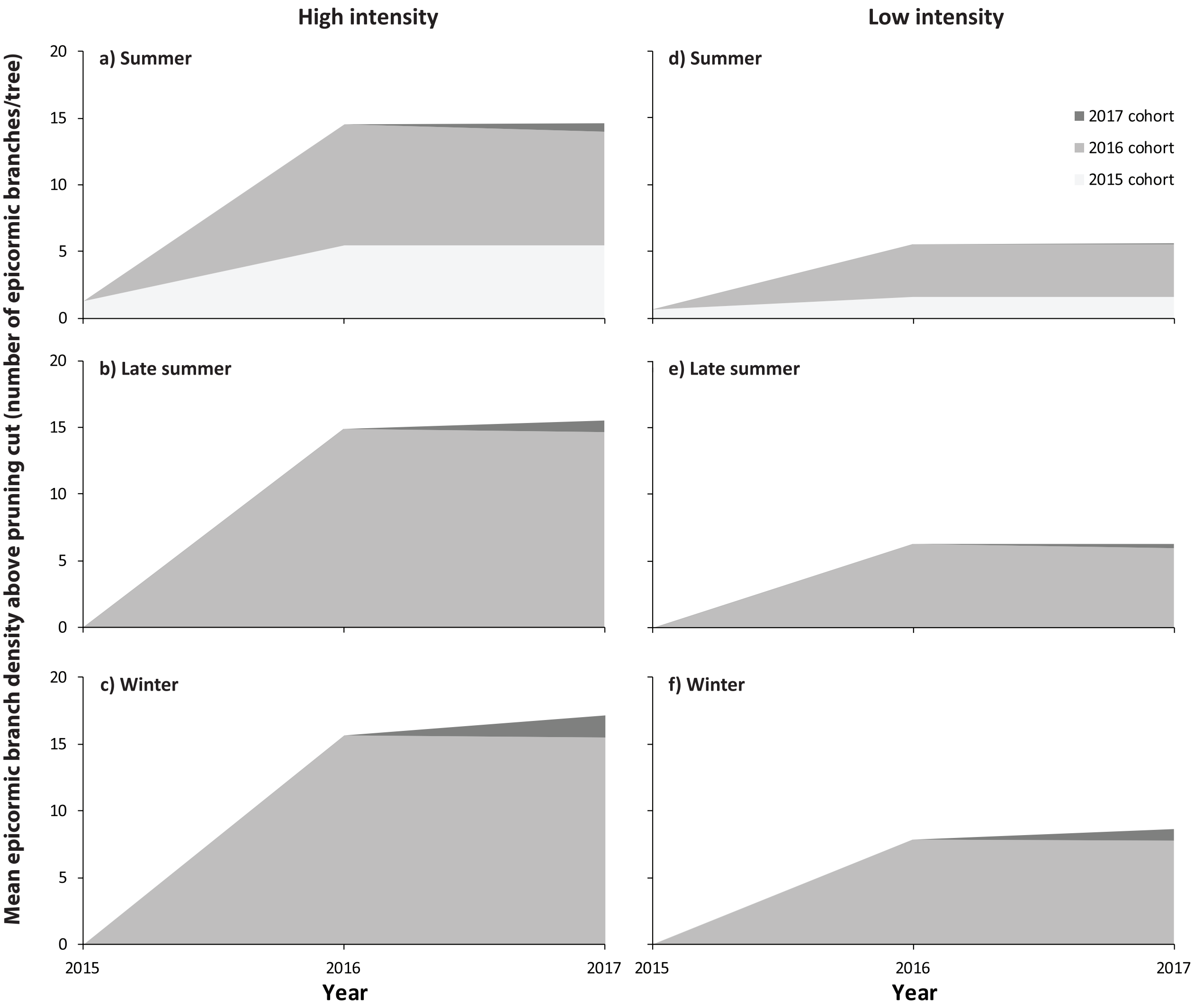

Figure 3. Temporal dynamics of epicormic branch densities after reduction of the main stem and above the pruning cut by cohort and by year for each of the pruning intensities and seasons. Legend for high-intensity pruning (left panel) is the same as that for low-intensity pruning (right panel).

interaction between treatments and years (MANOVA, $F_{10,84} = 1.56$, $p = 0.1326$). Subsequent univariate ANOVAs and Tukey honestly significant difference (HSD) post-hoc tests indicated that in 2016 and 2017, 1 and 2 years after reduction pruning of the main stem, the 2015 cohort was significantly denser in response to a higher summer pruning intensity compared to the lower summer pruning intensity and all other treatments. The 2016 epicormic branch cohort was also influenced by treatments of pruning intensities and seasons (MANOVA, $F_{5,42} = 11.56$, $p < 0.0001$) and by years (MANOVA, $F_{1,41} = 5.93$, $p = 0.0192$), but not by the interaction between treatments and years (MANOVA, $F_{4,42} = 0.66$, $p = 0.6524$). In 2016, the epicormic branch cohort was significantly denser in response to the higher intensity of reduction pruning treatments compared to the lower intensity of reduction pruning seasons, except for epicormic branch density during the high-intensity summer treatment, which had an intermediate density between that of late summer and winter with the high-intensity treatment and other seasons with the low-intensity treatment (univariate ANOVAs and Tukey HSD post-hoc tests). In 2017, the density of the 2016 epicormic branch cohort in all reduction pruning treatments was only slightly different than in 2016 (late summer and

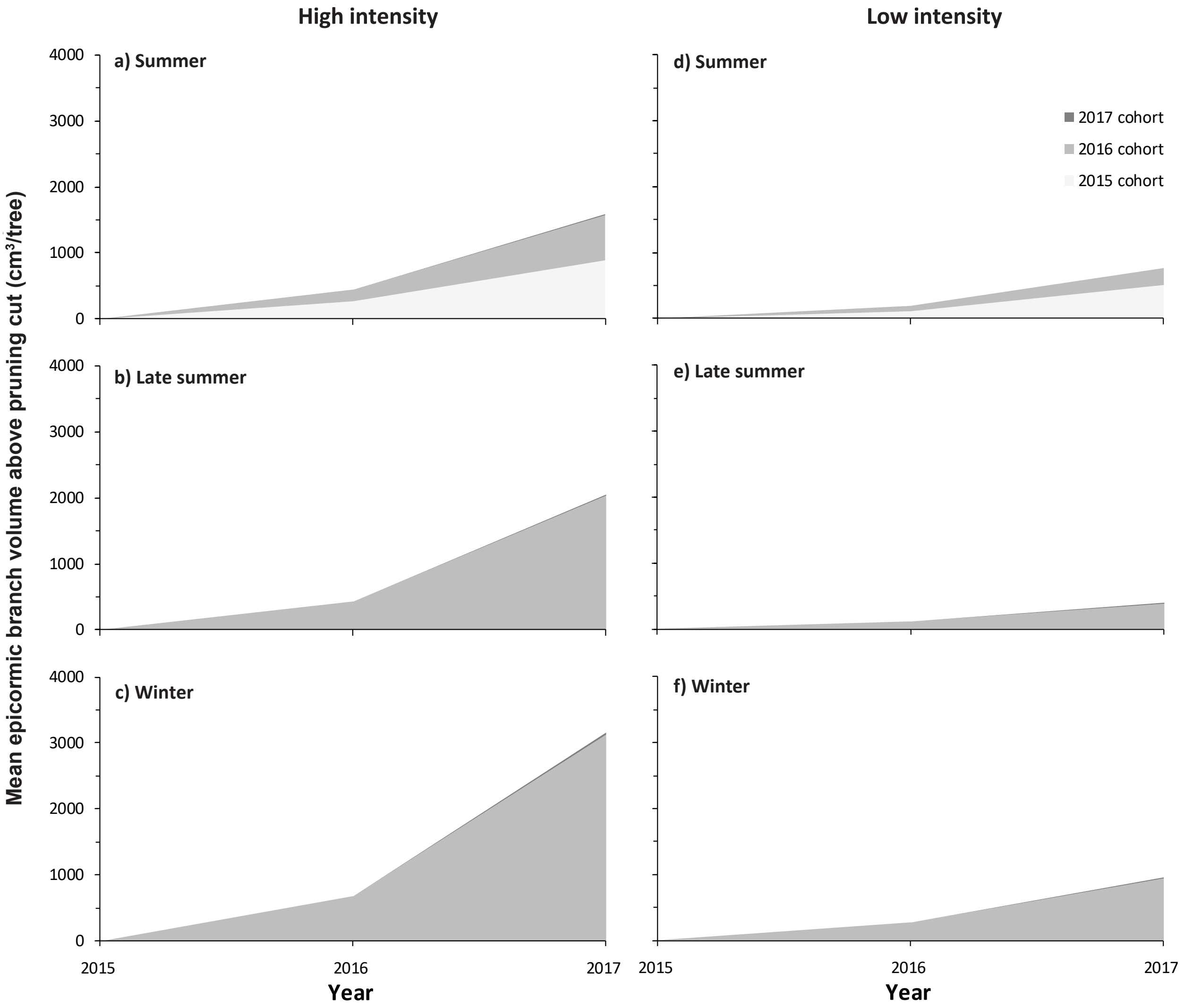

Figure 4. Temporal dynamics of epicormic branch volumes after reduction of the main stem and above the pruning cut by cohort and year for each of the pruning intensities and seasons. Legend for high-intensity pruning (left panel) is the same as that for low-intensity pruning (right panel).

winter with high-intensity > all other treatments). In 2017, the contribution of the 2016 epicormic branch cohort to the total density of epicormic branches was maximized in both the late-summer and winter reduction pruning treatments. The 2016 cohort compensated for the cohort initiated in 2015 in all summer reduction pruning treatments, and total density by intensity reached similar levels compared to all seasons from 2016 onwards. The contribution of the 2017 cohort to the total density of the epicormic branches in all treatments, 2 years after reduction pruning, was minimal, and no significant differences in absolute density occurred among seasons and intensities (Figure 3; univariate ANOVAs and Tukey's HSD post-hoc tests).

Epicormic Branch Volume Cohort and Recovery Dynamics

Following the main-stem reduction in 2015, total epicormic branch volume above the reduction pruning cut increased over time (Figure 4; MANOVA, $F_{2,41} = 86.27$, $p < 0.0001$). The volume of the 2015 epicormic branch cohort was influenced by treatments of pruning intensities and seasons (MANOVA, $F_{5,42} = 3.77$, $p = 0.0065$), years (MANOVA, $F_{2,41} = 5.12$, $p = 0.0103$), and the interaction between treatments and years

(MANOVA, $F_{10,84} = 3.09$, $p = 0.0021$). In 2016 and 2017, 1 and 2 years after reduction pruning of the main stem, the 2015 cohort contributed to the total epicormic branch volume in both summer treatments, but was absent in late-summer and winter treatments (univariate ANOVAs and Tukey's HSD post-hoc tests). The volume of the 2016 epicormic branch cohort was also influenced by treatments of pruning intensities and seasons (MANOVA, $F_{5,42} = 17.29$, $p < 0.0001$), years (MANOVA, $F_{1,42} = 112.68$, $p < 0.0001$), and the interaction between treatments and years (MANOVA, $F_{5,42} = 16.34$, $p < 0.0001$). Subsequent univariate ANOVAs and Tukey's HSD post-hoc tests indicated that, in 2016 and 2017, the volume of the 2016 cohort was more significant during winter with high intensity of reduction pruning compared with all other reduction pruning treatments. However, the volume of the 2016 cohort with low intensity of reduction pruning was the lowest in both summer and late summer, whereas volume was intermediate in late summer with the high intensity of reduction pruning treatment and in the winter with the low intensity of reduction pruning treatment. The only exception was the low-intensity reduction pruning treatment in 2016, where epicormic branch volume was no different than that of reduction pruning treatments with the lowest volume. In 2017, the contribution of the 2016 epicormic branch cohort to the total epicormic branch volume was maximal in both the late-summer and winter reduction pruning treatments, whereas in all summer reduction pruning treatments, the volume of the 2016 cohort was only marginally different from the volume of the 2015 cohort. The contribution of the 2017 cohort to the total epicormic branch volume in all treatments 2 years after reduction pruning of the main stem was minimal, and no significant differences in absolute volume occurred among seasons and intensities (Figure 4; univariate ANOVAs and Tukey's HSD post-hoc tests).

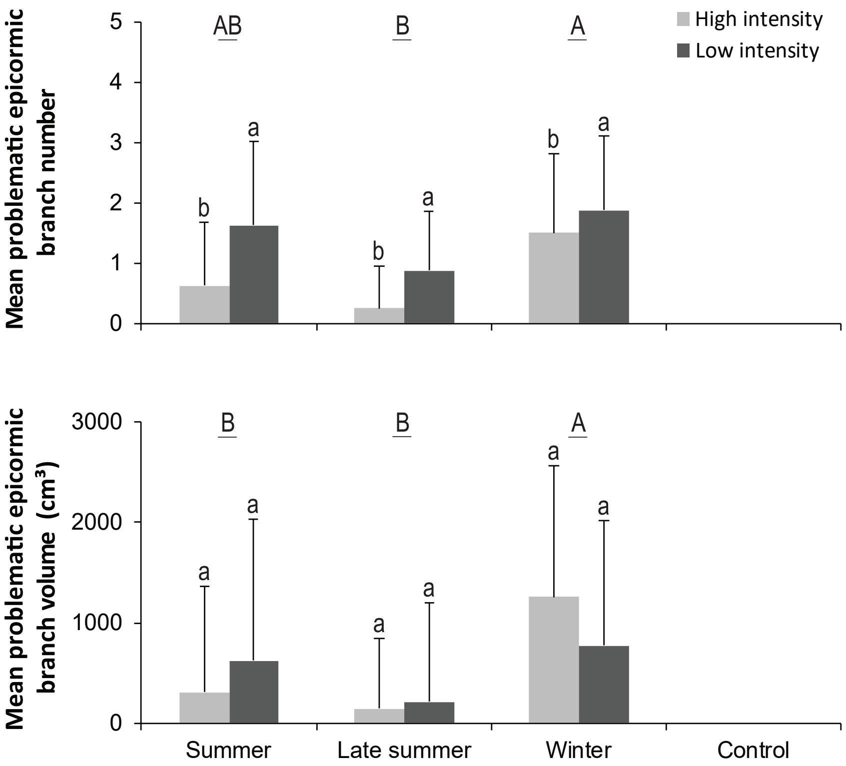

Figure 5. Mean (± SD) number and volume of problematic epicormic branches in contact with the corridor zone of a wire located 7 m above the ground after reduction of the main stem and 2 growing seasons by pruning intensity and by season. Differences between intensities within seasons: different letters above the bars indicate significant differences based on paired *t*-tests. Differences between seasons within intensities: capital letters above the bar pairs indicate significant differences based on Tukey's HSD post-hoc tests ($p > 0.05$). Note that there is no letter for controls because epicormic branch absence has not been included in the statistical general linear model.

Power Line Clearance Standards and Reduction Pruning Treatments

Two years after the main-stem reduction, in all season treatments, the number of problematic epicormic branches in contact with the virtual 2.5-m wire corridor zone was significantly higher in the lower intensity of reduction pruning treatments compared with higher intensity (Figure 5; $F_{1,7} = 12.44$, $p = 0.0096$). By contrast, no significant difference in the volume of problematic epicormic branches existed between intensity treatments (Figure 5; $F_{1,7} = 0.05$, $p = 0.8288$). At both intensities, reduction pruning during winter increased the number ($F_{2,14} = 4.04$, $p = 0.0412$) and volume ($F_{2,14} = 9.23$, $p = 0.0028$) of problematic epicormic branches compared with other reduction pruning seasons, except that the number of epicormic branches during summer reduction pruning had intermediate values between the late-summer and winter treatments.

Reduction Pruning Treatment and Wound Compartmentalization

In 2016 and 2017, 1 and 2 years after reduction pruning of the main stem, the pruning wound-closure rate followed the same significant pattern among treatments (Figure 6). The closure rate was similar between intensities (2016, $F_{1,7} = 0.01$, $p = 0.9091$; 2017, $F_{1,7} = 1.80$, $p = 0.2210$), but was higher when reduction pruning was performed during the summer (2016, $F_{2,14} = 7.00$, $p = 0.0078$; 2017, $F_{2,14} = 14.44$, $p = 0.0004$).

Conversely, the discolored area of the wound was significantly higher with higher pruning intensity after 2 growing seasons ($F_{1,7} = 51.98$, $p = 0.0002$), but was not influenced by pruning season ($F_{2,14} = 0.03$, $p = 0.9717$).

DISCUSSION AND CONCLUSIONS

Intensity and Timing of Reduction Pruning on Epicormic Branch Development

The results from our study show that trees can vigorously respond by epicormic branches after a main-stem reduction pruning (Figure 2). The fact that a higher pruning reduction intensity resulted in an increased number and volume of epicormic branches, and that the resulting epicormic branches were taller than those produced after lower-intensity pruning reductions, confirmed that reduction pruning intensity largely controls the epicormic branch response. However, the intensity was not the sole factor controlling the emergence of epicormic branches, as epicormic branches were also present in control trees. Colin et al. (2010) previously reported that epicormic branches can occur with an increase in light availability after stand thinning. This could explain the production of epicormic branches in our control trees after reduction of the main stem of adjacent trees. Still, the lack of, or very low, epicormic branching found on control trees compared with those in other reduction pruning treatments indicates that reduction pruning intensity was a major driver of the epicormic branch response. Although intensity has been reported as the primary factor causing epicormic branching with total removal of the main stem following harvesting (Kays and Canham 1991; Babeux and Mauffette 1994) or primary branch order following pruning (O'Hara et al. 2008; DesRochers et al. 2015), this is the first study to our knowledge linking pruning intensity to epicormic branch response when only the main stem of the tree is reduced. Therefore, our study provides key knowledge related to our overall understanding of the physiological response of the main stem with reduction pruning. However, to achieve a global perspective of the understanding of the physiological tree response to reduction pruning, a similar study should be undertaken at the branch scale.

The timing of main-stem reduction pruning during the year, corresponding to the leaf-on or leaf-off period, is a significant factor in the development of epicormic branches, although to a lesser extent than reduction pruning intensity (Figure 2). O'Hara et al. (2008) and DesRochers et al. (2015) previously demonstrated this with the removal of lower primary branch order of the living crown for silvicultural purposes. However, because winter pruning was performed before summer pruning in those studies, a delay equivalent to half a growing season for the initiation and development of the epicormic branch arose on trees pruned in summer, which could have significantly impacted the results (O'Hara et al. 2008). In our study, summer reduction pruning was applied before winter reduction pruning, and despite a decrease of density and mean height of epicormic branches on trees pruned in summer compared with those pruned in winter, the differences were not large enough to be statistically significant. Nonetheless, because at the end of the 2017 growing season, summer-pruned trees have more than half of a growing season compared to winter-pruned trees to restore the energy

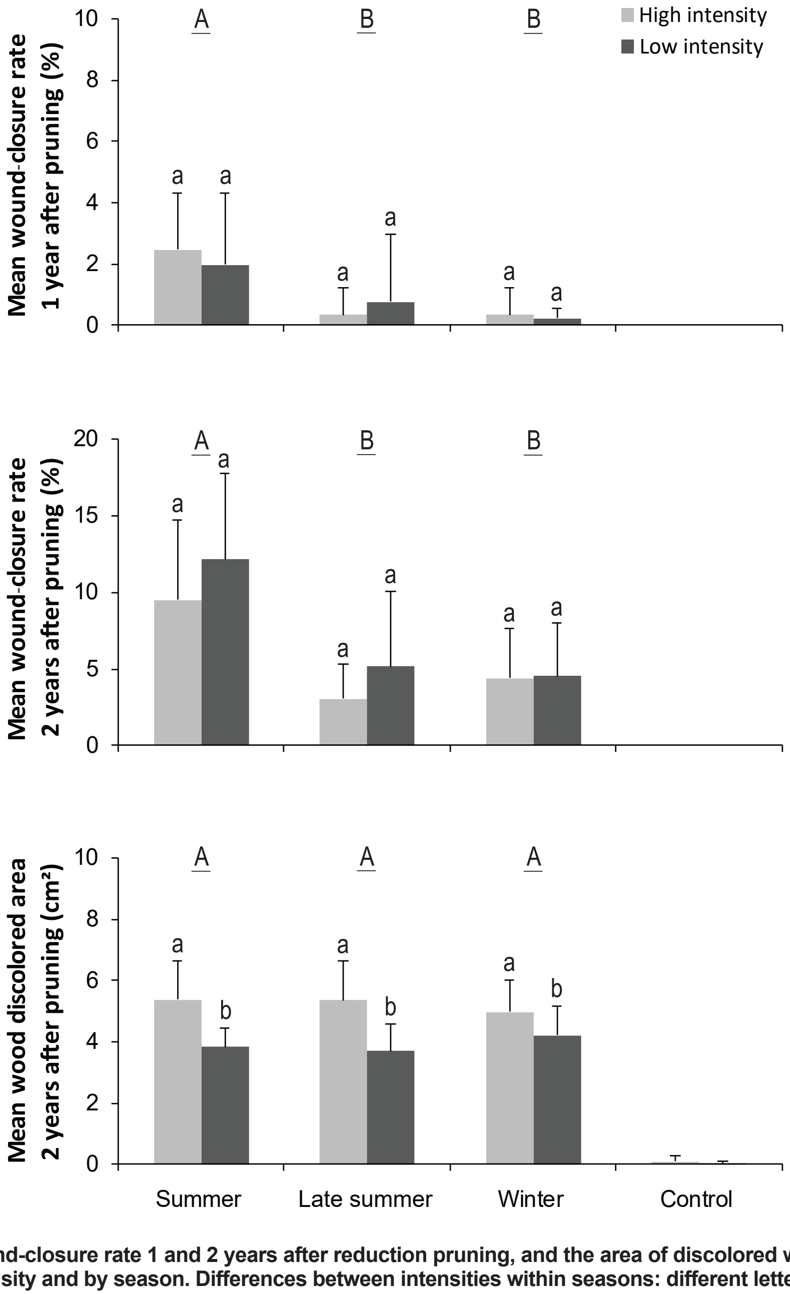

Figure 6. Mean (± SD) wound-closure rate 1 and 2 years after reduction pruning, and the area of discolored wood 2 years after pruning reduction, by pruning intensity and by season. Differences between intensities within seasons: different letters above the bars indicate significant differences based on paired *t*-tests. Differences between seasons within intensities: capital letters above the bar pairs indicate significant differences based on Tukey's HSD post-hoc tests ($p > 0.05$). Note that for controls there is no bar for wound-closure rate because no data were collected, and there is no letter for the area of discolored wood because data have not been included in the statistical general linear model.

balance between the above- and belowground systems, it appears safe to presume that summer or late-summer reduction pruning should result in epicormic branch densities and heights less than those obtained with winter reduction pruning, especially because the volume and the tallest epicormic branch were lower on trees pruned in the summer (Figure 2). These last results corroborate previous findings by Kays and Canham (1991) and Perrette et al. (2014) on deciduous broadleaved trees 3 years after total main-stem harvesting. According to Kays and Canham (1991), divergence in epicormic branch development between seasons is related to a phenological gradient in carbohydrate reserves. In fact, pruning during the leaf-on season, when stored reserves are low (Barbaroux and Bréda 2002; Furze et al. 2018), limits the potential for epicormic branch development. Conversely, epicormic branch development is higher when pruning occurs during the leaf-off season, when stored reserves are highest.

Epicormic Branch Cohort Recovery Dynamics

By examining individual epicormic branch cohorts generated after applying reduction pruning to the main stem, our study was able to show contrasting dynamics of density and volume over time (Figures 3 and 4). The first epicormic branch cohort was immediately initiated in the second half of the year of growth following both main-stem reduction intensities in the summer (Figure 3a and d). However, the initiation of a new cohort in the second growing season of summer reduction pruning that was denser than the first one showed that the contribution of the first cohort was not enough to restore the energy balance between the above- and belowground systems. Nevertheless, because the volume of the first cohort at the end of the third growing season was higher than the volume of the second cohort at both reduction pruning intensities, this finding emphasizes the predominance of the first cohort initiated in the process of recovery on a tree pruned in summer (Figure 4a and d). A similar finding was observed with both late-summer and winter reduction pruning intensities after the 2 growing seasons, as epicormic branch density and volume were primarily composed of the cohort initiated during the first growing season (Figures 3 and 4b, c, e, and f). On one hand, this result suggests an incapacity of trees pruned in late summer to instantly initiate the restoration process in the year of pruning. This could be related to the short length of the remaining growing season (Figures 3 and 4b and e). On the other hand, this once again highlights the dynamics and primary role of carbohydrate storage levels for epicormic branch development, as a lower volume of epicormic branches with a similar density were produced in late summer compared with winter reduction pruning at the end of both growing seasons (Figure 4b, c, e, and f). Considering that reduction pruning in late summer was performed at the time of maximal carbohydrate storage (Furze et al. 2018), late-summer pruning appears to have circumvented the buildup of carbohydrates for optimal epicormic branch development in the following growing season.

The minor establishment of a third cohort in the summer reduction pruning treatment and a second cohort in both the late-summer and winter reduction pruning treatments indicates that the entire system was equilibrated after 1.5 growing seasons for summer and only 1 growing season for late-summer and winter reduction pruning (Figure 3). Thus, the epicormic branch density dynamics in the time after reduction of the main stem and between the leaf-on and leaf-off periods are in agreement with previous studies, such as Perrette et al. (2014) following total harvesting, and DesRochers et al. (2015) after crown-raising of the main stem. This indicates that the epicormic branch dynamics initiated to rebuild the loss of leaf area is independent from the intensity of the operations completed on different parts of the tree.

Line Clearance and Problematic Epicormic Branches

Our study examined the number and volume of epicormic branches that should be removed in according to clearance standards 2 years after reduction pruning of the main stem. Unexpectedly, a lower pruning intensity increased the number of problematic epicormic branches when compared with the higher pruning intensity (Figure 5). Several authors reported that removing less than 30% (Collier and Turnblom 2001; O'Hara et al. 2008; Maurin and DesRochers 2013) or 20% (Grabosky and Gilman 2007; Dujesiefken et al. 2016) of the biomass limited epicormic branch development. In our study, a low pruning intensity removed 35% to 52% of the biomass, because the trees were in contact with a virtual power distribution network located 7 m above the ground. As a result, the low-intensity reduction pruning was performed between 3 m and 3.5 m above the ground, and problematic epicormic branches appeared 2 years later. Our results therefore suggest that this reduction pruning was high because it was carried out too late in tree development. From a management point of view, if the aim is to intervene less by reducing epicormic branch development, the reduction pruning intervention should be performed before trees reach anywhere from 4.5 m to 5.5 m tall in the case of moderately high wires (< 7 m to 8 m). In other words, trees should be reduced and shaped when younger and not yet in contact with wires. If not, reduction pruning intensity has to be increased, thus intensifying epicormic branch development (Millet and Bouchard 2003). In addition, intervening during the leaf-on season, and especially in late summer, (mid-August to September) before leaf fall, should result in the development of fewer problematic epicormic branches (Figure 5).

Intensity and Timing of Reduction Pruning on Wound Compartmentalization

All pruning reduction treatments were followed by an active establishment of wound compartmentalization at the reduction cutting point (Figure 6). Smaller pruning wounds have been extensively reported as occluding faster than bigger ones at least 5 years after pruning (Nicolescu et al. 2013; Dănescu et al. 2015; Sheppard et al. 2016). In our study, the wound-closure rate was similar between low- and high-intensity pruning after the first growing season. Although not significant, the wound-closure rate became more important with a lower pruning intensity at the end of the second growing season (Figure 6). This lack of a significant result may be associated with the fact that some wound diameters at the low pruning intensity were larger than those at the high pruning intensity, or because wound diameter in our study was nearly twice that reported in previous studies. This suggests that only 2 growing seasons after pruning was an insufficient length of time for a significant difference of wound-closure rate on bigger wounds to be revealed. However, the positive impact of low intensity of reduction pruning on wound compartmentalization at the cutting point was the proportion of the discolored wood area produced, which was significantly less than the area of discoloration resulting from the high intensity of reduction pruning treatment (Figure 6). This result highlights the importance of reducing the main stem (i.e., the diameter of the cut) as little as possible to limit large pruning wounds, thus lowering risk of decay (Dujesiefken and Stobbe 2002; Ow et al. 2013; Dănescu et al. 2015).

In relation to lowering or preventing decay, the season of pruning may also affect the efficiency of wound compartmentalization (Figure 6). Thus, with only half of an additional growing season, the wound-closure rate of summer reduction pruning was 2-fold higher than that of late-summer and winter reduction pruning in both years following pruning. Numerous studies on several species have shown similar responses between season of cambial activity and dormancy (Dujesiefken et al. 2005b; Lee and Lee 2010; Dănescu et al. 2015). Nonetheless, the fact that wound occlusion of trees that underwent late-summer and winter reduction pruning was comparable indicates that trees pruned in late summer fail to instantly initiate the wound recovery processes in the year of pruning, probably because the meristem activity is already in its dormancy mode or in preparation (Meier et al. 2012), whereas this process of recovery was noticeable around the wounds of trees pruned during the summer. However, our study was unable to provide a clear consensus on the optimal season to prune to reduce the proportion of the discolored wood area produced at the cutting point (Figure 6). Some summer pruning wounds had large discolored wood areas that were associated with a different color and were not observed in smaller wounds, suggesting that in some cases, pruning in summer may have hastened the spread of fungal infection (Chou and MacKenzie 1988). Still, a significant result between season and closure rate of wound was found, suggesting that summer pruning may promote faster recovery by limiting the entry time for invading microorganisms and oxygen on exposed wounds and may limit discoloration and decay expansion after several years (Boddy and Rayner 1983; Pearce 1991; Schwarze and Fink 1997), especially because winter pruning could enhance cambial dieback (Dujesiefken et al. 2005a; Lee and Lee 2010) and promote cracks near the wound edges (Gilman 2011).

MANAGEMENT IMPLICATIONS

The establishment and development of epicormic branches after reduction of the tree main stem follows similar trends from other silvicultural practices

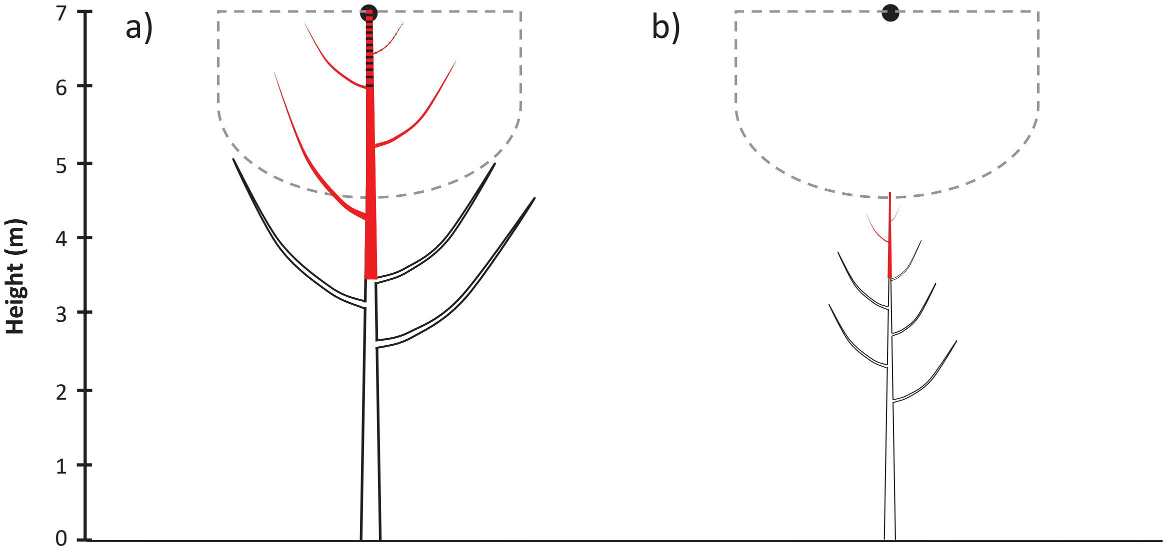

Figure 7. Illustration of reduction pruning of the main tree stem for a wire running 7 m above the ground (black filled circle) and the security corridor (dashed gray line). The red part indicates the biomass that needs to be removed in line with clearance standards and for the implantation of scaffold limbs at a safe distance with the wire. (a) The main-stem reduction pruning will remove more than 30% of the biomass because the main stem is in contact with the wire, which will exacerbate epicormic branches and reduce compartmentalization at the point of cutting. The black dashed lines represent an appropriate main-stem reduction pruning dose for a 7-m tree. (b) Reduction pruning of the main stem before a tree reaches the security corridor, which will remove less than 30% of the biomass (ideally ≤ 20%), decreases epicormic branches and improves compartmentalization at the point of cutting.

regarding the intensity and timing of the operation. Greater pruning intensities produced a greater number, length, and biomass of epicormic branches, as well as lower compartmentalization of the pruning wound, which highlights the importance of reducing the main stem as little as possible to prevent the occurrence of epicormic branches and decay. This study also showed that if a reduction of the main stem is required to encourage the occurrence and establishment of scaffold limbs at a safe distance from wires running 7 m above the ground, it would be preferable to perform this intervention before the tree main stem has reached the wire, and specifically before or soon after it reaches the security corridor zone (Figure 7). Otherwise, even when using a lower reduction pruning intensity, this intensity will remove more than 30% of the biomass in line with wire clearance standards, which can trigger problematic epicormic branch development. Thus, depending on the wire height and the minimum clearance height needed for urban infrastructure, reduction of the main stem should be undertaken during the first phase of the tree-training pruning schedule to limit the need for a stronger reduction pruning intensity later on (Dujesiefken et al. 2016). We suggest that the better approach would be to intervene less severely (≤ 20% of biomass removed at each pruning cycle) but more often (every 2 years) during the first 15 years following planting in order to train trees under the electrical distribution network before they reach maturity, as described by Dujesiefken et al. (2016) for ornamental trees. Such an approach should help to lengthen the maintenance return interval when trees will reach mature phases (McPherson et al. 2005; Dujesiefken et al. 2016).

Reduction pruning during the leaf-on season can also limit the occurrence and development of epicormic branches compared with reduction pruning during the leaf-off season. Summer reduction pruning with half a growing season more than winter reduction pruning to restore the energy balance between the above- and belowground systems reduced the biomass, number of epicormic branches, and tallest epicormic branch by 54%, 33%, and 15%, respectively, in contact with the corridor of the wire without further affecting the wound-closure rate or the area of discolored wood at the cutting point. Therefore, tree-training under electrical distribution networks should be prioritized during the leaf-on season. Similarly, maintenance pruning, when trees have reached the mature

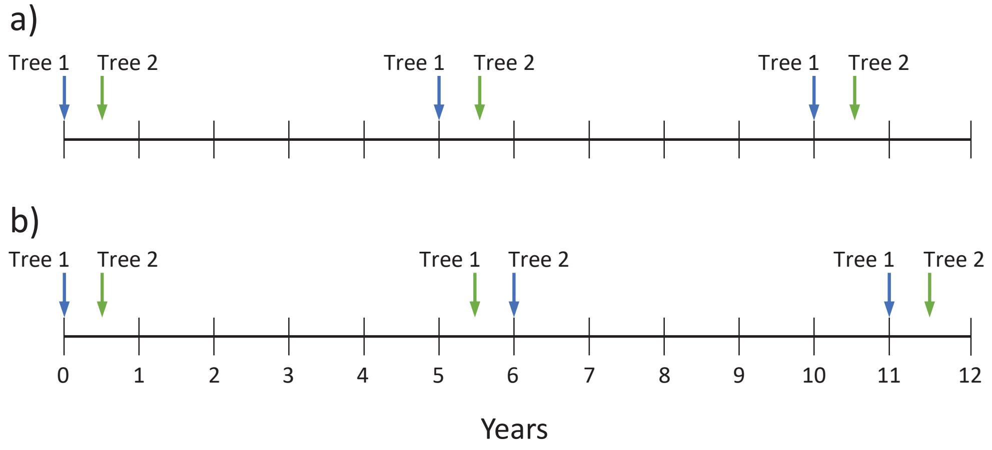

Figure 8. Illustration of the maintenance pruning schedule under the electricity distribution network over 2 pruning cycles, when trees reach the mature phase. The blue and green arrows represent winter and summer pruning, respectively. (a) Pruning cycles of 5 years without alternating pruning seasons between trees. (b) Alternating pruning seasons between cycles.

phase, should be undertaken during the leaf-on season as long as the number of trees to prune allow it. However, when the number of trees is beyond the capacity for response during the leaf-on season, tree maintenance pruning operations will span over the year. In that case, the return interval of maintenance trees could be optimized by alternating the pruning season (Figure 8). In fact, trees pruned in the summer could be pruned at the next cycle during winter, and so on. Accordingly, because the return interval can be increased by half a growing season or half a year following a summer pruning, at least half a year could be saved over 2 maintenance pruning cycles. For a 5-year maintenance return interval, the savings could correspond to at least 5% per year. All the more, pruning in late summer before leaf fall can also slightly affect the occurrence and development of epicormic branches in contact with the corridor of the power line compared with summer pruning and could be used to increase the return interval further. It should be noted that pruning during leaf flush could also decrease the epicormic branch response when compared with summer pruning; however, this period should be avoided, especially in urban areas, owing to bird nesting. Further economic analyses are suggested to validate this entire pruning season model.

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Conflicts of Interest:
The authors reported no conflicts of interest.

Résumé. La taille de raccourcissement de la tige principale est couramment utilisée lors de l'entretien des réseaux électriques afin de favoriser l'établissement et le développement de branches charpentières à l'écart des fils. Il est important de comprendre la physiologie de l'initiation et de la croissance des branches épicormiques tout autant que la compartimentation des plaies après une taille de raccourcissement afin d'optimiser le cycle d'élagage et maintenir des arbres en santé et sécuritaires. Dans cette étude, l'influence de l'intensité et de la période de l'année de la taille sur la réaction des branches épicormiques et la compartimentation des plaies a été étudiée sur 56 frênes de Pennsylvanie âgés de 11 ans et hauts de 5 à 7 mètres, dans le cadre d'un environnement contrôlé en pépinière. Lors de la seconde saison de croissance suivant le raccourcissement de la tige principale, le nombre, la hauteur et le volume des branches épicormiques, ainsi que les branches épicormiques les plus hautes et la zone de bois décoloré, ont augmenté avec l'intensité de la taille. La taille réalisée pendant la saison de feuillaison par rapport à celle effectuée en dehors de cette période a limité l'établissement et le développement de branches épicormiques sans affecter le taux de fermeture des plaies ou la zone de décoloration du bois à l'endroit de la coupe. Ces résultats sont cohérents avec la fluctuation saisonnière bien connue, des réserves de glucides. Dans le contexte d'un réseau de distribution électrique, où les arbres sont susceptibles d'être élagués en tout temps de l'année, les arbres taillés en été lors d'un cycle d'entretien pourraient être élagués le cycle suivant en hiver, afin d'optimiser ainsi l'intervalle du cycle d'élagage.

Zusammenfassung. Das Zurückschneiden des Hauptstammes wird häufig bei der Wartung von Stromleitungen verwendet, um die Errichtung und Entwicklung von Gerüstelementen weg von Drähten zu fördern. Das Verständnis der Physiologie der epikormischen Verzweigungsinitiation und des Wachstums sowie der Wundkompartimentierung nach dem Reduktionsschnitt sind wichtig, um den Schnittzyklus zu optimieren und gesunde und sichere Bäume zu bewahren. In dieser Studie wurde der Einfluss sowohl der Intensität als auch der Jahreszeit des Beschneidens auf die epikormische Zweigreaktion und die Wundkompartimentierung an 56 11-jährigen Eschen (*Fraxinus pennsylvanica* Marsh.) aus Pennsylvania (Pennsylvania Esche) mit einer Höhe von 5 bis 7 meter in einer kontrollierten Baumschulumgebung untersucht. Während der zweiten Wachstumssaison nach der Reduktion des Hauptstammes nahmen Anzahl, Höhe und

Volumen der epikormischen Äste sowie der höchsten epikormischen Äste und die Fläche des verfärbten Holzes mit der Intensität des Rückschnitts zu. Das Beschneiden während der Blatt-Saison im Vergleich zur Nicht-Blatt-Saison begrenzte die Etablierung und Entwicklung von epikormischen Zweigen, ohne die Wundverschlussrate oder die Fläche der Holzverfärbung an der Schnittstelle zu beeinflussen. Die Ergebnisse stimmen mit der bekannten saisonalen Fluktuation der Kohlenhydratreserven überein. Im Kontext des elektrischen Verteilungsnetzes, in dem die Bäume das ganze Jahr über beschnitten werden, könnten Bäume, die im Sommer während eines Pflegezyklus beschnitten werden, im nächsten Zyklus, im Winter usw. beschnitten werden, um das Wiederkehrintervall des Schnittzyklus zu optimieren.

Resumen. La poda de despunte se utiliza comúnmente durante el mantenimiento de las líneas eléctricas para fomentar el establecimiento y desarrollo de las extremidades de los andamios lejos de los cables. Comprender la fisiología de la iniciación y el crecimiento de las ramas epicórmicas, así como la compartimentación de la herida después de la poda de reducción es importante para optimizar el ciclo de poda y mantener árboles sanos y seguros. En este estudio, la influencia de la intensidad de la poda y la época del año en la respuesta de ramas epicórmicas y la compartimentación de heridas se investigó en 56 fresnos de Pensilvania de 11 años de edad *(Fraxinus pennsylvanica* Marsh.) de aproximadamente 5 a 7 m de altura dentro de un entorno de vivero controlado. Durante la segunda temporada de cultivo, tras la reducción del tallo principal, el número, la altura y el volumen de las ramas epicórmicas, así como las ramas epicórmicas más altas y la zona de madera decolorada, aumentaron con la intensidad de poda. La poda durante la temporada de hojas nuevas en comparación con la temporada de hojas caducas limitó el establecimiento y desarrollo de ramas epicórmicas sin afectar la tasa de cierre de la herida o el área de decoloración de la madera en el punto de corte. Los resultados son consistentes con la fluctuación estacional conocida de las reservas de carbohidratos. En el contexto de la red de distribución eléctrica, donde los árboles son sometidos a poda durante todo el año, los árboles podados en verano durante un ciclo de mantenimiento podrían ser podados durante el siguiente ciclo, en invierno, etc., para optimizar el intervalo de retorno del ciclo de poda.

Arboriculture & Urban Forestry Quiz Questions

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Add the quiz to your cart, proceed through checkout, and look for the content to appear on your personal dashboard under the header, “My Quizzes.” If you need a username and password, send us an e-mail (isa@isa-arbor.com).

A passing score for this quiz requires sixteen correct answers. Quiz results will display immediately upon quiz completion. CEU(s) are processed immediately. You may take the quiz as often as is necessary to pass.

CEU quiz by Eric North, University of Nebraska-Lincoln, Lincoln, Nebraska, USA