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Research papers

Factors affecting branch wound occlusion and associated decay following pruning - a case study with wild cherry (*Prunus avium* L.)

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Abstract - Pruning wild cherry (*Prunus avium* L.) is a common silvicultural practice carried out to produce valuable timber at a veneer wood quality. Sub-optimal pruning treatments can permit un-occluded pruning wounds to develop devaluing decay. The aim of this study is to determine relevant branch, tree and pruning characteristics affecting the occlusion process of pruning wounds. Important factors influencing occlusion time for an optimised pruning treatment for valuable timber production utilising wild cherry are derived. 85 artificially pruned branches originating from ten wild cherry trees were retrospectively analysed. Branch stub length, branch diameter and radial stem increment during occlusion were found to be significant predictors for occlusion time. From the results it could be concluded that for the long term success of artificial pruning of wild cherry it is crucial to (*i*) keep branch stubs short (while avoiding damage to the branch collar), (*ii*) to enable the tree to maintain significant radial growth after pruning, (*iii*) to avoid large pruning wounds (>2.5 cm) by removing steeply angled and fast growing branches at an early stage.

Keywords - high value timber production, wound occlusion, stub occlusion

Introduction

Modern forestry management should simultaneously satisfy ecological, economical and social demands of both the public and of forest owners. Valuable broadleaf tree species can be especially regarded as an option to fulfil the multidimensional requirements of today's forestry sector, where an economic return is crucial. The inclusion of valuable broadleaves can also simultaneously increase biodiversity and aesthetics within forests and agricultural land (Rapey 1994, Dupraz 1994, Bell 2009).

High value logs destined for veneer must meet a number of quality parameters: large diameter, cylindrical shaft forms, high volume of knotless wood, a uniform colour and an absence of decay (Mahler 1988, Spiecker 2003, Kupka 2007, Springmann et al. 2011a). Large dimensioned high quality logs with a small knotty core reach the highest prices. The reduction of the width of the occlusion zone to a minimum in order to harvest greater amounts of branch free timber is one important goal for silvicultural management. This goal requires timely and repeated interventions especially in juvenile stages. Of particular importance is artificial pruning in order to reach the production target of branch free valuable timber (Balandier 1997, Oosterban et al. 2009). This is especially true for open grown trees (Balandier and Dupraz 1999) where natural pruning occurs to a lesser extent. The same is true for tree species that do not self prune well (Röhrig et al. 2006). Both points are relevant for wild cherry (*Prunus avium* L.) cultivated in widely spaced systems.

Wild cherry is often considered to be a valuable broadleaved species yielding high prices under relatively short rotations (Bulfin and Radford 1998, Balandier and Dupraz 1999, Morhart et al. 2014). In order to obtain a high quality product, artificial pruning is of upmost necessity (Otter 1954, Balandier and Dupraz 1999, Thies et al. 2009, Springmann et al. 2011b). This results in a small dimensioned knotty core surrounded by branch free wood. The longer it takes for a pruning wound to occlude the larger the knotty core becomes. Therefore, in order to maximise clear wood, the time taken for complete branch stub occlusion must be minimised. The influencing factors for occlusion time and their effects play an important role for silvicultural management. Pruning operations undertaken in conifer stands have been the subject of much research (Møller 1960, Långström and Hellqvist 1991, O'Hara and Buckland 1996) while studies centred around hardwood species are less frequent (Kerr and Morgan 2006, Hein and Spiecker 2007, Dănescu et al. 2015). Previous research conducted on ash (*Fraxinus excelsior* L.) and sycamore (*Acer pseudoplatanus* L.) by Hein and Spiecker (2007) and Dănescu et al.

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(2015) could identify significant effects presented by branch diameter and radial increment during the time of wound occlusion. Current literature advises that branch diameters of wild cherry at the time of pruning should not exceed 3.0 cm at the branch collar (Pryor 1988, Spiecker and Spiecker 1988, Seifert et al. 2010, Springmann et al. 2011b). Additionally, the quality of the pruning cut, as expressed by the roughness of the cut surface and the length of the remaining stub is believed to have an effect on occlusion time (Dujesiefken et al. 1998, Springmann et al. 2011b).

Pruning methods such as selective pruning (Spiecker 2010, Springmann et al. 2011b) can improve the production of veneer quality timber from wild cherry due to the early removal of the most vital branches. This results in smaller branch diameter of the pruned branches, and hence, smaller pruning wounds. An employment of this method means that occlusion time should be reduced, which in turn implies a lesser risk of infection of the pruning wound (Spiecker 2010) by wood decaying fungi such as *Phellinus tuberculosus* Baumg. and *Trametes* spp. (Seifert et al. 2010). Hence, the first objective of this study is to evaluate the influence of different parameters such as branch-stub length, branch diameter, radial growth, insertion angle of the branch and cardinal direction on the occlusion time of pruned branches. The second objective was to reveal how branch diameter and occlusion time influence the development of wood decay.

Materials & Methods

The 2.5 ha experimental site is located on the floodplain of the river Rhine in south western Germany close to the town of Breisach (48.071N; 7.589E, 182 m a.s.l.) situated on former agricultural land. The soils are not considered deficient in essential minerals and nutrients. A detailed description of the site, soils and climate conditions can be found in Morhart et al. (2016). The site and climatic conditions can be considered suitable for the growth of wild cherry. The site index for pruned cherry is described as class II: a tree height of 26.7 m at an age of 60 years is to be expected according to applicable yield tables (Spiecker 1994).

The research site was planted in 1997 with 1+1 wild cherry stock derived from the Liliental seed orchard, established within a randomised block design. The initial spacing of all trees on the research plot was 1.5 m x 7.5 m and 1.5 m x 15.0 m in a mixture with other broadleaves species including European ash, pedunculate oak (*Quercus. robur* L.), sycamore, small-leaved lime (*Tilia cordata* Mill.) and European hornbeam (*Carpinus betulus* L.). This mixture relates to the site's aim of investigating the growth of valuable broadleaved tree species within a widely spaced planting design. Thinning was carried out to favour future crop trees, i.e. those displaying a high radial increment and suitable form.

In 2015 a total of 10 wild cherry classified as dominant and co-dominant trees (Kraft 1884) were sampled. These trees were artificially pruned in three year intervals (2007, 2010 and 2013), thus, reflecting representative crop tree management practices. After felling the trees, each whorl was carefully examined for partially or fully occluded branches and the respective whorls were sampled. This yielded 63 occluded and 22 partially occluded artificially pruned branches for further analyses. In addition stem discs were taken for retrospective radial increment analysis at 1.3 m, 2.5 m, 5.0 m and 7.5 m from the ground.

Samples were air-dried under ventilated conditions for three weeks before being prepared for examination. Branch whorls were cut parallel to the stem axis so that the included branches could be divided centrally (see Fig.1 left).

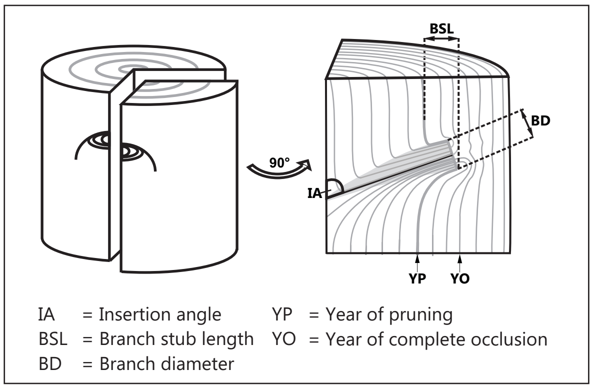

Figure 1 - Measured parameters within sampled whorl sections.

All cut surfaces, plus the stem discs, were sanded with 240 grit sandpaper to prepare them for further analyses. Cardinal direction (CD) of the occluded branches was measured in respect to a north datum that was marked in the field. Tree ring width, as a proxy for radial increment during pruning wound occlusion, was measured on all stem discs, using the software WinDENDRO TM (Regent Instruments Inc.). The yearly quadratic mean radial increment during occlusion was calculated from four orthogonal radii.

For determination of occlusion time (*OT*), the year of pruning (*YP*) and the year of complete occlusion (*YO*) were established (*OT* = *YO* – *YP*). *YP* was defined as the last year in which a defined tree ring originates in the stem and converges within the branch, while *YO* was identified as the first defect free tree ring entirely covering the pruning wound.

The branch cross sectional diameter (*BD*) at the site of the cut face, and the insertion angle (*IA*) of the pruned branch were additionally measured. To obtain the best possible measurement of IA, 50% of BD was utilised as a point of measurement with the vertex of the angle located where the branch pith met the stem pith. Branch stub length (*BSL*) was measured on the underside of the branch using the distance between *YP* and the lower lip of the pruning cut. All measurement sites are illustrated within Fig. 1. To determine the radial increment during the time of wound occlusion (*irO*) we used the yearly quadratic mean radial increment of the stem disc that was located closest to the pruned branch.

Investigation of stem decay as a result of artificial pruning is based on data derived from a total of 85 branches, 63 of which were completely occluded and 22 that remained un occluded, In order to retrospectively investigate stem decay associated with fungal infection, branches were first visually sampled for signs of decay. Three levels of decay were defined: No visible wood decay, wood decay limited to the pruned branch (Level I) and wood decay spreading through the pruned branch into the stem wood (Level II).

Statistical analysis and modelling

Data analysis was carried out using SPSS for Windows 22.0 software (IBM Corp. 2013). The level of significance was set at $p = 0.05$ for all analyses. Normality was tested with a Shapiro-Wilk test. Stepwise ordinary least squares regression was performed to model branch occlusion time as a consequence of *BD*, *irO*, *BSL*, *IA* and *CD*. The independent predictor variables were included within the model in a stepwise method ensuring significance. Residuals were assessed for homoscedasticity by visual analysis of the studentised residuals plotted against predicted values and a normal distribution was ensured using normal Q-Q plots. A Durbin-Watson test was carried out to assess whether there was autocorrelation between residuals and the Variance Inflation Factor (VIF) evaluated in order to assess multicolliniarity within the model. The Akaike Information Criterion (AIC) was utilised to reinforce the choice of model (values can be seen in Tab. 2). The derived model followed the form of Eq. 1 where *OT* is pruning wound occlusion time (years) and X the respective independent predictor variables with associated beta values (β) as derived from the regression analysis.

$$OT = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \ldots \beta_p X_\mathrm{p} \qquad \text{Eq. 1}$$

Results

The following data were attained from 63 completely occluded and 22 non occluded pruned branches.

Tab. 1 displays descriptive statistics for the parameters measured for all fully occluded branches within the sample (n=63). Occlusion time ranged between two and seven years, branch diameter was measured between 7.0 mm and 40.0 mm, branch stub length presented a maximum length of 25.0 mm within the sample while branch radial increment growth ranged between 1.60 mm/year to 4.59 mm/year for fast growing branches. *BSL*, *BD* and *irO* all proved to significantly contribute to the model and hence, model III (F(3,59) = 14.4, p=<0.001) was chosen providing the best model fit and lowest AIC value (see Tab. 2).

Table 1 - Descriptive statistics for occlusion time (*OT*), branch diameter (*BD*), radial increment during occlusion (*irO*), branch stub length (*BSL*) and insertion angle (*IA*) for completely occluded branches (n=63).

Variable	Min.	Max.	Mean.	S.D.
OT (years)	2.0	7.0	4.3	1.2
BD (cm)	0.7	4.0	1.9	0.7
irO (mm)	1.6	4.6	3.0	0.8
BSL (cm)	0.0	2.5	0.6	0.7
IA (°)	31.0	86.0	53.7	12.2

Table 2 - Model parameters for the prediction of wound occlusion time (*OT*) utilising branch stub length (*BSL*), branch diameter (BD) and radial increment during occlusion (*irO*) as predictor variables (n=63).

Model	Included Variables	F	df	R	r^2_{adj}	p	AIC
I	*BSL*	27.5	1,61	0.557	0.299	<0.001	-0.978
II	*BSL, BD*	17.7	2,60	0.609	0.350	<0.001	-4.789
III	*BSL, BD, irO*	14.4	3,59	0.650	0.394	<0.001	-8.223

Table 3 - Regression parameters of model III for the prediction of wound occlusion time (*OT*) utilising branch stub length (*BSL*), branch diameter (*BD*) and radial increment during occlusion (*irO*) as predictor variables (n=63), where β is the beta coefficient and Se the standard error.

Var.	β	Se	*p*-Value	Partial r²	Structure Coefficients
Constant	4.206	0.595	<0.001	---	---
BSL	0.818	0.174	<0.001	0.22	0.857
BD	0.352	0.149	0.0214	0.05	0.315
irO	-0.350	0.152	0.0247	0.05	-0.632

The model was statistically significant and accounts for approximately 40% of the variance of pruned branch occlusion time ($r^2_{adj} = 0.394$). Partial r^2 values suggest that BSL provides the backbone of the model (22%) with *BD* and *irO* supporting with 5% respectively. This is also supported by the stated structure coefficients also given in Tab. 3. Both *IA* (*p*=0.239) and *CD* (*p*= 0.277) did not contribute significantly to the model and were, therefore, excluded.

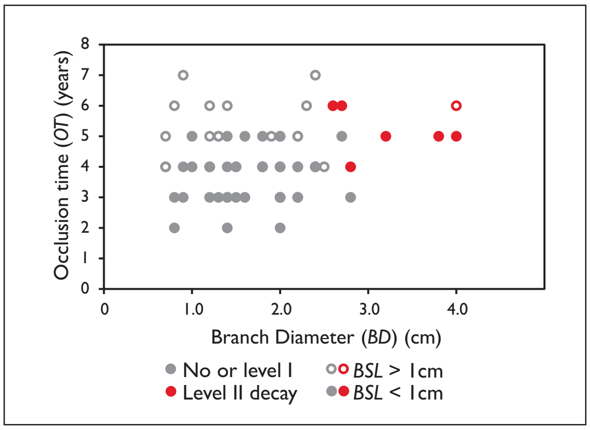

Figure 2 - Occlusion time (*OT*) as a function of branch diameter (*BD*) with marker types indicating branch stub length (*BSL*). Level II decay is indicated by red markers (n=63).

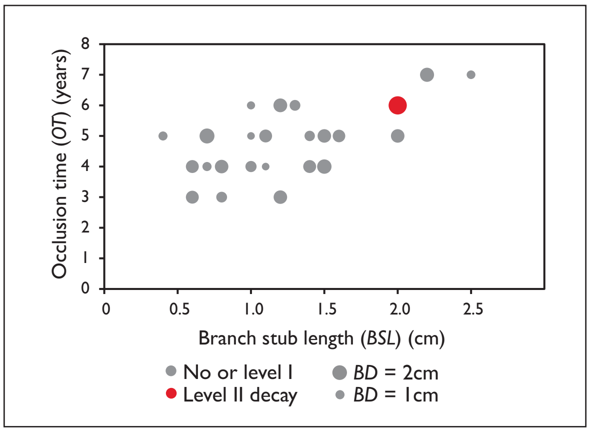

Figure 3 - Occlusion time (*OT*) as a function of branch stub length (*BSL*) (n=30). Size of the markers corresponds to branch diameter (*BD*), size of data points are proportional to branch diameter. Level II decay is indicated in red.

To visually demonstrate the influence of *BD*, *BSL* and *irO* as important contributing factors affecting *OT* Fig. 2, Fig. 3 and Fig. 4 are presented. Fig. 2 shows occlusion time against branches of different diameters. A significant increase (p=0.021) in occlusion time related to increasing branch diameter can be observed. The pruning of larger branches, thus, results in an extension of the time of wound occlusion. It can be seen that even small branches of less than 1.0 cm in diameter can take up to seven years to be completely occluded. Such long occlusion times for small diameter branches can be attributed to other factors such as the *BSL* (Fig. 2 *BSL* > 1.0 cm shown with unfilled points) and the *irO*. *OT* for pruning wounds with a *BSL* of more than 1.0 cm in length is significantly longer (p=0.001) than that for branch stubs shorter than 1.0 cm. Fig. 3 illustrates the correlation between occlusion time and branch stub length with longer branch stubs resulting in a significant (p<0.001) prolongation of occlusion time, irrespective of branch diameter. Fig. 4 exhibits the relationship between occlusion time and radial increment during the period of wound occlusion, where a significant negative correlation (p=0.025) can be observed.

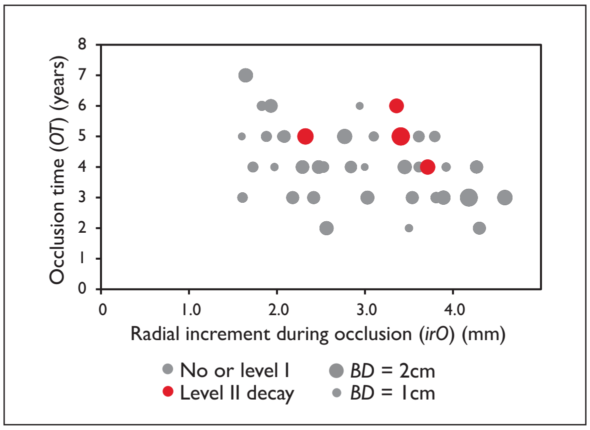

Figure 4 - Occlusion time (*OT*) as a function of radial increment during occlusion (*irO*) (n=63). Size of the markers corresponds to branch diameter (*BD*), size of data points are proportional to branch diameter. Level II decay is indicated in red.

From the sampled branch stubs 89% of fully occluded branches show no decay or decay classed as level I, while 50% of surveyed branches which have not fully occluded after eight or more years show a decay of level II. 18% of un-occluded branches showed no symptoms of decay at the time of analysis. A Kruskal-Wallis H test showed that the distribution of occlusion time as a function of *BD*, *BSL* and *irO* between decay levels is not the same ($\chi^2(2) = 22.248$, p = <0.001). mean rank scores of 31.03, 43.29 and 64.39 were calculated for no decay, decay level I and decay level II respectively. Fig. 5 illustrates the correlation between the occurrence of decay in artificially pruned branches and the duration of wound occlusion. Pruning wounds that are completely occluded within two to three years exhibit negligible amounts of level I decay and none of the 17 branches in that category could be diagnosed with severe stem decay (level II). If complete occlusion takes up to four years, a large increase (55% of studied branches) of decay within the pruned branches can be observed. Occlusion times of four years and beyond show the first occurrences of severe stem decay, spreading through the pruning wound in an axial direction into the stem wood. Analysis of Fig. 5 suggests that if the pruning wound takes up to five years to be completely occluded almost 20% of the branches will exhibit decay at level II. While at six years and above there are 19% of branches that are completely unaffected by wood decay while 45% are severely infected by level II decay.

To examine the correlation between the formation of decay and branch diameter we investigated those branches that were pruned with a *BSL* of less than 0.5 cm. This way we could include branches that had been pruned with a correct cut peripheral

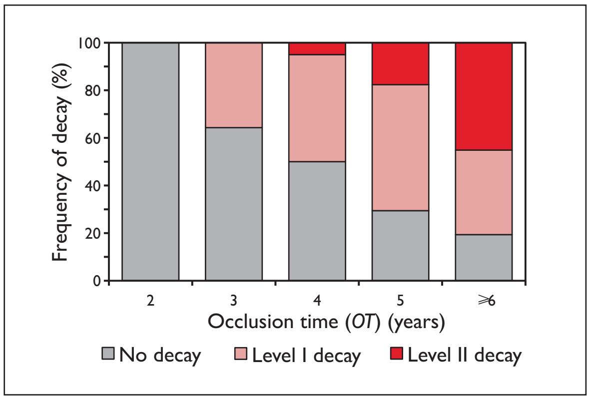

Figure 5 - Percentage frequency of the three levels of decay following artificial pruning (n=85).

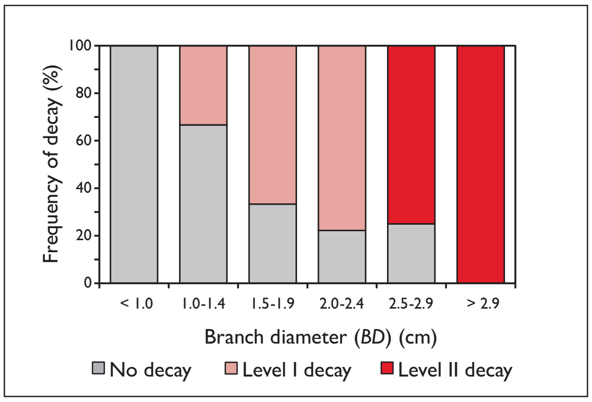

Figure 6 - Percentage frequency of the three levels of decay following artificial pruning for different branch diameters with BSL <0.5 cm (n=34).

to the branch collar. Stubs resulting from the existence of a branch collar never exceeded 0.5 cm in all samples. By setting this threshold we eliminated the large influence of *BSL* on occlusion time which results from poor pruning cuts to be able to assess the occurrence of decay for arising from pruning cuts that follow best practice. This limited the sample size to 34 branches. The correlation between pruned branch diameter and the occurrence of wood decay is illustrated in Fig. 6. Level I decay can be observed with increasing branch diameters starting in the diameter range from 1.0 to 1.5 cm. About 40% of the 22 sampled branches in the diameter range from 1.0 to 2.5 cm exhibit level I decay. Severe stem decay (i.e. level II) can be found commencing at pruned branch diameters of 2.5 cm with 85% of pruned branches showing axial spread of decay into the stem wood.

Discussion

This article retrospectively investigates the occlusion of pruning wounds on wild cherry trees. The impact of different stub parameters such as branch diameter, stub length or branch insertion angle in relation to the bole on the occlusion zone was analysed. It was shown that increased radial increment within the stem results in a reduction in occlusion time, i.e. fast growing trees occlude pruning wounds faster, a logical conclusion. Occlusion time is delayed by an increase in the diameter of pruned branches and by the increased length of the remaining branch stub.

Modelled results suggest that branch stub length, branch diameter and radial increment of the stem during the time of occlusion are all significant predictors of pruned branch occlusion time with a standard error of the estimate of 0.9 years.

The largest contributory factor towards a fast occlusion time is branch stub length, a consequence of the accuracy of pruning operations. Within the model *BSL* contributed 22% of the total for the explanation of variance. This variable has a larger effect on the duration of wound occlusion than the diameter of the branch itself or the radial increment of the stem during the occlusion period. Multiple studies found similar relations in various conifer and broadleaved tree species (Anderson 1951, Finnis 1953, O'Hara and Buckland 1996, Metzler 1997, Dănescu et al. 2015). It could be shown that the majority of fully occluded branches presented a pruned branch stub <1.0 cm. Such pruning wounds were occluded within two to five years dependent on the rate of radial increment within the stem. A recommendation suggesting that branch stubs are a maximum of 1 cm in length constitutes clear easy to follow advice for the practitioner. Nevertheless, an optimal pruning cut should be made close to the bole, as longer branch stubs will significantly extend occlusion time, and therefore, increase the risk of severe stem decay. However, care must be taken not to cut into the branch collar if present (Springmann et al. 2011a). Correct pruning practice must be carried out by making the cut adjacent to the outer perimeter of a branch collar.

These finding concur with current literature: Hein (2003) explicitly suggests the elimination of long branch stubs as one of the key advantages of artificial pruning compared to natural pruning in ash and sycamore, since the wound occlusion time is significantly shortened. Petruncio et al. (1997), utilising a stepwise regression method in order to model branch occlusion in coastal Douglas fir (*Pseudotsuga menziesii* var. menziesii [Mirb.] Franco), concluded that total occlusion time increases with large diameter stem sections (whorl diameter), with long branch stubs and if branches are dead at the time of pruning.

Results of the regression suggest that branch diameter contributes 5% towards the explanation of wound occlusion arising from pruning treatments. Wounds resulting from the artificial pruning of smaller branches occlude significantly faster than those of larger ones. This correlation has been confirmed by various studies on a broad range of tree species including valuable broadleaved species such as red oak (*Q. rubra* L.), ash or sycamore (Petruncio et al. 1997, Joyce et al. 1998, Hein and Spiecker 2007, Seifert et al. 2010, Nicolescu et al. 2013, Dănescu et al. 2015). The diameter of pruned branches is essential when considering wound occlusion time. Recommendations that branches of wild cherry should be pruned before they reach a maximum threshold of 2.5 cm to 3.0 cm can be reinforced (Pryor 1988, Spiecker and Spiecker 1988).

The results of our study confirm a significant reduction of occlusion time for increasing *irO*. Moreover, it could be proven that *irO* outweighs the influence of *BD* as far as occlusion time is concerned. This corresponds with the findings of Finnis (1953) relating to *P. menziesii*. The correlation between *irO* and *OT* suggest that thresholds for ideal pruning diameters cannot be generalised but must be site related and that artificial pruning should be focused on the most vital individuals within a stand. Similar conclusions have been drawn by Žumer (1966) and Dănescu et al. (2015). The sampled wild cherry within this study were derived from a site displaying an average annual ring width increment of approximately 3 mm during the time of occlusion. Since growth rates of 4 to 5 mm have also been measured for trees on this site, the application of silvicultural treatments to promote fast growth can also be suggested. This may include a reduction of competitive pressure amongst trees with lower annual radial increment applied after pruning treatments in order to support rapid wound closure.

The results of this study show a correlation between pruning wound occlusion time and the occurrence of decay. With increasing occlusion time the frequency and severity of decay also increases. This concurs with results presented by both Pretzsch et al. (2010) and Seifert et al. (2010). We suggest that if a pruning wound is occluded within two years, there is limited risk of decay. This study showed that coupled with an occlusion time of four years the first instances of stem decay are observed. Any further prolongation of occlusion time increases the frequency and intensity of infections and consequent decay. As a result, it is of vital importance for silvicultural management to aim for full occlusion within a maximum of three years. Location and site quality are important parameters for radial increment increases, and therefore also play a major role in the occlusion process of pruning wounds. Seifert et al. (2010) developed a model whereby dependent on annual radial increases, branch diameter thresholds to avoid decay arising from pruning wounds can be suggested. They also found that wild cherry located on poor sites invested greater energy in the defence of fungal infection of pruning wounds, and thus presenting a lower decay rate for the same occlusion time as trees located on higher quality sites. The sampled wild cherry within this study were derived from only one site, displaying an average ring width increment of approximately 3 mm during the time of occlusion. According to the model by Seifert et al. (2010), on a site comparable to the one we investigated, branches in the diameter range of up to 2.5 cm can be pruned without or with modest risk of severe stem decay. This is in agreement with results presented within this study.

All three variables manipulating wound occlusion can be influenced by forest managers: *BD* can be minimised by pruning both early and repeatedly in the rotation, *BSL* can also be minimised by improved pruning technique and accuracy, this can be reinforced by training forest workers in best practice techniques. Finally, *irO* can be maximised by utilising targeted silvicultural measures that encourage diameter growth coupled with applied pruning treatments. The selective pruning methodology where large diameter and steeply angled branches are removed within the entire length of the planned branch free bole vs. a classical whorl-wise pruning methodology allows the forest manager to effectively control factors such as *BD* while retaining a high radial increment for a decreased wound occlusion time resulting in a reduced risk of decay.

Conclusion

We conclude that if valuable timber is to be produced the artificial pruning of wild cherry must aim for an accurate pruning cut, leaving the remaining stubs short. We suggest that branches to be pruned should not exceed a diameter of 2.5 cm on order to promote a rapid wound occlusion which can limit the potential for decay. Finally, it can be concluded that the promotion of large radial increments during wound occlusion is of major importance to ensure swift occlusion of the pruning wound.

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