

Effects of Pruning Season on Compartmentalization of Pruning Wounds in *Acer palmatum* and *Pinus strobus*

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Abstract : This study was conducted to examine the effects of pruning season on the compartmentalization of pruning wounds in *Acer palmatum* and *Pinus strobus*. A total of eighty five field-grown trees for each species were allocated to five different seasons, early- and late-winter, mid-spring, mid- and late-summer, for pruning treatments. Wound closure rate (WCR) of the two species for one year after treatment, area of discolored stem tissue on the medial longitudinal surface and cambial dieback length under the pruning wound of *A. palmatum* were measured. Changes of total phenols and variations of extractives, holocellulose and lignin at the treated branch unions were examined. In WCR of *A. palmatum*, late-winter (March, 39.8%) and mid-spring (May, 39.7%) were higher than any other seasons, while early-winter (November, 28.4%) was significantly lower than late-winter and mid-spring. *P. strobus* showed similar results with *A. palmatum*. The WCR of early-winter (57.2%) was the lowest significantly among the five seasons, and mid-spring (73.5%) and late-winter (71.4%) showed higher a WCR than other seasons. In the discolored/wound area ratio of *A. palmatum*, early-winter (73.2%) was the highest by far, and mid- (July) and late-summer (September, 36.7%, respectively) were the lowest among the five seasons. In the length of cambial dieback, two dormant seasons, early- and late-winter were longer than any other seasons. Phenol contents at the treated branch union were changed in line with the seasonal fluctuation of the tree. Total phenols in the below core of the treated union were higher than those of the branch union with living branch, while little differences were seen in the above core. At the branch core of the treated union, phenols of *A. palmatum* decreased one month after the treatments, but *P. strobus* maintained similar to or a little higher than those at the controls. The major changes in chemical composition at pruning wounds were extractives and lignin increased by less than 20% in *A. palmatum*, while extractives in *P. strobus* remarkably increased by 70%.

Key words : wound closure, total phenols, holocellulose, lignin, discolored area, cambial dieback

Introduction

Tree pruning is performed for various purposes. In horticulture, the major objectives of pruning are to influence the productivity of fruit trees and appearances of ornamental trees, while the aim in silviculture is to produce knot-free lumber. Pruning in arboriculture is an integral part of the tree maintenance of any landscape site. Correct pruning helps maintain vigorous plants and can aid the supply of additional energy for development of flowers, fruit and limbs. But it is inevitable for trees to get injuries by the pruning practice, and those pruning wounds are to be compartmentalized by the trees.

According to the CODIT model (Shigo and Marx, 1977), lesions in functional sapwood are bounded by

four walls laid down in the wood, envisaged as essentially static barriers preventing the spread of infection. Walls 1 to 3, formed in wood present at the time of wounding, are equivalent to reaction zones rich in phenolic compounds, but wall 4 is distinct, comprising a tissue laid down *de novo* by the cambium in the vicinity of wounds, and is the most durable of the four kinds of compartmentalization walls.

The phloem as well as the sapwood of trees has an effective defense system to secure their vital function of transport and storage, to restrict the embolism of air and, in later stages, also the spread of pathogens. The response capacity is primarily influenced by the physiological state, e.g. the prevailing season (Dujesiefken *et al.*, 2005; Kozłowski and Pallardy, 1997; Leben, 1985; Neely, 1970; Shortle, 1979). So it is very important to ascertain the most effective time for the pruning of individual species, considering its growing environments.

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Meanwhile, recommendable times for pruning are different from person to person. Winter is recommended as the best season, while some people prohibit pruning during the winter period, especially in early winter. Pruning in late winter or early spring is generally recommended, but spring pruning after budbreak is undesirable. This is because the bark is at its most tender moment and damage to the bark is most likely. Mid-summer is an acceptable pruning time for some trees known as “bleeders”, such as *Ulmus* sp., *Betula* sp. and *Acer* sp., but root growth is slowed temporarily when live branches are removed in the summer (Gilman, 2002; Harris *et al.*, 2004; Hartman *et al.*, 2000).

Pruning in the late summer is considered undesirable because it removes foliar carbohydrates that would be sent to the tree before the leaves fall, and new growth which will not be sufficiently hardened to prevent winter damage may be encouraged. In the fall, a number of important decay fungi have been observed to produce their largest numbers of spores. Evergreens are considered to be pruned any time the wood is not frozen (Gilman, 2002; Harris *et al.*, 2004; Hartman *et al.*, 2000; Hensley, 1979; Lee and Lee, 2001; Shigo, 1989).

Among the several considerations in decision of pruning season, enclosing speed of pruning wounds is the most important because the decay process continues as long as the wound remains open (Shigo and Larson, 1969). But most researches on wound closure were performed with the artificial wounds made on the stems for silvicultural purposes. The objective of this study was to examine the effects of pruning season on the compartmentalization of pruning wounds, and the trees selected for this experiment were *Acer palmatum*, a deciduous hardwood, and *Pinus strobus*, a evergreen conifer, both of which are planted broadly in the urban forests of Korea.

Materials and Methods

1. Seasonal onsets and timing of pruning treatments

Choi *et al.* (2006) reported the long-term spatial patterns of seasonal onsets defined by daily temperatures in South Korea for the period of 1973-2004. According to the study, two experimental sites, Yeosu, Gyeonggi, and Jincheon, Chungbuk, had similar spatial patterns of seasonal onsets with each other, and their seasonal onsets were March 21 for spring, May 30 for summer, September 17 for fall, and November 16 for winter (Table 1).

Pruning treatments were made during five different seasons. Early- and late-winter and mid-summer were recommendable seasons for pruning, and mid-spring and late-summer were the undesirable seasons. Pruning treatments for each season were made on March 1, 2008 for late-winter, May 16, 2008 for mid-spring, July 18, 2008

Table 1. Seasonal onsets at the two experimental sites, Yeosu, Gyeonggi and Jincheon, Chungbuk, defined by daily temperatures for the period of 1973-2004 in South Korea (Choi *et al.*, 2006).

Seasons	Spring	Summer	Fall	Winter
Onset dates	March 21	May 30	September 17	November 16

Table 2. Dates of the pruning treatment by season based on seasonal onsets of the experimental sites.

Pruning seasons	Dates of Pruning treatment	Remarks
Late-winter	March 1, 2008	Recommendable season
Mid-spring	May 16, 2008	Undesirable season
Mid-summer	July 18, 2008	Recommendable season
Late-summer	September 8, 2007	Undesirable season
Early-winter	November 24, 2007	Recommendable season

for mid-summer, September 8, 2007 for late-summer, and November 24, 2007 for early-winter (Table 2).

2. Tree species for the study

Eighty five field-grown *A. palmatum* (Japanese maple) and the same number of *P. strobus* (eastern white pine) were used for this study. Eighty five trees of each species were allocated seventeen trees to every five pruning seasons. Two trees out of the seventeen were used to monitor the changes of phenolic compounds at the pruning wounds. Of the two, one tree was harvested one month after pruning treatment and the other one was harvested six months after the treatment.

A. palmatum growing in Yeosu, Gyeonggi, Korea (37.10.841 N, 127.38.900 E) were thirteen years old, 10.9 cm thick in average diameter at 30 cm above the ground and 360 cm tall in average height. *P. strobus* growing in Jincheon, Chungbuk, Korea (36.49.543 N, 127.27.020 E) were eleven years old, 11.9 cm thick in average diameter at 30 cm above the ground and 460 cm tall in average height. During the experimental period, the annual average temperature of both sites was around 12°C and those annual precipitations were between 796 and 1,764 mm (Korea Meteorological Administration, 2009).

3. Experimental design

Fifteen trees of each species were allocated to treatment season according to the randomized block design. The stands of each species were divided into three blocks, which were border, intermediate between border and interior, and interior of the stand. Each block for the season consisted of five trees.

4. Pruning cuts

Pruning cuts were conformable with an American National

Standard (American National Standard Institute, 2001). A pruning cut was made close to the trunk or parent limb, without cutting into the branch bark ridge (BBR) or collar, or leaving a stub (Lee and Lee, 2009). In case where the branch collar was not readily apparent, the cut bisected the angle between its BBR and an imaginary line perpendicular to the branch. A branch that was too large to support with one hand was precut to avoid splitting of the wood or tearing of the bark. The proper angle of cut depends on the branch collar. Conifers have flat branch collars and a straight cut close to the collar was made for *P. strobus* (Shigo, 1989).

The size of the branch for pruning cut was between 1 cm and 4 cm in diameter at 1.5 cm above the BBR. Four to twenty branches per tree were removed depending on the branch density of the tree.

5. Measurements

1) Branch and stem diameter, area of pruning wound and length of cambial dieback

Prior to pruning, diameters of branches and stems at 1.5 cm above the BBR were gauged with a caliper. Immediately after each cut, horizontal width and vertical length of the pruning wound crossing the center of branch were measured to calculate the wound area. The vertical length of cambial dieback under the pruning wound was also measured from the sample of *A. palmatum* to examine the variation of cambial dieback under the wound by pruning season (Figure 1).

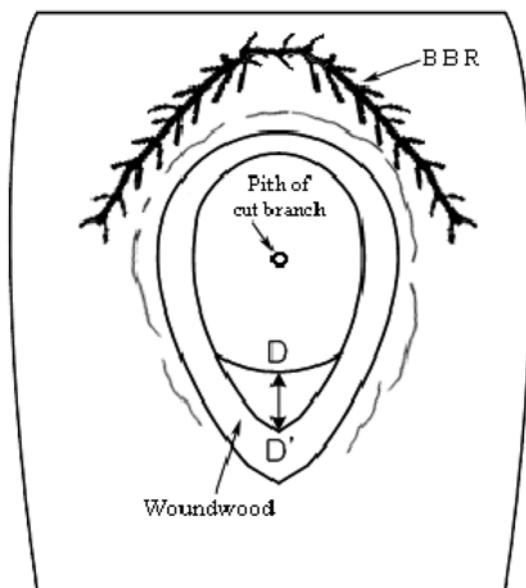


Figure 1. A diagram of the sample of branch union with pruning wound one year after pruning. The branch bark ridge (BBR) was protected when the cut was made. A ring of woundwood is closing the wound, but cambial dieback (D-D') under the pruning wound is still open.

2) Discolored area

The samples from the harvested *A. palmatum* were dissected with a cleaver along the medial longitudinal plane and shaved with a sharpened knife to measure discolored areas formed after branch removal. The area of discolored stem tissue on the medial longitudinal surface was estimated by the length of pruning wound and the deepest penetration of discolored wood into the trunk (Lee *et al.*, 2009). In case of *P. strobus*, which differed from *A. palmatum*, the whole area of the branch core after the pruning cut was darkened with increased resin concentration, and measuring discolored areas formed after branch removal was meaningless.

6. Determination of total phenols

Phenolic compounds are concentrated at the reaction zone to resist the spread of organisms into the trunk. They were determined three times, one month, six months and twelve months after treatments. Eight branch union samples were obtained from one tree in each treatment at each point of time after treatments. The eight samples consisted of four with pruning wounds and the other four with living branches. The 0.06 g Fresh Weight (FW) of wood tissues was collected with a chisel from three separated parts of each sample, which were core of the branch, above core and below core (Lee *et al.*, 2009).

A total of 0.24 g of FW shavings for each part collected from four samples were extracted in 4 mL of 100% methanol for 24 hours at 4°C. After the extraction, the wood tissues were dried at 105±1°C and then weighed. The methanol solution was filtered with 0.50 µm of pore hydrophobic syringe filter. Total phenols were estimated by the Folin-Ciocalteu method as described by Bonello and Pearce (1993). For each sample, 15 µL of methanol extract was diluted to 1500 µL of water. To this solution, 750 µL of Folin and Ciocalteu's reagent (Sigma Chemical Co.), diluted two-fold with water, was added and left for 3 minutes, followed by the addition of 750 µL of 1 M aqueous Na₂CO₃. The solution was shaken and left for 1 hour before the absorbance was measured at 725 nm with a spectrophotometer.

Concentrations of total phenols were calculated with reference to a gallic acid standard curve (10-200 µg/mL) by applying the regression analysis and results were expressed as gallic acid equivalent (mg) per g Dry Weight (DW).

7. Determinations of extractives, holocellulose and lignin

Chemical analyses for the tissues of the branch core, and the above and below core were performed to examine the changes of their chemical properties one year after treatments. Two trees from each treatment were

Table 3. Indicators to analyze the changes in the area of pruning wound, and development of discolored wood on the medial longitudinal surface after treatments.

Indicators	Formulae
Wound Closure Rate (WCR, %)	$\frac{PWA_{y_0} - PWA_{y_1}}{PWA_{y_0}} \times 100$ PWA _{y₀} : area of pruning wound when pruning PWA _{y₁} : area of pruning wound one year after pruning
Discolored/Wound Area Ratio (D/W ratio, %)	$\frac{DA_{y+1}}{PWA_{y_0}} \times 100$ DA _{y+1} : area of discolored stem tissue on the medial longitudinal surface one year after pruning PWA _{y₀} : area of pruning wound when pruning

selected for the analysis. A total of sixteen branch union samples, eight from each tree, were collected from each treatment, and eight samples of each tree consisted of four with pruning wounds and the other four with living branches.

The samples were dissected with a cleaver along the medial longitudinal plane, and the parts beyond an imaginary line perpendicular to the stem pith at 1.5 cm above the BBR and an imaginary line perpendicular to the stem pith at 1.5 cm below the end of branch pith were trimmed off (Lee *et al.*, 2009). The trimmed samples were air-dried, split into three parts (core of branch, above and below core) and then ground through a 40 mesh screen.

The content of the extractives was determined by the soxhlet method (Technical Association of Pulp and Paper Industry, 1994). Two grams of sample in a thimble filter was extracted by 150 mL of ethanol/benzene mixture (1:2 v/v) using a soxhlet extractor with reflux condenser at 80°C for 6 hours. The extracted solution was evaporated under reduced pressure. The extractive was dried at 105±1°C and then weighed. The extractive-free sample left in the thimble filter was used for analyses of holocellulose and Klason lignin.

The content of holocellulose was determined as the delignified residue by NaClO₂ (Wise *et al.*, 1946). The 1.25 g of extractive-free sample in 250 mL flask was treated with 75 mL of distilled water, 0.5 g of NaClO₂ and 0.1 mL of CH₃COOH at 80°C for 1 hr. This procedure was repeated 2 more times. The solution was filtered by using a glass filter (1G3, Iwaki, Japan), and then washed with 250 mL of cold distilled water and 25 mL of acetone, successively. The filtrated residue was dried at 105±1°C and then weighed.

Klason lignin was analyzed according to the standard NREL procedures (National Renewable Energy Laboratory, 2005). The 0.3 g of extractive-free sample in 50 mL flasks was hydrolyzed with 3 mL of 72% H₂SO₄ at 30°C for 1 hr. The hydrolysate was then transferred to 100 mL flask and diluted to 4% H₂SO₄ by adding 84 mL of distilled water. The flasks were sealed and autoclaved

for 1 hr at 121°C. The solution was then filtered by using a glass filter (1G4, Iwaki, Japan). The filtrated residue was dried at 105±1°C and then weighed.

8. Data analysis

Some indicators were introduced for this study (Table 3). The wound closure rate (WCR) and the discolored/wound area ratio (D/W ratio) were introduced to examine the variations of ability to compartmentalize the pruning wounds after the pruning treatments. The WCR represented the enclosing extent of the pruning wound during the year after treatments, and the D/W ratio was computed by comparing the area of discolored stem tissue on the medial longitudinal surface one year after treatments with the area of pruning wound at the time of pruning. In the CODIT model, the WCR indicated vitality of the cambium around the wound which formed wall 4 after the tree was wounded, while the D/W ratio expressed the ability of a tree to limit the spread of wood discolorations and decays with wall 1, 2 and 3 which were already present in the wood at the time of the pruning.

The two-way ANOVA for the block design was used to calculate the ratio of the variance among the means to the variance within the samples. Duncan's multiple comparison procedure was adopted to test the differences among the treatments. SAS 9.1 (SAS Institute Inc., USA) was used for the analysis, and the significance level, α -value, was 0.05 unless otherwise specified.

Results

1. Wound closure and discolored area

Table 4 shows means and statistical differences in the WCR of both species, and the D/W Ratio and length of cambial dieback by pruning season one year after pruning treatments for *A. palmatum*. In the WCR of *A. palmatum*, late-winter (March, 39.8%) and mid-spring (May, 39.7%) were higher than any other seasons, while early-winter (November, 28.4%) was the lowest and signifi-

Table 4. Variations of wound closure rate (WCR) of *Acer palmatum* and *Pinus strobus*, and discolored/wound area ratio (D/W ratio) and length of cambial dieback (Dieback) of *A. palmatum* by pruning season one year after pruning treatments. mean \pm standard error. Means with the same letter are not significantly different at $P < 0.05$.

Pruning seasons	<i>Acer palmatum</i>			<i>Pinus strobus</i>
	WCR (%)	D/W Ratio (%)	Dieback (mm)	WCR (%)
Late-winter (Mar.)	39.8 \pm 2.7 c	44.8 \pm 1.3 b	7.7 \pm 0.6 ab	71.4 \pm 1.3 cd
Mid-spring (May)	39.7 \pm 2.5 c	40.4 \pm 1.0 c	5.1 \pm 0.4 c	73.5 \pm 1.1 d
Mid-summer (July)	30.9 \pm 1.7 ab	36.7 \pm 0.9 d	6.6 \pm 0.4 b	68.8 \pm 1.1 c
Late-summer (Sep.)	35.8 \pm 1.9 bc	36.7 \pm 1.2 d	5.1 \pm 0.2 c	62.6 \pm 1.2 b
Early-winter (Nov.)	28.4 \pm 1.7 a	73.2 \pm 2.7 a	9.1 \pm 0.6 a	57.2 \pm 0.9 a

Table 5. Changes of total phenols at the three parts (above core, branch core, and below core) between treated branch union with pruning wound (Tr.) and control one with living branch (Co.) by pruning season in *Acer palmatum* and *Pinus strobus*. (unit: gallic acid equivalent (mg) per g DW).

Pruning seasons		Late-winter (Mar.)			Mid-spring (May)			Mid-summer (July)			Late-summer (Sep.)			Early-winter (Nov.)		
Month(s) after pruning		1M	6Ms	12Ms	1M	6Ms	12Ms	1M	6Ms	12Ms	1M	6Ms	12Ms	1M	6Ms	12Ms
<i>Acer palmatum</i>																
Above core	Tr.	65	57	59	85	75	49	77	80	75	51	76	56	149	102	27
	Co.	67	53	53	75	66	57	70	85	80	52	76	52	158	95	28
Branch core	Tr.	72	33	58	86	21	29	86	79	57	79	80	44	150	72	141
	Co.	68	50	57	74	63	57	63	65	81	41	76	58	170	90	162
Below core	Tr.	72	76	67	102	99	60	84	100	88	56	88	82	152	119	66
	Co.	71	54	65	76	69	56	72	88	72	49	85	56	155	99	34
<i>Pinus strobus</i>																
Above core	Tr.	22	25	45	45	25	39	26	63	27	16	66	27	46	47	60
	Co.	22	21	39	40	27	35	27	54	23	20	72	29	40	44	34
Branch core	Tr.	930	946	1,127	5,430	1,424	4,190	940	1,235	973	762	1,027	1,014	1,249	4,402	2,123
	Co.	989	913	1,067	5,250	1,167	4,523	918	1,143	881	788	1,009	939	1,238	3,917	1,477
Below core	Tr.	27	33	89	67	27	139	28	108	90	33	52	45	40	68	148
	Co.	22	23	54	45	25	92	25	55	24	21	36	25	39	42	37

cantly different with late-winter and mid-spring ($P < 0.01$). Late-summer (September, 35.8%) was higher than mid-summer (July, 30.9%), but the difference was not significant.

P. strobus showed similar results with *A. palmatum*. The WCR of early-winter (57.2%) was the lowest significantly among the five seasons ($P < 0.01$), and mid-spring and later-winter showed a higher WCR than other seasons. But the mid-summer (68.8%) was higher than late-summer (62.6%), which differed from *A. palmatum*. Comparing the WCR of the two species, *P. strobus* was much higher than *A. palmatum* in general.

In the D/W ratio of *A. palmatum*, early-winter (73.2%) was the highest by far, and mid- and late-summer were the lowest among the five seasons. Late-winter (44.8%) was also significantly higher than mid-/late-summer ($P < 0.05$). In the length of the cambial dieback, two dormant seasons, early- and late-winter (9.1 mm and 7.7 mm, respectively), were longer than any other seasons. Mid-summer (6.6 mm) was the longest among the growing

seasons, but the differences were not significant.

2. Wood chemical properties

Table 5 shows the changes of total phenols at the three parts (above core, branch core, and below core) between the treated branch union with pruning wound and the control one with living branch by pruning season in both *A. palmatum* and *P. strobus*. On the whole, contents of total phenols showed seasonal fluctuation, and phenol contents at the treated branch union were changed in line with the seasonal fluctuation of the tree. There were little differences in phenol contents at the above cores between treated and control branch unions, but the contents at the below cores were higher at the treated branch union, especially in *P. strobus*. At the branch core, there was a minor difference between the two species. In case of *A. palmatum*, phenol contents of the treated union increased one month after the treatments, and then decreased below the levels of the controls. But in *P. strobus*, the phenol contents at the treated union were similar

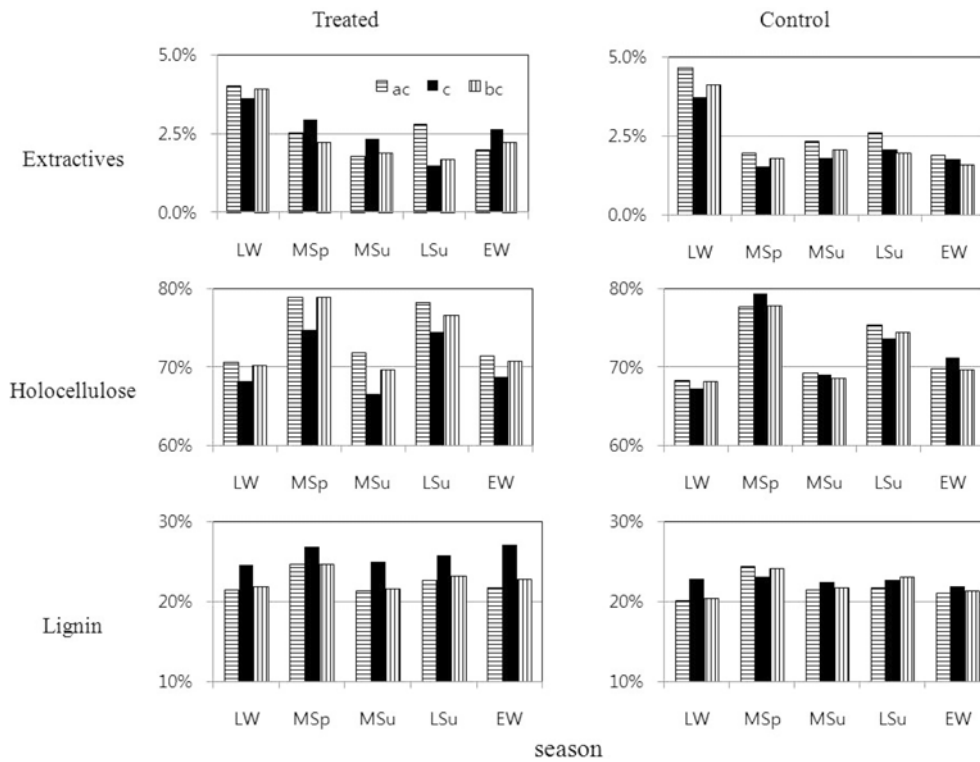


Figure 2. Variations of extractives, holocellulose and lignin in branch union at the three parts (ac: above core, c: branch core, bc: below core) between branch union with pruning wound (Treated) and control one with living branch (Control) by pruning season in *Acer palmatum*. LW: Late-winter (March), MSp: Mid-spring (May), MSu: Mid-summer (July), LSu: Late-summer (September), EW: Early winter (November).

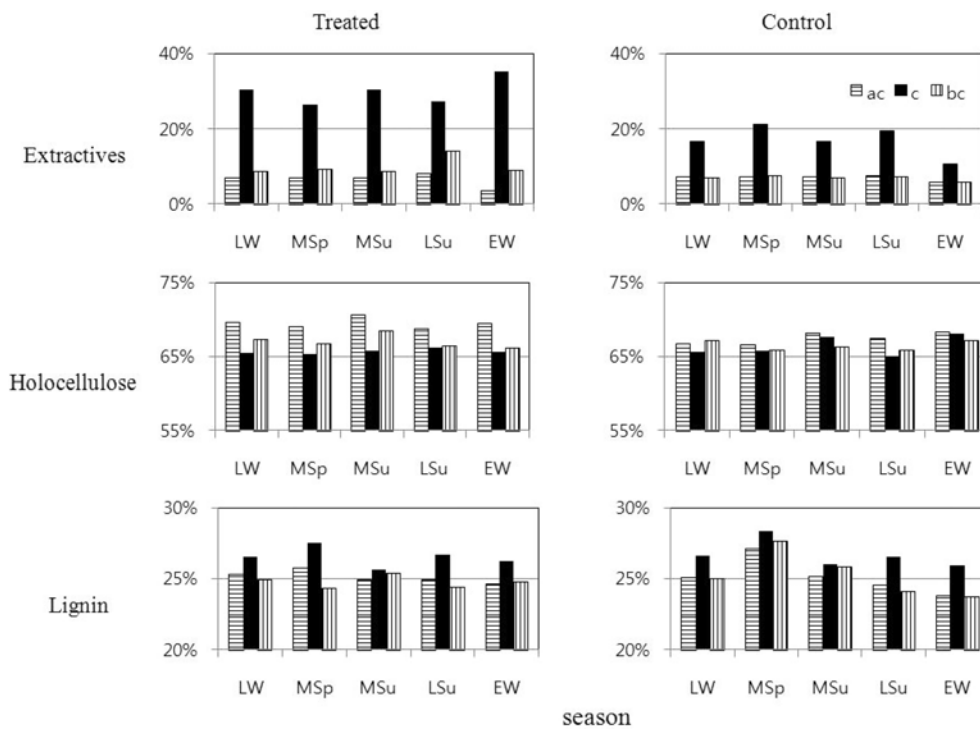


Figure 3. Variations of extractives, holocellulose and lignin at the three parts (ac: above core, c: branch core, bc: below core) between branch union with pruning wound (Treated) and control one with living branch (Control) by pruning season in *Pinus strobus*. LW: Late-winter (March), MSp: Mid-spring (May), MSu: Mid-summer (July), LSu: Late-summer (September), EW: Early winter (November).

to or a little higher than those at the controls.

Figure 2 and 3 show variations of extractives, holocellulose and lignin at the three parts (above core, branch core and below core) between the treated branch union with pruning wound and the control one with living branch by pruning season in *A. palmatum* and *P. strobus*, respectively. In *A. palmatum*, extractives and lignin at the branch core of the treated branch union (2.6% and 25.9% in average, respectively) were higher than those at the same part of the control one (2.2% and 22.6% in average, respectively), but holocellulose contents at the treated union (70.5% in average) were lower than those at the control one (72.1% in average). In *P. strobus*, differences in holocellulose and lignin between the treated and control branch union (65.6% vs. 66.4%, and 26.5% vs. 26.7% in average, respectively) were not significant. But contents of extractives at the branch core increased sharply after pruning treatments (from 16.8% at the control to 30.0% at treated in average).

Discussion

No other research on the effects of pruning season has been done for *A. palmatum* and *P. strobus*. The results of the present study, detailing wounds in late-winter and early growing season would be more effectively compartmentalized than those in the autumn and early-winter, are generally consistent with the findings for other tree species (Dujesiefken *et al.*, 2005). Neely (1970) reported that wounds made in late winter (March) and in May healed much more than wounds made in fall (October) and in July, respectively, in the experiment on white ashes, honey locusts, and pin oaks. In *Eucalyptus camaldulensis*, wounds made in spring closed most rapidly, and the slowest closure was recorded for wounds made during late fall and early winter. Wounds made in late winter and summer closed at similar rates as the results of *P. strobus* in the present study (Perry and Hickman, 1987). In red maple (*Acer rubrum* L.), wounds made in the spring, March to May, also caused greater wound occlusion than wounds made in the autumn, mid September to early November (Leben, 1985). Debell *et al.* (2006), however, found that pruning just prior to the beginning of the growing season (March 1) resulted in longer time for the formation of clear wood than pruning during the growing season (May 1 and June 15) for red alder. The time of year during which the cambium is active varies with climate, species, etc., which might cause such differences among experiments (Winget and Kozlowski, 1965).

Researches on the speed of wound closure by tree species were limited. Neely (1970; 1973; 1983) reported the differences among species in the rate of wound closure.

According to the experiments, tulip trees and pin oaks were the fastest in wound closure, while American elm and soft maple trees were faster than white ashes and honey locusts. In the present study, *P. strobus* was faster in wound closure than *A. palmatum*, which showed a variation in healing ability in previous studies.

A certain correlation was found between the D/W ratio and the length of cambial dieback, except in mid-summer pruning. Greater phloem dieback increased the wound size, and the larger area of exposed xylem apparently resulted in larger volumes of discolored wood (Blanchette, 1992). The cambial growth was very responsive to environmental stresses (Kozlowski and Pallardy, 1997), and wounds made in October or early winter suffered from considerable tissue dieback beyond the original wound margins (Neely, 1970; Perry and Hickman, 1987). Longer cambial dieback in wounds made in early-winter also was related to the lower WCR of the treatment, as shown by the results of the present study (Leben, 1985).

Another important consideration that directly influences bark dieback was moisture loss from the tree (Blanchette, 1992). Loss of moisture and replacement with air in xylem could affect discoloration processes and subsequent invasion by fungi (Boddy and Rayner, 1983; Rayner, 1986). The amount to which air would enter the xylem could vary at different times of the year depending upon whether water columns were under positive or negative hydrostatic pressure when the xylem was wounded (Rayner, 1986). In the present study, a longer cambial dieback length and a higher D/W ratio in early- and late-winter treatments might be caused by a longer winter and less precipitation than an average year after treatments in November 2007 and March 2008, respectively.

Mid-summer pruning (July 2008) in the present study showed a relatively longer cambial dieback, still shorter than winter treatments, and a lower or equal D/W ratio when comparing with other treatments in a growing season. Wounds made in the summer (June) did not suffer from extensive dieback like wounds made in early-winter (Perry and Hickman, 1987), but the correlations between the length of cambial dieback and discolored wood column were not significant (Leben, 1985). Further study is necessary to examine the reasons, but changes of cambial electrical resistance (CER) would be helpful to understand the result (Lee *et al.*, 2009). The CER one month after treatment (10.8 k Ω on August 16) was higher compared to one month before treatment (9.5 k Ω on June 16), and a less vigorous cambial zone might affect the cambial dieback after treatment.

A tree begins to form a protective chemical shield, a reaction zone with mostly phenolic compounds in angiosperms and resins in conifers, around and immediately behind

the wound, and the barrier could eventually be eroded and retreated by fungal activities (Prior, 1976; Shigo, 1979). Levels of the phenolic contents at the treated union changed in accordance with seasonal variation in the production of phenolic compounds (Barry *et al.*, 2000; Jalal *et al.*, 1982; Mireku and Wilkes, 1989) as the case of the above core, while more discussion is necessary for the changes of the contents at the core and the below core of the both treatments.

The vascular cambium and the growth rings it produces are continuous from trunk to branch, but cells formed by the cambium in the upper junction of branch and trunk are oriented in a right angle to the normal orientation in the trunk and branch, while the branch xylem is oriented downward at the branch base and encircles it to form a collar which meets on the trunk below the branch. Thus conduction into and out of the branch followed the pathway of the branch collar and there was no local direct conduction between the trunk xylem above a branch and within a branch (Shigo, 1985). Consequently, the phenol contents at the above core were not affected by the treatments during a year in the present study, and the contents at the branch core and the below core changed in accordance with the extension of discolored sapwood, which proceeded further in the axial rather than radial or tangential wood alignments (Deflorio *et al.*, 2007).

In *Eucalyptus nitens*, total phenols at the reaction zone after wounding increased slowly, reaching a maximum after 21 days, and then would decrease with the extension of the discolored area and the retreat of reaction zones rich in phenols as time went by (Barry *et al.*, 2001). But in Scots pine, there was no significant difference between healthy roots and roots infected with *Cylindrocarpon destructans* in total phenols (Bonello and Pearce, 1993). Total phenols at the branch core of *A. palmatum* and *P. strobus* of the present study changed consistently with the previous studies on hardwoods and conifers. Higher total phenols at the below core in the present study would be caused by a downward extension of discolored area along the conduction pathway.

In Scots pine, there was little difference in lignin between healthy roots and roots infected with *Cylindrocarpon destructans* (Bonello and Pearce, 1993). But resins contribute to defense in conifers by forming mechanical barriers in resin-soaked tissues (Pearce, 1987; Prior, 1976; Shain, 1979), and oleoresin was accumulated in the reaction zone and infected sapwood to the extent of about 30% of the moisture-free weight of the tissue (Shain, 1967), as shown by the results of the present study.

Formation of lignin is one of the defense mechanisms in the wood tissues to protect trees from wounding and microbial invasion (Yamada, 2001). Geiger *et al.* (1986)

reported an increase of 25-30% in lignin-like material in the wood of *Hevea brasiliensis* taproots close to the infection front of *Rigidoporus lignosus*. Increases of lignin contents at the core of the treated union by about 15%, when comparing with the core of the control in the present study, would result from lignification of exposed xylem tissues as a defense mechanism of the trees. The content of holocellulose is a relative proportion per unit weight, and the higher lignin content is accompanied by the lower relative content of holocellulose.

This study showed a little different response in compartmentalizing the pruning wounds between *A. palmatum* and *P. strobus*. This suggests each tree species has its own pattern to compartmentalize the wounds according to its phenological cycle. Therefore, more pruning researches on major tree species in urban forest are required to keep the forest healthy. One useful information from this study is that the area with a cold winter should avoid an early-winter pruning.

Literature Cited

1. American National Standard Institute. 2001. American National Standard for Tree Care Operations-Tree, Shrub, and Other Woody Plant Maintenance-Standard Practices (Pruning). ANSI A300 (Part 1)-2001 Pruning. American National Standard Institute, Washington, DC.
2. Barry, K.M., Pearce, R.B., Evans, S.D., Hall, L.D. and Mohammed, C.M. 2001. Initial defence responses in sapwood of *Eucalyptus nitens* (Maiden) following wounding and fungal inoculation. *Physiological and Molecular Plant Pathology* 58: 63-72.
3. Barry, K.M., Pearce, R.B. and Mohammed, C.M. 2000. Properties of reaction zones associated with decay from pruning wounds in plantation-grown *Eucalyptus nitens*. *Forest Pathology* 30: 233-245.
4. Blanchette, R.A. 1992. Anatomical responses of xylem to injury and invasion by fungi. pp. 76-95. In: Blanchette, R.A. and Biggs, A.R. (ed.). *Defense Mechanisms of Woody Plants against Fungi*. Springer-Verlag, Berlin.
5. Boddy, L. and Rayner, A.D.M. 1983. Origins of decay in living deciduous trees: the role of moisture content and a re-appraisal of the expanded concept of tree decay. *New Phytologist* 94: 623-641.
6. Bonello, P. and Pearce, A.D.M. 1993. Biochemical defence responses in primary roots of Scots pine challenged *in vitro* with *Cylindrocarpon destructans*. *Plant Pathology* 42: 203-211.
7. Choi, G.Y., Kwon, W.T. and Robinson, D.A. 2006. Seasonal onset and duration in South Korea. *Journal of the Korean Geographical Society* 41: 435-456.
8. DeBell, D.S., Harrington, C.A., Gartner, B.L. and Singleton, R. 2006. Time and distance to clear wood in pruned red alder saplings. In: Deal, R.L. and Har-

- rington, C.A. (ed.). pp. 103-113. Red Alder - a state of knowledge. General Technical Report PNW-GTR-669. Pacific Northwest Research Station, USDA, Portland, OR.
9. Deflorio, G., Barry, K.M., Johnson, C. and Mohammed, C.L. 2007. The influence of wound location on decay extent in plantation-grown *Eucalyptus globulus* and *Eucalyptus nitens*. *Forest Ecology and Management* 242: 353-362.
 10. Dujesiefken, D., Liese, W. and Shortle, W. 2005. Response of beech and oaks to wounds made at different times of the year. *European Journal of Forest Research* 124: 113-117.
 11. Geiger, J.P., Rio, B., Nicole, M. and Nandris, D. 1986. Biodegradation of *Hevea brasiliensis* wood by *Rigidoporus lignosus* and *Phellinus noxius*. *European Journal of Forest Pathology* 16: 147-159.
 12. Gilman, E.F. 2002. *An Illustrated Guide to Pruning* (second edition). Delmar, Albany, NY.
 13. Harris, R.W., Clark, J.R. and Matheny, N.P. 2004. *Arboriculture* (4th ed.). Prentice Hall, Upper Saddle River, NJ.
 14. Hartman, J.R., Pirone, T.P. and Sall, M.A. 2000. *Pirone's Tree Maintenance* (7th ed.). Oxford University Press, Inc., New York.
 15. Hensley, D.L. 1979. Pruning - why, when and how. *Journal of Arboriculture* 5: 239-240.
 16. Jalal, M.A.F., Read, D.J. and Haslam, E. 1982. Phenolic composition and its seasonal variation in *Calluna vulgaris*. *Phytochemistry* 21: 1397-1401.
 17. Korea Meteorological Administration. 2009. Weather information. Available from http://www.kma.go.kr/sfc/sfc_03_01.jsp (cited 24 September 2009).
 18. Kozlowski, T.T. and Pallardy, S.G. 1997. *Physiology of Woody Plants*. Academic Press, San Diego, CA.
 19. Leben, C. 1985. Wound occlusion and discoloration columns in red maple. *New Phytologist* 99: 485-490.
 20. Lee, K.H. and Lee, K.J. 2009. Impact of pruning intensity on tree growth and closure of pruning wounds of *Pinus strobus* L. and *Acer palmatum* Thunb. *Journal of Korean Forest Society* 98: 584-592.
 21. Lee, K.H., Lee, K.J., Gwak, K.S. and Choi, I.G. 2009. Impact of transplanting on tree growth and compartmentalization of pruning wounds in *Acer palmatum* Thunb. *Journal of Korean Forest Society* 98: 618-629.
 22. Lee, K.J. and Lee, S.J. 2001. *Arboriculture* (1st ed.). Seoul National University Press, Seoul.
 23. Mireku, E. and Wilkes, J. 1989. Seasonal variation in the ability of the sapwood of *Eucalyptus maculata* to compartmentalize discoloration and decay. *Forest Ecology and Management* 28: 131-140.
 24. National Renewable Energy Laboratory. 2005. Biomass Analysis Technology Team Laboratory Analytical Procedure. National Renewable Energy Laboratory, US Department of Energy.
 25. Neely, D. 1970. Healing of wounds on trees. *Journal of the American Society for Horticultural Science* 95: 536-540.
 26. Neely, D. 1973. Tree wound healing and radial growth correlations. *HortScience* 8: 384-385.
 27. Neely, D. 1983. Tree trunk growth and wound closure. *HortScience* 18: 99-100.
 28. Pearce, R.B. 1987. Antimicrobial defences in secondary tissues of woody plants. pp. 219-238. In: Pegg, G.F. and Ayres, P.G. (ed.). *Fungal Infection of Plants*. Cambridge University Press, Cambridge, UK.
 29. Perry, E. and Hickman, G. 1987. Wound closure in eucalyptus. *Journal of Arboriculture* 13: 148-152.
 30. Prior, C. 1976. Resistance by Corsican pine to attack by *Heterobasidion annosum*. *Annals of Botany* 40: 261-279.
 31. Rayner, A.D.M. 1986. Water and the origins of decay in trees. pp. 321-341 In: Ayres, P.G. and Boddy, L. (ed.). *Water, Fungi and Plants*. Cambridge University Press, Cambridge, UK.
 32. Shain, L. 1967. Resistance of sapwood in stems of loblolly pine to infection by *Fomes annosus*. *Phytopathology* 57: 1034-1045.
 33. Shain, L. 1979. Dynamic responses of differentiated sapwood to injury and infection. *Phytopathology* 69: 1143-1147.
 34. Shigo, A.L. 1979. *Tree Decay - an Expanded Concept*. USDA Forest Service, Durham, NH.
 35. Shigo, A.L. 1985. How tree branches are attached to trunks. *Canadian Journal of Botany* 63: 1391-1401.
 36. Shigo, A.L. 1989. *Tree Pruning: a Worldwide Photo Guide for the Proper Pruning of Trees*. Shigo and Trees, Associates, Durham, NH.
 37. Shigo, A.L. and Larson, E.H. 1969. *A Photo Guide to the Patterns of Discoloration and Decay in Living Northern Hardwood Trees*. USDA Forest Service, Upper Darby, PA.
 38. Shigo, A.L. and Marx, H.G. 1977. *Compartmentalization of Decay In Trees*. USDA Forest Service.
 39. Shortle, W.C. 1979. Compartmentalization of decay in red maple and hybrid poplar trees. *Phytopathology* 69: 410-413.
 40. Technical Association of Pulp and Paper Industry. 1994. Solvent extractives of wood and pulp; S.L. (T-204 OM-88).
 41. Winget, C.H. and Kozlowski, T.T. 1965. Seasonal basal area growth as an expression of competition in northern hardwoods. *Ecology* 46: 786-793.
 42. Wise, L.E., Murphy, M., and D'Addieco, A.A. 1946. Chlorite holocellulose, its fractionation and bearing on summative wood analysis and on studies on the hemicelluloses. *Paper Trade Journal* 122: 35-43.
 43. Yamada, T. 2001. Defense mechanisms in the sapwood of living trees against microbial infection. *Journal of Forest Research* 6: 127-137.