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Development of stem cracks in young hybrid aspen plantations

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Abstract. Cracks expose wood to fungal infections that significantly affects wood quality, while rapid wound occlusion decreases probability of infections. Assessment of scars was done at four grade scale in three adjacent hybrid aspen trials at the age of 8–10 years in central part of Latvia three years after bark crack occurrence. Occluded wounds were found for 95% of damaged trees, regardless of tree age. Among trees that had cracks wider than 1 cm, 42% had uniformly healed bark, but 7% still had open wounds. Wound development was significantly affected by crack width and length (both $p < 0.001$), but had no clear relation with tree DBH (diameter at breast height) and relative DBH increment (both $p > 0.05$). At clonal mean level, scar grade was significantly affected by grade of crack three years earlier and clone (both $p < 0.001$), but mean DBH of clone had no relation ($p > 0.05$) to proportion of trees evaluated by any of the scar grades. The results suggest that three years after the bark crack formation most of them had successfully occluded and selection of clones with better diameter growth has no influence on development of cracks.

Key words*:* bark wounds, frost cracks, sunscald injuries, wound occlusion, *Populus tremula* × *P. tremuloides.*

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Introduction

Hybrid aspen is commonly grown for solid wood production, using planting density ca. 1,100–1,500 trees per ha on former agricultural land (Tullus *et al.*, 2007; Tullus *et al.*, 2012b). High yield of qualitative assortments is essential to ensure even a minimal profit from the first rotation for hybrid aspen plantations (Tullus *et al.*, 2012a; Smilga *et al.*, 2015), thus risk of any damage should be reduced. In contrast to trees grown in forest, open exposure and low density of trees in plantations provides almost no shelter and shading, especially during the first years of establishment. In such conditions trees are more subjected to weather extremes, including increased possibility of frost induced damage. Only few studies had analysed stem cracks of forest trees so far, although some authors have reported incidence of cracks on *Populus* species and their hybrids in the Northern Europe. In these studies, notable differences in frequency of stem cracks as well as their length (reaching up to 2 m) were found (Christersson, 2006; Merdikes, 2015). Trees with thin and smooth bark, such as hybrid aspen, have low tolerance to rapid temperature fluctuations (Nicolai, 1986); hence trees in orchards and urban areas are protected mainly by physical barriers and white paint on stems (Litzow & Pellett, 1983; Wagner & Kuhns, 2011; Sheppard *et al.*, 2016). Up to now,

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there is no costefficient method to prevent stem cracks on trees in large scale plantations. They are unlikely to cause tree death, but can considerably decrease tree vitality due to fungal infections and wood quality due to discoloration, as had been found for several types of stem damages (Bier, 1965; Bucciarelli *et al*., 1999; Vasaitis *et al*., 2012; Arhipova *et al*., 2015; Burnevičа *et al*., 2016); consequently decreasing yield and profit. Crack size and time required for its occlusion influence possibility of fungal infections, and the latter is found to be closely related to radial growth of trees (Neely, 1979; Vasiliauskas & Stenlid, 1998; Pallardy, 2008). The aim of this study was to assess development of stem cracks and its relation to tree radial growth on young hybrid aspen three years after their occurrence.

Material and Methods

The study was done in three directly adjacent hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) trials, located in the central part of Latvia (56°27′ N, 22°53′ E) on abandoned agricultural land, referred to by their numbers in database of long term forest experiments. All trials were established using one-year-old containerized seedlings on fertile mineral soil with normal moisture regime; planting density 1,100 trees ha^{-1}. In total 22 clones were assessed (Table 1), among which 12 were represented only in one of the trails, nine clones were represented in two trials and one clone was represented in all three trials. Used hybrid aspen clones are crosses between mother-tree growing in botanical garden in central part of Latvia (no information on its origin is available) and local plus trees from different regions of Latvia.

Stem cracks occurred during the winter 2012/2013, affecting majority of trees – 457 (67%) in trial No 699, 325 (72%) in 640 and 103 (65%) in 620 – presumably caused by rapid temperature fluctuations during sunny winter day (Zeps *et al*., 2016, in prep.). No cracks were observed in the annual assessment of the trials prior to this winter. The cracks had only damaged bark, and no injury of wood was visible. Further in text we use "c racks" referring to damage of bark assessed in 2013, and we use "scars" referring development of cracks assessed in 2016.

In April of 2013, tree diameter at breast height (DBH_{2013}) and length of the cracks were measured. Bark cracks ($Grade_{2013}$) were evaluated on four grade scale: (0) no injuries; (1) bark crack, but wood not visible; (2) bark crack, visible wood; and (3) bark crack wider than 1 cm (results presented and discussed in Zeps *et al*., 2016, in prep.). In April of 2016, repeated measurements of tree diameter at breast height (DBH_{2016}) were done, and relative and absolute DBH increments were calculated. Scars ($Grade_{2016}$) were assessed on four grade scale: (0) no external signs of damage/uniformly healed bark; (1) healed bark, clearly visible scar; (2) healed bark, thickening on both sides of crack; and

Table 1. Main characteristics of the trials.

Trial	Year of planting (age in 2016)	Number of replications	Design	Area, ha	Number of trees	Number of clones	Mean number of ramets per clone	Range of number of ramets per clone
699	2009 (8)	4	block plots	0.75	680	13	52	25–64
640	2008 (9)	4	block plots	0.45	454	5	91	68–136
620	2007 (10)	25	single tree plots	0.34	158	15	11	8–13

(3) unhealed, open crack. In this study, we use term "healed bark" with meaning of wound closure (occlusion), i.e. wound is completely covered by callus; however we were not able to assess compartmentalization below the newly formed bark which is essential and separate process of healing (Shigo, 1984).

Normality of data was assessed by Shapiro-Wilk test. Kruskal-Wallis test was used to assess differences of crack length (i) between trees that had uniformly healed scar ($Grade_{2016}$ 0) and trees that had more substantial scar (pooled $Grades_{2016}$ 1–3) and (ii) between trees that had occluded scars (pooled $Grades_{2016}$ 0–2) and still open wounds ($Grade_{2016}$ 3). Differences between groups were tested using Dunn's multiple comparison. During the analysis, crack length, DBH_{2016}, relative and absolute DBH was divided into groups. Chi-squared test was used to assess distribution of trees among scar grades ($Grades_{2016}$) between the trials, crack grades ($Grades_{2013}$) and groups of crack length, tree DBH_{2016}, relative and absolute DBH increment. Generalized linear model was used to assess effect of crack grade ($Grade_{2013}$) and tree DBH_{2013} to tree DBH_{2016}. Ordered linear regression was used (i) to assess effect of crack width ($Grades_{2013}$) and length on scar grades ($Grades_{2016}$), (ii) to assess effect of crack grade ($Grade_{2013}$), tree DBH_{2016} and relative DBH increment on scar grade ($Grade_{2016}$) and (iii) to assess effect of clone and crack width ($Grade_{2013}$) on scar grade ($Grade_{2016}$). Spearman rank correlation was used to assess the relationship (i) between tree DBH_{2013} and DBH_{2016}, (ii) between tree DBH_{2016} and absolute DBH increment, (iii) between clonal mean DBH and proportion of trees in each $Grade_{2016}$ and (vi) between clonal mean crack length and proportion of trees in each $Grade_{2016}$. All tests were performed at $a = 0.05$; mean values and their confidence intervals are shown. All calculations were done in R 3.0.2. (R Core Team, 2013).

Results and Discussion

Mean DBH_{2016} of hybrid aspen trees was 11.4 ± 0.17, 12.9 ± 0.22 and 12.9 ± 0.37 cm in trails with the age of 8, 9 and 10 years (in 2016), respectively. In the year of damage occurrence, most of the cracks were evaluated by $Grade_{2013}$ 3, i.e. bark crack were wider than 1 cm; however three years later open cracks ($Grade_{2016}$ 3) were found for 3.6% of trees and most of the trees had no external bark injury, i.e. were not damaged initially, or had uniformly healed bark ($Grade_{2016}$ 0; Figure 1). One of the potential reasons for so efficient healing of the cracks could be hybridization, that changes quantitative and qualitative composition of secondary metabolites (Orians, 2000) and had been proven to determines plant resistance to abiotic stresses (Chen *et al.*, 2009). However, this aspect needs to be analysed in greater detail in further studies. Distribution of proportions of trees among the $Grades_{2016}$ was similar (all $p > 0.05$) regardless of tree age. Wound development largely depends on its characteristics. In our study we observed only damage to bark down to cambium layer but no external damage of wood. In general, damage that only slightly injures the cambium heals rapidly (Pallardy, 2008). For instance, in bark scoring experiment, three-year-old *Populus* trees had complete restoration and functioning of phloem in about 20 days (Soe, 1959). Also time of crack occurrence could have fostered their occlusion. In Latvia, cambial growth of hybrid aspen starts in May (Zeps *et al.*, 2015). If time lag between wound occurrence and cambium activity is sufficiently short, cambium zone is not killed by desiccation (Neely, 1979) and wounds which occur prior growing season generally heal rapidly (Pallardy, 2008).

We observed small proportion of trees that had no bark cracks before ($Grade_{2013}$ 0) but had visible scars three years later – 2.0, 1.0 and 0.2% of trees were evaluated by $Grade_{2016}$ 1, 2 and 3, respectively. This indicates reoccurrence of suitable conditions

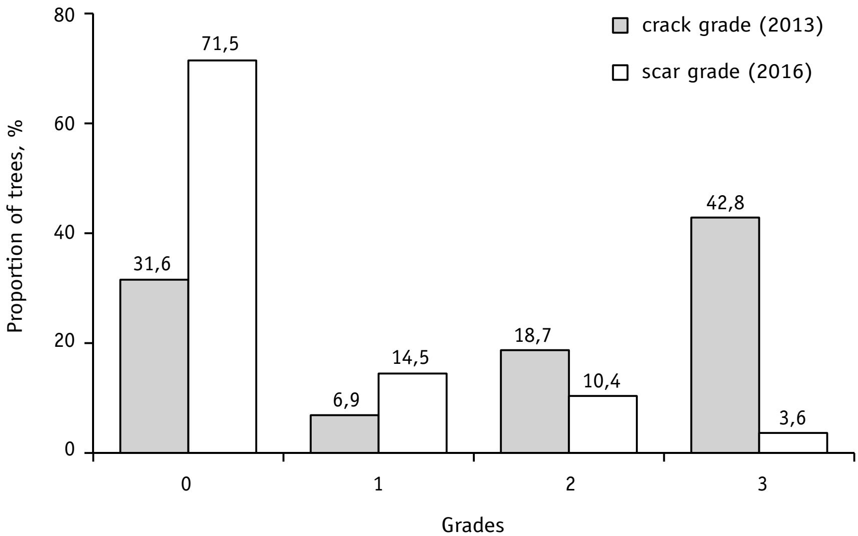

Figure 1. Proportion of trees among crack ($Grade_{2013}$) and scar ($Grade_{2016}$) grades.

for crack formation, which most presumably also affected crack occlusion. As discussed above, wounds that are formed in the beginning of growing season heal rapidly (Neely, 1979). However, if callus layer is not sufficiently thick, wounds may open up again during sharp temperature fluctuations (Pallardy, 2008). We observed 10.4% of trees with callus thickening in the both sides of scar ($Grade_{2016}$ 2; Figure 1), indicating that wound occlusion took longer than one growing season – wounds that open repeatedly have abundant callus formation and might develop "frost ribs" along the edges of injury (Pallardy, 2008).

Distribution of trees among scar grades ($Grades_{2016}$) differed significantly between groups of crack length and width (both $p < 0.001$). Among groups of crack length distribution of trees changed gradually. Trees with initially shorter cracks three years later had higher proportion of trees with uniformly healed scars ($Grade_{2016}$ 0) – uniformly healed scars were found for 88, 59, 41 and 30% of trees with crack length ≤ 10, 11–20, 21–30 and ≥ 31 cm, respectively. Proportion of still open cracks ($Grade_{2016}$ 3) increased from 4.5% for trees with cracks shorter than 10 cm to 10.9% for trees with cracks longer than 30 cm. Trees with uniformly healed bark had significantly ($p < 0.001$) shorter cracks than trees that had more substantial scars (pooled Grades 1–3) – 13.9 ± 0.75 and 21.0 ± 0.97 cm, respectively. However, no significant ($p > 0.05$) differences were found for crack length of occluded and still open wounds. Similarly, Vasaitis *et al.* (2012) found slightly, but not significantly longer injuries for open wounds in comparison to occluded ones for *Betula pendula* Roth. trees.

Analysis of ordered logistic regression indicated that crack width ($Grade_{2013}$) had stronger effect on scar grade ($Grade_{2016}$) than crack length, although both variables were highly significant (both $p < 0.001$). Formation of callus starts from the side edges of wound, progressing toward the centre (Neely, 1979). Hence, our results are in accordance with other studies that have revealed effect of wound width on time required for occlusion, regardless of wound

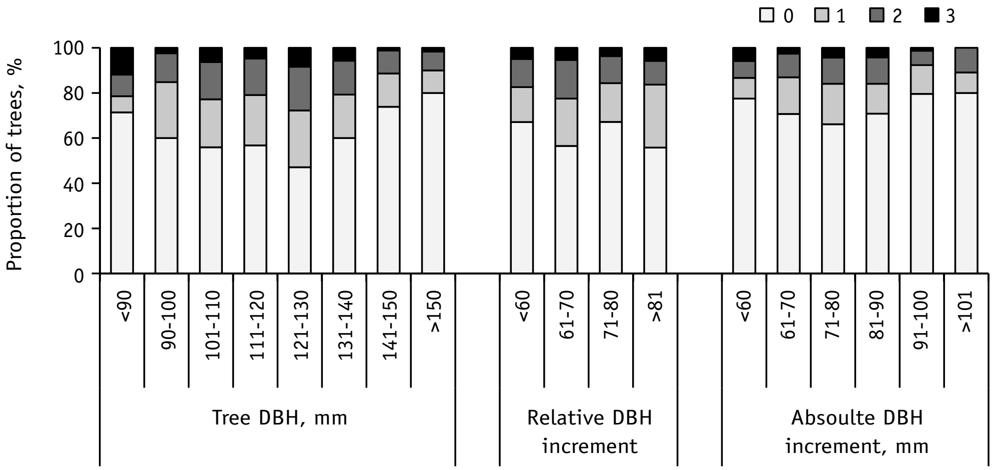

Figure 2. Proportion of previously damaged trees among scar grades ($Grade_{2016}$; 0–3) according to tree DBH_{2016}, relative and absolute DBH increment groups.

shape (Neely, 1979). In our study, most notable differences between distributions of trees among scar grades ($Grades_{2016}$) were found between trees that had cracks wider than 1 cm ($Grade_{2013}$ 3) and trees that had narrower cracks. Proportion of uniformly healed scars decreased from 91.0% for trees with the narrowest cracks ($Grade_{2013}$ 1) to 42.2% for trees with cracks wider than 1 cm ($Grade_{2013}$ 3). Among the latter, 7.2% of trees still had open, unhealed cracks. These sharp differences between groups of crack width ($Grade_{2013}$) are partly a consequence of relations between crack dimensions – as previously found (Zeps *et al.*, 2016, in prep.), the widest ($Grade_{2013}$ 3) bark cracks were also significantly longer than the narrower cracks ($Grades_{2013}$ 1 and 2).

Distribution of previously damaged trees ($Grades_{2013}$ 1–3) among scar grades ($Grades_{2016}$) had significant differences between tree DBH_{2016} groups ($p < 0.01$). Proportion of trees evaluated by $Grade_{2016}$ 0 was lowest for medium sized trees (Figure 2), gradually increasing for both smaller and larger trees. First, these results are consequent with pattern of proportion of trees evaluated by $Grade_{2013}$ 3 (Zeps *et al.*, 2016, in prep.) – higher proportion of medium size trees had $Grade_{2013}$ 3 cracks than both small and large trees. Second, crack grade ($Grade_{2013}$) had no effect on tree DBH three years later ($p > 0.05$), and tree DBH measured in both years correlated tightly and significantly ($p < 0.001$, $rho = 0.90$). And third, as described above, trees that had the widest cracks, had lower proportion of trees with uniformly healed scars and highest proportion of still open (unhealed) cracks. Thus, distribution of proportion of trees among scar grades ($Grades_{2016}$) between tree DBH_{2016} groups is largely consequence of distribution of proportion of trees among crack grades ($Grade_{2013}$).

Distribution of previously damaged trees ($Grades_{2013}$ 1–3) among scar grades ($Grades_{2016}$) between relative ($p = 0.11$) and absolute ($p = 0.07$) DBH increment groups was similar (Figure 2). Relative DBH increment showed no clear pattern of relation between proportion of trees in any of grades and relative DBH increment, while tree distribution between absolute DBH increment groups had similar pattern to distribution between DBH_{2016} groups due to tight correlation between these two variables ($p < 0.001$, $rho = 0.84$). Scar grade ($Grade_{2016}$) was significantly ($p < 0.001$)

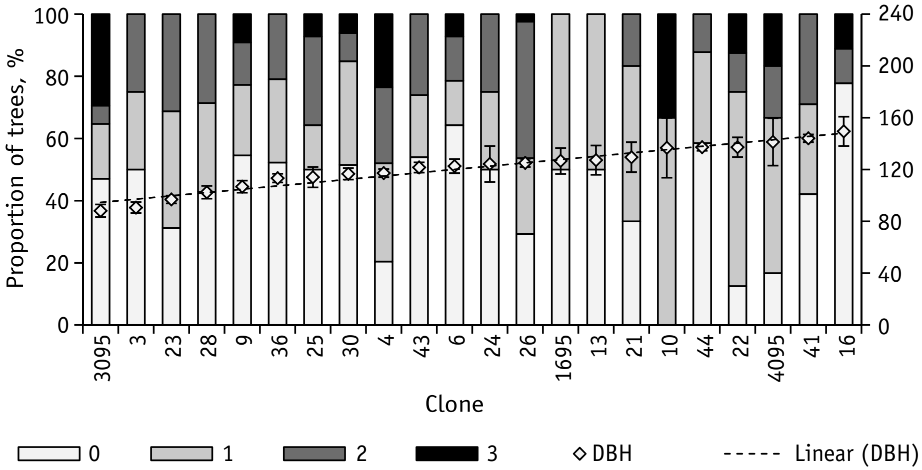

Figure 3. Clonal mean DBH and crack length (both ± confidence interval) and distribution of trees that initially had cracks wider than 1 cm ($Grade_{2013}$ 3) among scar grades ($Grades_{2016}$; 0–3) according to clones.

affected by crack grade ($Grade_{2013}$), but not by tree DBH in the year of scar assessment and relative DBH increment (both $p > 0.05$). Thus, results suggest that tree dimensions and radial increment after crack occurrence had no effect on scar development.

Our results show some disagreement with other studies which have found positive correlation between radial tree growth and wound closure (Neely, 1979; Vasiliauskas & Stenlid, 1998; Vasiliauskas, 1998). This might be related to relatively narrow wounds in our study in comparison to other studies. We rarely observed cracks wider than 3 cm, while Neely (1979) had wounds at least 2.5 cm and wider, Vasiliauskas & Stenlid (1998) had wound width from 6.3 to 46.8 cm, but Vasiliauskas (1998) had mean wound width 11.6 ± 6.3 cm.

Clone and crack width ($Grade_{2013}$) had significant (both $p < 0.001$) effect on scar grade ($Grade_{2016}$). For instance, proportion of trees that initially had crack wider than 1 cm ($Grade_{2013}$ 3), but the crack was uniformly healed three years later was from 0 to 77.8% between clones (Figure 3). But proportion of trees that initially had crack wider than 1 cm and it was still open three years later, was from 0 to 33.7% between clones (Figure 3). No pattern between clonal DBH and distribution of trees among scar grades ($Grades_{2016}$) was found for trees that initially had the widest cracks (Figure 3). Also no relation (all $p > 0.05$) was found between clonal mean DBH and proportions of trees evaluated by any of scar grades ($Grades_{2016}$). Similar observations are done by Shigo *et al*. (1977) – six month after wounding by drill nine clones of *P. deltoides* W. Bartram ex Marshall × *P. trichocarpa* Torr. & Gray had different patterns of wound occlusion regardless of tree size and radial growth, suggesting genetic control of this process.

Crack length ranged from 9.3 ± 3.9 cm to 42.2 ± 14.5 cm for different clones, not reaching the size found in other studies – up to 2m (Christersson, 2006).We found relation between clonal mean crack length and proportion of trees that initially had the widest cracks ($Grade_{2013}$ 3) but three years later were evaluated by $Grade_{2016}$ 0 and 1 – clones that had longer cracks had higher proportion of trees with visible scar ($Grade_{2016}$ 1; $rho = 0.49$, $p = 0.02$) and lower proportion of trees with uniformly healed scar ($Grdae_{2016}$ 0; $rho = 0.52$, $p = 0.01$). Yet, both had large variation for a given mean crack length. No relation ($p = 0.39$) was found between clonal mean crack length and proportion of trees with initially widest ($Grade_{2013}$ 3) crack that still was unhealed ($Grade_{2016}$ 3). Previous results (Zeps *et al.*, 2016, in prep.) showed significant relation between clonal mean DBH and crack length, although large variation of mean crack length was found for clones with largest DBH. Therefore, our results suggest that fast radial growth and successful wound occlusion are not mutually exclusive traits and clone selection by DBH will not have significant effect on proportion of damaged trees that have healed cracks three years after crack occurrence.

Yet, any type of wounds expose wood and *Populus* species and hybrids are susceptible to fungal infections (Laflamme, 1979; Chakravarty & Hiratsuka, 1992; Ullah, 2012; Johansson, 2013; Zeps *et al.*, 2016). Therefore, formation of cracks should not be ignored during clone selection, until further studies had been carried out to assess the impact of this type of damages to probability of fungal infections and consequently to stem-wood quality.

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