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Thinning effects on growth and occurrence of rotting in aspen stands

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Abstract: Poplar species such as aspen (*Populus tremula* L.) play a very important role in the forest formation process not only in Eastern European regions. Unfortunately, such aspen stands are often severely affected by fungal diseases, causing mainly core rot. In this study, the indirect effects of thinning on the phytosanitary condition of aspen by promotion of tree growth were investigated. Two thinning methods, manual (thinning from below) and mechanical thinning (schematic), were applied to young stands dominated by Eurasian aspen to study their effects on tree growth and health. All trees were measured at breast height and diameter frequency distribution was determined twice, i.e. three and 24 years after the beginning of the experiment. In addition, during the second measurement, tree-ring samples were obtained from individual trees to evaluate growth and wood decay damage. Neither manual nor mechanical thinning of aspen significantly increased its growth at the stand level, but positive effects on individual trees were observed in plots where mechanical thinning was applied. The thicker the trees, the less decayed they were. The analysis suggests that thinning in general should not be used to increase stand production, but the positive effects of mechanical thinning on individual aspens can be recommended to promote the growth of individual vigorous trees.

Keywords: clear-cutting; core rot; mechanical thinning; *Populus tremula* (L.); thinning from below; tree-ring analysis

Eurasian aspen (*Populus tremula* L.) is a fast-growing broadleaved tree species which is native to the colder temperate and boreal zones of Europe and Asia (Caudullo, de Rigo 2016). Aspen is a pioneer tree species and is therefore most abundant among young successional stands, e.g. following large-scale perturbations such as forest fires and clear-cutting (Myking et al. 2011). Aspen is propagated by both vegetative and seed reproduction, although the sexual propagation is reported to be of marginal importance (Worrell 1995; Latva-Karjanmaa et al. 2003). Young trees up to 5–6 years old are capable to produce shoots from stumps, while shoots from shallow roots are the most important medium for vegetative propagation, and several hundred suckers can be developed from the roots of a single individual tree (Worrell 1995). It is well known that in the last 30 years, there has

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been an increasing interest in the management of broad-leaved species (Johansson 2013) and, in general, fast growth, ability to reproduce successfully by seeds and rootstocks, relatively undemanding nature of environmental conditions combined with a high quality of physical and mechanical properties of healthy wood, allow to consider aspen as one of the important tree species for this purpose.

Aspen plays an extremely important role in the forest formation process in Eastern European regions of Russia such as the Republic of Tatarstan. Here, aspen is one of the fastest-growing tree species, with stands maturing 2–2.5 times faster than oak or coniferous tree species. Aspen timber is highly demanded as construction wood and ornamental material, as well as a source for furniture, cellulose and matchmaking (Chernov 2015). Unfortunately, however, these aspen stands are strongly affected by fungal diseases primarily causing heart rot, having negative economic consequences. In Finland, where *P. tremula* is the fifth most common tree species (Heräjärvi, Junkkonen 2006), the fungus *Phellinus tremulae* (Bond.) Bond. et Boriss. is present in almost all aspen populations and is the main and nearly sole reason for the phenomenon that nearly every adult aspen trunk shows heart rot (Niemelä, Kotiranta 1982). A survey on 37–49-year-old aspen stands in Latvia revealed that about 80% of trees were infected as well (Smilga 1995). According to studies of the geographical distribution of *Ph. tremulae* by Niemelä (1974), the fungus is considered one of the most serious parasites of European and American (quaking) aspen (*Populus tremuloides* Michx.) and one of the most dangerous polyporous pathogens of hardwoods across the northern temperate and boreal zones.

Numerous studies explored the potential of active management to counteract adverse effects of the fungus, for example, selection of aspen by morphological traits like bark colour (Scherban 2000; Eliseev, Ermolin 2009; Chernov 2015), selection of more resistant female trees (Vihrov et al. 1966), sourcing and breeding of triploid aspen (Garipov 2014), as well as estimating the most suitable felling age (Vihrov et al. 1966; Baranchugov 1995; Scherban 2000; Garipov, Puryaev 2017). It was demonstrated that, amongst others, the resistance of aspen to heart rot also depended on the number of generations. Whereas stands from seed generation as well as the first and second generations from sprouts were infested (relatively) little, the following generations are severely damaged (Scherban 2000; Hayrov 2012). Furthermore, many studies also showed the importance of soil conditions for the health of aspen trees. They reported that the phytosanitary condition of aspen forests decreased on water-logged soils, while more fertile soils supported more healthy aspen (Gazizullin et al. 1993; Baranchugov 1995; Scherban 2000; Hayrov 2012).

What is actually not well studied is the indirect effect of thinning on the phytosanitary condition of aspen stands by promoting tree growth. The rate of rot development was reported to depend on the growth rate of aspen (Vihrov et al. 1966), suggesting that thinning as a management action could help to reduce the risk of fungus manifestation. Studies of aspen thinning suggested that removal of up to 20–25% (of total standing stock) increased the diameter growth of aspen, whereas more intense thinning treatments did not result in a further increase (Georgievsky 1957) and thinning of aspen stands does not prove to be economically viable, which was also confirmed by some studies (Jones et al. 1990; Bella, Yang 1991). Concurrently, Smilga (1995) argued that thinning might promote the growth of healthy stems in the shortest period of time. To look further into this problem, in the late 1990s a research team of the All-Russian Research Institute of Silviculture and Mechanization of Forestry (ARRISMF), led by Barantchugov, started their investigations. Based on long-term studies in aspen forests of the Middle Volga region, they showed that aspen was already affected by heart rot before the harvesting age of 40 years, at the age of 50 years every third tree was infected and after 63 years every second was damaged. The obtained results prompted additional field experiments in the Republic of Tatarstan including different types of thinning to study the effects on wood quality and tree health of aspen (Baranchugov 2001).

The current study aims to further exploit the scientific potential that the experimental sites have to offer. Research objectives are (*i*) to quantify the effects of thinning on the diameter growth of aspen, (*ii*) to analyse thinning effects on wood quality and wood rot, and (*iii*) to determine differences in response between different thinning types (i.e. manual vs. mechanical) and intensities. Thereby, this study will make a contribution towards understanding the response of wood rot

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to thinning in aspen. Results will be discussed in combination with the data obtained from other studies on trembling or quacking aspen (*Populus tremuloides* Michx.).

MATERIAL AND METHODS

Study area. The study was conducted in the physical-geographical region 'Predkamje' in Tatarstan at two sites within the forest districts Kama and Mamadysh, hereafter named site A and B (Figure 1).

In the region, aspen covers about 9.6% of the forest area. The climatic conditions are moderate continental with warm summers and cold-temperate winters. The warmest month is July with an average maximum temperature of 25 °C, the coldest month is January with an average minimum temperature of –7 °C. The duration of a warm period with a stable temperature above 0 °C varies between 198 and 209 days; total annual precipitation sums up to 460–540 mm. Soils of Predkamje vary from Leptosol to Phaeozem, whereby the soils of the investigated plots can be characterised as Phaeozem.

Both study sites are dominated by *P. tremula* (> 95% basal area) with individual trees of *Acer platanoides* (L.), *Betula pendula* (Roth), *Tilia cordata* (Mill.), and *Ulmus glabra* (Huds.) admixed. Forests in this region are managed using a clear-cutting method with a rotation period of about 40 years. After clear-cutting, stands are rejuvenated through the process of natural regeneration mostly by root suckering. Since the last clearcuts in 1982 (site A) and 1979 (site B), the research sites were not managed until autumn 1997. That year, Baranchugov set up a thinning trial with control and two types of thinning measures: (*i*) manual thinning from below with 30 to 50% of the *P. tremula* stem number removed [treatment tfbelow; according to Barantchugov: felling of trees with the least diameter at breast height (*DBH*) (i.e. most trees with *DBH* smaller than 6 cm) including accumulation of the felled trees at the place of felling (Baranchugov 2001)] and (*ii*) schematic mechanical thinning with 64% of all trees of the plot area removed (treatment tmechanic), using a three-meter-wide roller chopper [lightening roller for silvicultural applications (KOK-2, Russia)] which travelled through the stand in a grid-wise pattern, leaving 4.7 m × 4.3 m spots which corresponded to about 36% of the previous stand area that was left untreated. See results (Table 1) for the proportion of basal area (*BA*) corresponding to the aforementioned stem numbers.

Study site A consists of four different plots: two tfbelow plots and two control plots (Figure 2A). The plot area varies between 0.25 and 0.3 ha. The age of aspen at the time of treatment was 15 years (time after the last clearcut). Site B consists of six different plots: three tfbelow, two tmechanic and one control (Figure 2B). The plots have an area of 0.25 ha each. The age of aspen in autumn 1997 was 18 years. Thus, the experiment is not per-

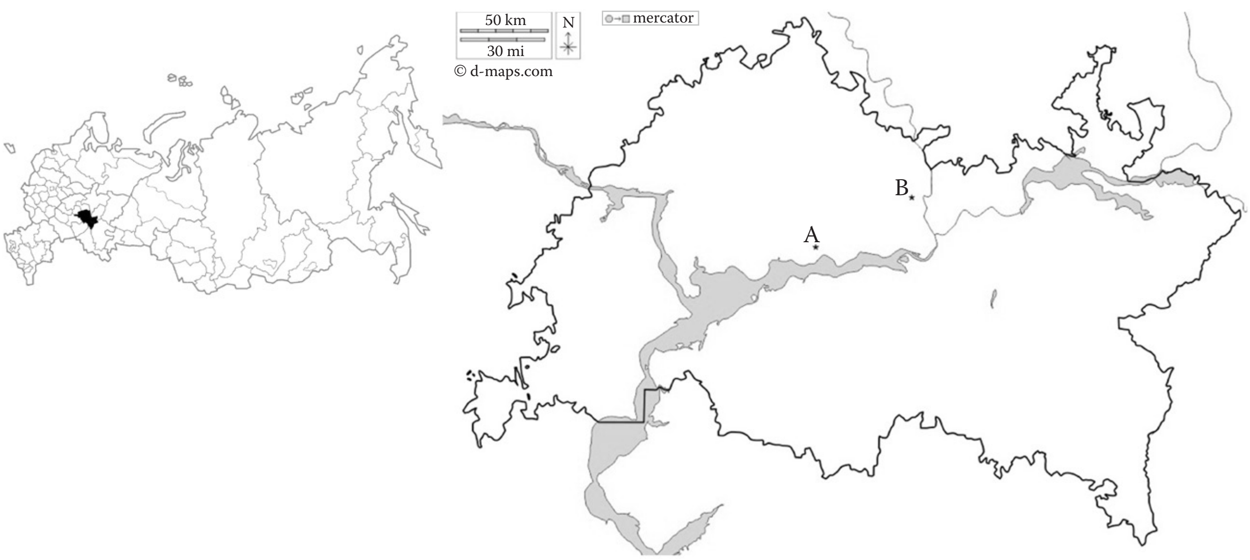

Figure 1. Map of the research area with the study sites A (Kama) and B (Mamadysh) indicated

The inset map of Russia shows the location of the Republic of Tatarstan in black

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Table 1. Data from 2000 and 2021 for basal area (*BA*), where *BA*7 includes numbers for all trees with *DBH* from 7 cm onwards and *BA*3 for all trees from 3 cm onwards

Site	Treatment	*BA*7_2000 (m^2)	*BA*3_2000 (m^2)	*BA*7_2021 (m^2)
A	control	20.5	23.5	19.3
A	tfbelow	14.9	15.6	28.4
B	control	15.4	19.1	28.1
B	tfbelow	15.4	17.1	31.5
B	tmechanic	6.3	7.7	30.7

Control – control treatment; *DBH* – diameter at breast height; tfbelow – thinning from below; tmechanic – mechanical thinning

fectly balanced. However, control plots on both sites allow for testing of site effects. This was done during the tree-ring analysis (see part 'Response of growth to thinning').

Measurements. The first data collection was performed in 2000. All living individual trees were calipered at breast height (1.3 m) and diameter frequency distributions were established. These original data were obtained from the archive of ARRISMF for the present analysis.

In August 2021, we studied the same plots and measured the diameter at breast height (*DBH*, cm) and tree height (m). All living trees with *DBH* from 7 cm onwards were calipered. Tree height was measured using a Vertex clinometer (Haglöf Sweden AB, Sweden) on two randomly selected trees for five diameter classes: trees with a *DBH* of up to 10, 15, 20, 25, and 30 cm.

Tree-ring analysis. Tree-ring samples of 91 trees belonging to the 10% thickest trees in any single plot at the two sites were collected in August 2021. More specifically, two 5.2-mm increment cores were taken per tree at breast height with a Haglöf increment borer (Haglöf Sweden AB, Sweden), resulting in a total number of 182 cores. Per plot, 10 aspen trees were sampled, whereby the two control plots at site A were treated as one, as the boundary between the two controls was previously not well signed (Figure 2). After sample collection, cores were air dried and glued on wooden holders, whereafter the surface of the cores was prepared with a WSL Core Microtome (WSL, Switzerland) (Gärtner, Nievergelt 2010) to highlight annual rings. Cores were then digitalised using an ATRICS system (Levanič 2007). Measurements of tree-ring width were directly done on the resulting digital images and crossdated visually and statistically using the CooRecorder/CDendro software (Version 9.6.3., Cybis Elektronik & Data AB, Sweden).

Wood rot analysis. Wood cores from a tree trunk can be studied for discolouration or decay

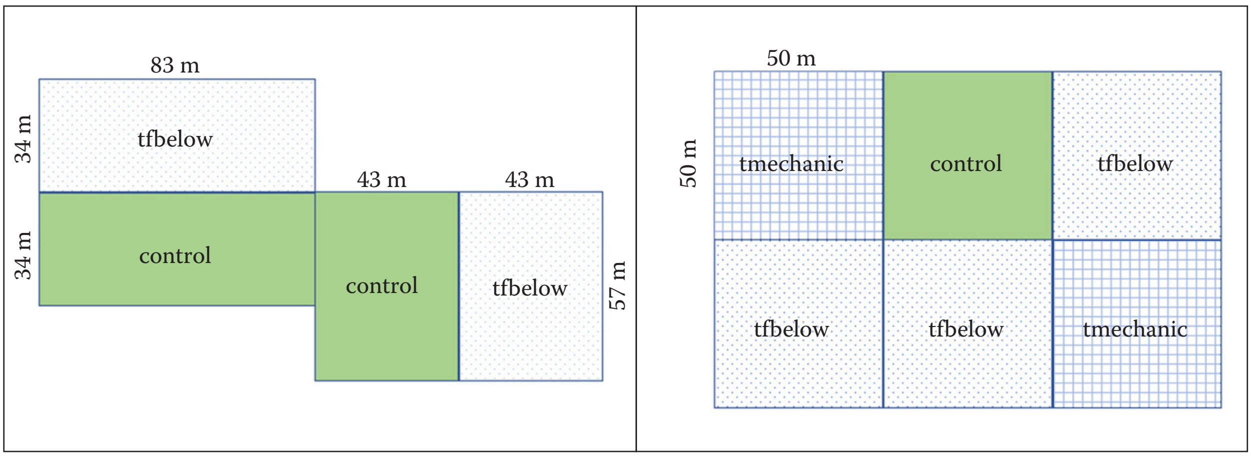

Figure 2. Experimental design of trial plots at the study sites A (Figure 2A) and B (Figure 2B)

Control – control treatment; tfbelow – thinning from below; tmechanic – mechanical thinning

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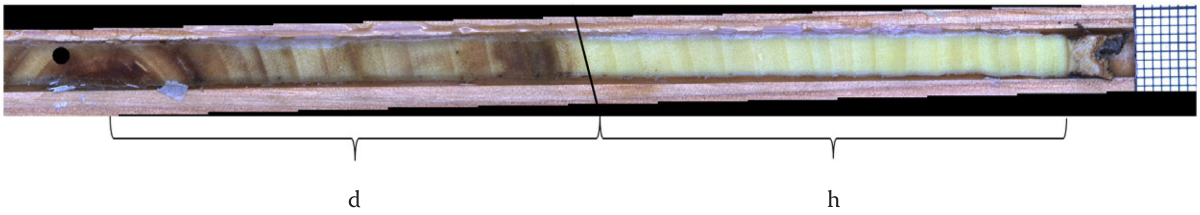

Figure 3. Digital image of an increment core with fungal damage towards the pith

d – damaged wood; h – healthy wood

along the wood cross-section (Soge et al. 2020). The discolouration of core samples was measured visually using CooRecorder (Figure 3). The boundary of fungal damage (last rotten ring) was defined for all 182 core samples and included in the statistical wood rot analyses of the investigated sites.

Statistical analysis. According to West et al. (2014), linear mixed modelling (LMM) is a parametric linear model for clustered, longitudinal or repeated data that identifies the relationship between a continuous dependent variable and various predictor variables. We used this approach to analyse our data.

To demonstrate thinning treatment effects, the tree-ring widths of the core samples were taken as longitudinal data. When modelling the increment of stem diameter in time series (radial growth), we generally followed Zeide (1993) and Schröder et al. (2002), that is, we utilised an age-independent linear approach in a mixed model framework. Thus, we established a time series of diameter outside bark. To test the hypothesis that tree growth differs between variants after the date of treatment by the most parsimonious approach, we fitted a 'segmented' model (Fortin 2014), which divides the data into two segments regarding time. Location of the joint was the year 1997, i.e. the year before treatment. The period whose annual rings were analysed after the intervention was 13 years long. After 2010 (i.e. 1997 + 13), the annual ring widths of plants decreased continuously (age trend) so that values were constantly below the mean ring widths before treatment and the clear differences between the treatments disappeared. However, residuals were checked for an effect of year. This was done by computing pairwise multiple comparisons of mean rank sums between year levels according to Dunn. The method for adjusting *P*-values then was the Bonferroni correction. As the residuals of the simple segmented models showed clear effects of year, 'year' was included as a categorical crossed random effect. As the effect of year differed between the two forest districts, the interaction between 'district × year' was accounted for. Corresponding to this, nested random effects were in place for 'tree in plot'.

Akaike's information criterion (*AIC*) and Bayesian information criterion (*BIC*) values were computed and an ANOVA procedure was implemented to test for significant differences between models, e.g. models having different random or fixed effects.

The general model formula was Equation (1):

$$Y = X\beta + u + \varepsilon \tag{1}$$

where:

Y – increment value of diameter;

X – design matrix of the model;

β – vector of estimable parameters;

u – vector of random effects such that $u \sim N(0,\sigma_u^2)$;

ε – vector of the residuals such that $\varepsilon \sim N(0,\sigma_\varepsilon^2)$;

$\sigma_u^2, \sigma_\varepsilon^2$ – variance of the random effects and the residuals, respectively.

The model was formulated as shown in the following Equation (2):

$$\Delta diameter_{i,j,k} = \beta_0 + \beta_1 diameter_{i,j-1} + \beta_2 segment + \beta_{3|4} variant + \beta_{5|6} variant \times segment + \mu_k + \mu_{i|k} + \mu_j + \varepsilon \tag{2}$$

where:

μ_k – random effect parameter relating to the *k*-th plot;

$\mu_{i|k}$ – random effect parameter relating to the *i*-th tree in the *k*-th plot;

μ_j – random effect parameter relating to forest district × year.

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Table 2. Linear mixed modelling (LMM) for tree ring width of stem for period of 1991 to 2010 in relation to diameter at breast height (*DBH*) of previous year and treatment

Parameter	Fixed effect	Parameter	Standard error	*P*-value
β_0	intercept	2.610e+00	2.646e−01	1.87e−13***
β_1	diameter (year −1)	1.134e−03	9.965e−04	0.25570
β_2	segment (after 1997)	−2.728e−02	2.502e−01	0.91399
β_3	variant tfbelow	−2.615e−01	1.503e−01	0.14958
β_4	variant tmechanic	4.998e−02	1.885e−01	0.80158
β_5	segment (after 1997): variant tfbelow	1.870e−01	6.217e−02	0.00266**
β_6	segment (after 1997): variant tmechanic	5.662e−01	8.052e−02	2.61e−12***

** *P*-value < 0.01; *** *P*-value < 0.001; tfbelow – thinning from below; tmechanic – mechanical thinning; the intercept refers to values for the stem of aspen for control plots

As 'variant' has three levels, we need two parameters in addition to the intercept (i.e. control). See Table 2 for the variables, interaction of variables and parameter estimates.

To determine the effect of thinning treatment on wood rot, we computed and analysed diameter (cm), area (cm²), and percentage of area (%) with rot in the cross-section in relation to *DBH* for the three treatment variants. The maximum diameter of the trees, i.e. the condition in 2021, was used for the analysis of the rot data. As all variables of rotten wood mentioned did not show relevant deviation from normal, we applied an LMM again to test the hypothesis that wood rot damage depends on the type of thinning. All cores sampled had signs of rotting. We fitted the LMM using the Restricted Maximum Likelihood (REML) approach. Thus, the type of thinning (tfbelow, tmechanic, or control) and *DBH* are fixed effects. We explicitly considered an interaction effect between the *DBH* and the thinning variant on the dependent variable. Plot (9 plots) and tree (91 individuals) are nested random effects.

The model reads as Equation (3):

$$Y_{i,k} = \beta_0 + \beta_1 DBH_{i,k} + \beta_{2|3} variant_k + \beta_{4|5} DBH_{i,k} \times variant_k + \mu_k + \varepsilon \quad (3)$$

where:

- Y – dependent variable (i.e. 'area of the rotten part of the trees basal area' or 'percentage area of the rotten part of the trees basal area', respectively);
- i – index denoting the tree;
- k – index denoting the plot;
- μ_k – random effect parameter relating to the k-th plot.

As 'variant' has three levels, we need two parameters in addition to the intercept (i.e. control).

The Satterthwaites method was implemented for approximating degrees of freedom for the *t*-tests.

Statistical analyses were carried out using the open-source software R (Version 4.2.0, 2022), packages lattice (Sarkar 2008) and lme4 (Bates et al. 2015). Graphics were made using R statistical software and sjPlot (Lüdecke et al. 2021).

RESULTS

Diameter frequency distribution. The data for total basal area are shown in Table 1.

In 2000, the control variant on site A had the highest basal area (20.5 m²); the tfbelow variant had a stocking index relative to the control of 0.73. On site B, the control had the highest *BA* as well (15.4 m²). However, the tfbelow variant had a stocking index relative to the control of 1.0. The treatment of thinning from below was thus detectable only in the *BA* of trees thinner than 7 cm *DBH*. Taking these trees into account as well, the stocking index relative to the control is 0.9. The tmechanic variant had a stocking index relative to the control of 0.4.

In 2021, all variants had a *BA* higher than 28 $m^2 \cdot ha^{-1}$ with the exception of the control variant on site A (19.3). The control variant on site A thus had a lower *BA* in 2021 than the corresponding tfbelow variant. However, also on site B the control variant has a lower *BA* than both the variants tfbelow and tmechanic.

The distributions of tree diameters shortly after the thinning treatment in 2000 show no ma-

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jor differences between treatments (Figure 4). In 2021, three features of the diameter frequency distributions seem remarkable: The distributions cover a much wider range of diameters than those in 2000, the distributions on site A (Kama) seem to be truncated at diameters lower than 12 cm and the distributions on site B (Mamadysh) for tfbelow and tmechanic in particular show some exceptionally large diameters. The thickest trees (*DBH* 45–47 cm) were observed in the tmechanic variant.

Response of growth to thinning. The tree-ring width of aspen before thinning varies between 2.2 mm and 4.2 mm per year (Figure 5). No significant effect of site was detected (test results not shown); however, site B which hosts the tmechanic treatment had a slightly lower ring width than site A. This is important when the effects of tmechanic are discussed in relation to control.

No significant differences were found between growth before and after the intervention, taking the control as a reference. The period after 1997 has the same increment compared to before 1997 (Table 2; the parameter for 'segment after 1997' is insignificant). The treated variants do not show significant differences in growth to the control in general during the entire observation period. However, looking at the parameters for 'interaction of variant with segment', the two variants tfbelow and tmechanic show significantly higher increment after treatment in 1997 than the control. The parameter for tmechanic is three times as large as that for tfbelow.

The annual rings after 1997 reached a mean ring width of 2.7 mm per year in the control, 2.7 mm

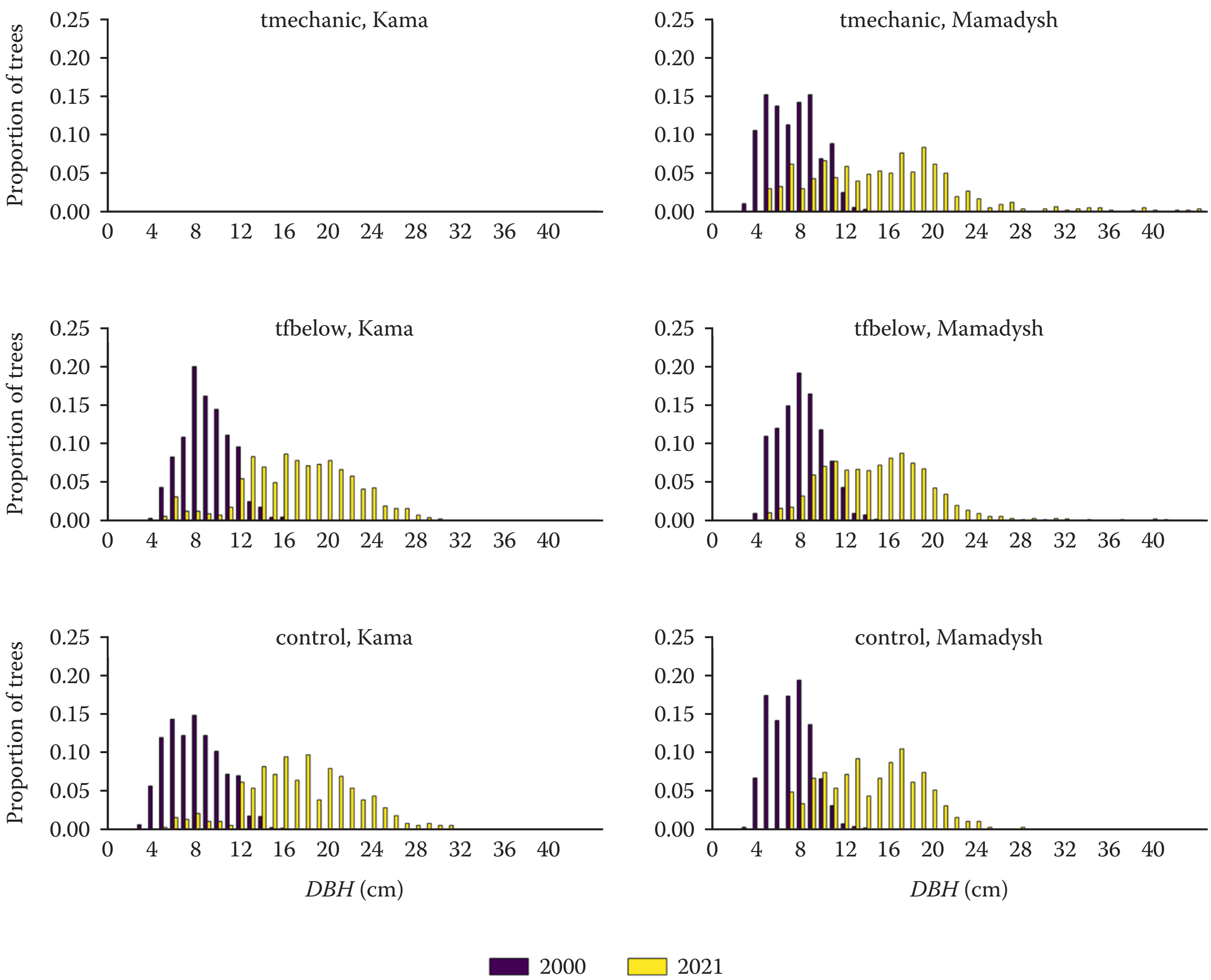

Figure 4. Diameter distributions for site A (Kama, left) and site B (Mamadysh, right) sites in 2000 and 2021

Control – control treatment; *DBH* – diameter at breast height; tfbelow – thinning from below; tmechanic – mechanical thinning; at site A no mechanical thinning was performed

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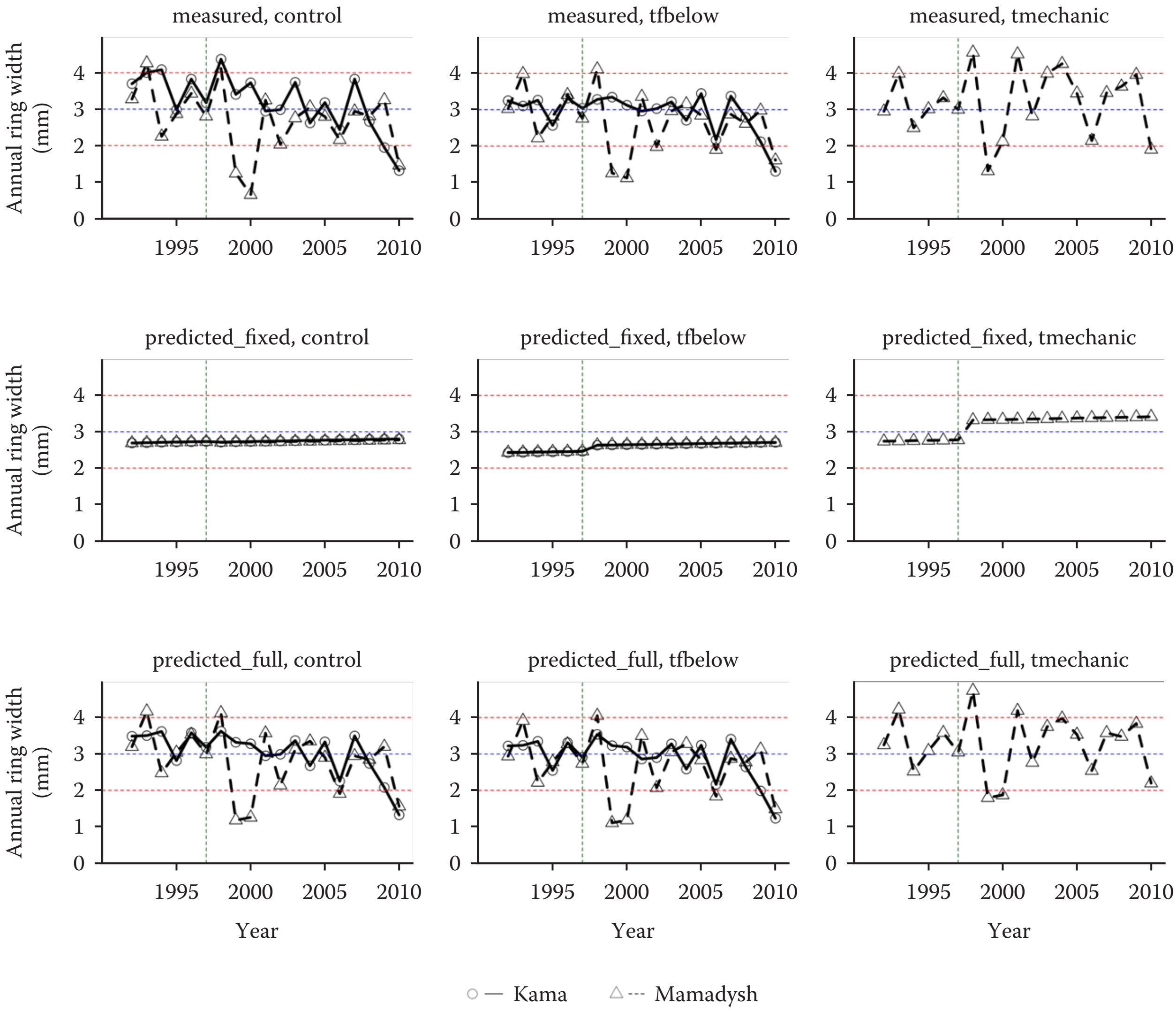

Figure 5. Tree-ring width of aspen in the period 1991 to 2010

Control – control treatment; tfbelow – thinning from below; tmechanic – mechanical thinning; the sections 'measured' and 'predicted_full' take into account the random effect of the year; the section 'predicted_fixed' shows the trend of fixed effects only; the graph is separated by treatment type; the dashed vertical line indicates the time of thinning in autumn 1997

per year in tfbelow plots and 3.4 mm per year in the variant tmechanic (Figure 5). In addition, site B shows the smallest ring width in the years 2000 and 2010; site A in 2010.

Diameter and degree of rotting. Mean diameter of trees in the samples of 2021 are 24.0 cm, 22.8 cm and 25.2 cm for control, variant tfbelow and variant tmechanic, respectively. Analysed trees have diameters between 18 cm and 30 cm in all variants (Figure 4), mean diameters of analysed trees are not significantly different between the variants. The degree of rotting in the core samples ranged from 10% to 53%, i.e. every core taken had signs of rotting.

The first model analyses the absolute area of the rotten part as a function of *DBH* and variant and the second model analyses the proportion of rotten area in the cross-section in relation to *DBH* and variant (Table 3). In principle, both effects of variant and *DBH* on the dependent variables cannot be assessed in isolation, as the interaction between *DBH* and variant tmechanic is significant in both models.

Figure 6 shows that starting from a diameter of approximately 23 cm onwards, the rotten area in square centimetres and the proportion of rotten area of the cross-section of DBH is significantly lower for variant tmechanic than of the control variant.

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Table 3. Linear mixed modelling (LMM) values for wood rot damage in relation to radial growth of trees from plots with different thinning methods (variants tfbelow and tmechanic); reference is a control without thinning

Variant	Parameter	Fixed effect	Parameter	Standard error	*P*-value
Absolute area of rot	β_0	intercept	–271.340	69.205	0.00013***
	β_1	*DBH*	17.300	2.789	3.88e-09***
	β_2	variant tfbelow	120.883	80.479	0.13502
	β_3	variant tmechanic	371.545	87.671	4.03e-05***
	β_4	*DBH* × variant tfbelow	–5.069	3.287	0.12491
	β_5	*DBH* × variant tmechanic	–16.019	3.441	6.36e-06***
Proportion of rotten area in cross-section	β_0	intercept	0.104489	0.137997	0.450046
	β_1	*DBH*	0.008430	0.005538	0.129760
	β_2	variant tfbelow	0.240309	0.160479	0.136239
	β_3	variant tmechanic	0.542165	0.175245	0.002384**
	β_4	*DBH* × variant tfbelow	–0.009996	0.006525	0.127341
	β_5	*DBH* × variant tmechanic	–0.023271	0.006841	0.000828***

** *P*-value < 0.01; *** *P*-value < 0.001; control – control treatment; *DBH* – diameter at breast height; tfbelow – thinning from below; tmechanic – mechanical thinning; the intercept refers to gradient difference released for the control variant

Below this threshold diameter, the opposite is true. The threshold of 23 cm of DBH is close to the mean of the sampled trees. In combination, the proportion of rotten area decreases with increasing diameter in variant tmechanic (see Table 3; fixed effect of interaction DBH × variant tmechanic).

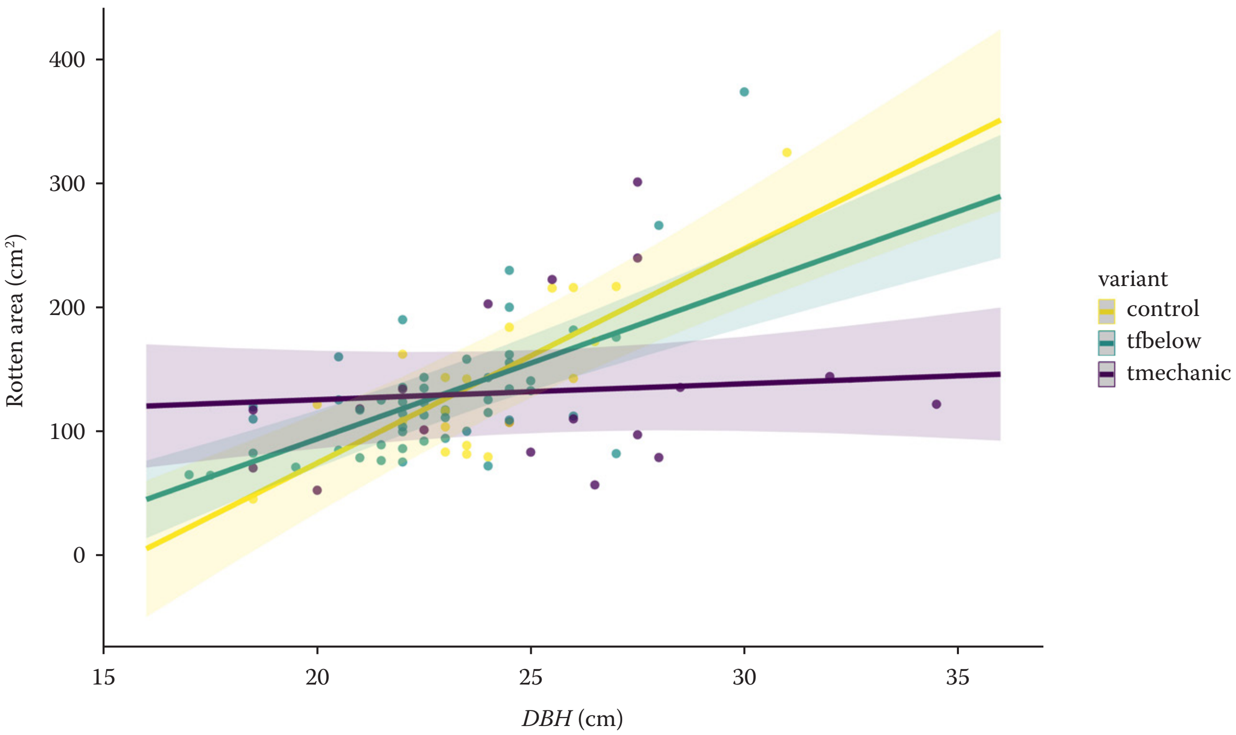

Figure 6. Prediction of linear mixed modelling (LMM) for the proportion of rotten area in the cross-section over diameter at breast height (*DBH*)

Control – control treatment; tfbelow – thinning from below; tmechanic – mechanical thinning; the different treatments are distinguished by colour; confidence bands show predicted values conditioned on fixed effects only

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DISCUSSION

Growth response analysis. The tree-ring widths of the core samples were used as longitudinal data to show the effects of the thinning measures. Core samples are most applied to determine the age and growth of trees, and for most species, the rings on a well-prepared core can be easily determined (Maeglin 1979). Commonly discussed in all dendroecological studies is how tree rings reflect the growth responses of trees to environmental conditions, including thinning effects (Spiecker 2002; Grundmann et al. 2008; Bowman et al. 2013).

To analyse and interpret a growth response of young trees a few years after a radical change in environmental conditions, (static) growth variables and (dynamic) increment parameters need to be analysed separately (Weidig, Wagner 2021). Growth variables are recorded annually to reflect a current growth pattern which is highly sensitive to environmental effects and possible changes in the surrounding area (Dittmar et al. 2003; Eichhorn et al. 2008; Grundmann et al. 2008) and is suitable for the identification of short-term growth responses (Collet et al. 2001). In contrast, static growth parameters summarise the cumulative growth during a tree's life and show effects on individual stands in the context of this study.

Diameter growth and temporary effect of thinning. Our data for basal area (Table 1) show that the control on site A clearly had the highest basal area in 2000 and it is well known that in dry years under such conditions it is mainly the weaker trees that die (because of the high competition); in 2021 in both treatments (control and tfbelow) on site A practically all trees with a diameter of less than 12 cm were lost – i.e. the weakest ones. This can be well understood as a drought effect (in 2010, see also Figure 5). But it is very difficult to express this effect exactly in terms of m² of basal area loss. On site B, the same process of dying of small trees due to drought and competition seems to happen on a low level only in the control plot (trees < 7 cm are missing here). In contrast, tmechanic plots have kept very weak specimens (5 cm). This is typical of small basal areas when the competition between the trees is low. It is worth noting (Table 1) that *BA* in 2021 is similar in all treated variants (i.e. > 28 m²), indicating a strong growth response in these stands where up to 60% of *BA* was removed 20 years earlier (i.e. tmechanic). From the static growth variables (i.e. the *DBH* distributions) a remarkable thinning effect might be derived by some large *DBH* in the tfbelow and the tmechanic variant on site B which is not obvious on site A (Figure 4).

We set up a LMM to calculate aspen growth and the effects of different methods of thinning. The analysis revealed that both thinning methods had a positive effect deviating from the untreated control. However, this effect was most pronounced in tmechanic. In addition, a distinction must be made between the stand-based and tree-based perspectives. When a stand-wise perspective is taken (diameter distribution, Figure 4), manual thinning from below to remove individual trees in young dense stands, as was done in the present study, is not feasible in practice as it is labour-intensive with no or a weak stand response, making this method unprofitable. Bella and Yang (1991) evaluated the profitability of thinning young trembling aspen (*P. tremuloides*) in boreal forests of western Canada and advised against the thinning of young stands. Since the American taxon *P. tremuloides* and its close Eurasian relative *P. tremula* are considered to be either sister species (Cervera et al. 2005; Pakull et al. 2009; Grant, Mitton 2010) or conspecific subspecies (Eckenwalder 1996), we compared the experiments involving the two relatives coming to a similar conclusion that thinning is only justified when treatment costs are low and timber costs are high. In their experiments with *P. tremuloides*, Rice et al. (2001) showed that 15 to 17 years after treatment, gross total volume (*GTV*) was the highest in unthinned plots, decreased as residual tree spacing increased, and gross merchantable volume (*GMV*) did not vary significantly in all but the oldest stand. The results of their study do not support the use of pre-commercial thinning to increase aspen fibre yield.

When a tree-wise perspective is taken (Figure 5), our results show that individual trees do benefit from the roller chopper treatment which can be regarded as a heavy impact. Between 1997 and 2021, we measured an average annual ring width of 3.4 mm which is 0.7 mm more compared to the 2.7 mm of the control plots. In other words, within 13 years the trees subjected to the roller chopper treatment gained 18.2 mm (13 mm × 0.7 mm × 2 mm) in diameter width compared to the trees without the treatment. Since this observation was made on individuals from the group of the 10% thickest trees, it can be concluded that the mechanical intervention

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in a certain rotation period may increase the diameter of individual trees (see also Figure 4).

Additional information concerning Figure 5: The narrow rings of the years 2000 and 2010 on site B and of 2010 on site A were formed in years with warm and (or) dry conditions (2000 and 2010, respectively). The drought of 2010 was very drastic in the Republic of Tatarstan (Singatullin 2018).

Effect of thinning on rot infestation. The degree of rot infestation was easily detectable in the core samples, confirming that in addition to the thinning effect evaluation (Spiecker 2002; Bowman et al. 2012), analysis of increment cores allows a fast and simple examination of different wood compounds (Vroblesky 2008) as well as a visual quality evaluation of rot damage (Soge et al. 2020).

The most important result is that the thicker the aspen trees in the tmechanic plots (*DBH* ≥ 28 cm), the lower the proportion of rotten area at breast height is. This effect was not significant in the variant with manual thinning, where annual growth did not increase on the most vital trees as much as in the plots with mechanical thinning. The data obtained also support the theory of Vihrov et al. (1966) that the rate of spread of heart rot in the trunks of growing aspens depends, among other factors, on age and growth rate (assuming that the thickest trees also have the highest growth rate).

Feasibility. The diameter distribution data of 2021 show no major differences between thinned and not thinned plots, where the removal of aspen ranged from 10% to 30% of *BA* (Figure 4), in 1997. However, a positive effect of thinning was observed for individual trees with large diameters in tmechanic and tfbelow plots at site B (Figure 4). In addition, trees in the tmechanic plots grow faster than the fungal growth in the stems resulting in less rot damage (Figure 6). The diameter distribution and our diameter-ring width prediction model show a relevant thinning effect only among individual trees and not in aspen stands in general. The rot damage evaluation indicates that the thicker *P. tremula* trees (*DBH* ≥ 28 cm), the less rotted they are, which was again only significant in mechanically thinned plots. The analysis of *P. tremuloides* showed a similar trend and does not support the use of thinning to increase the fibre yield of aspen, but recommends it to maximise the growth of single trees (Rice et al. 2001).

The relevance of our findings therefore depends on the aim of aspen management. Light, soft wood shrinks just barely, with high qualities used for lumber and matchwood. Aspen wood is used for the manufacture of pulp and paper, chosen for its easy delignification, bleaching and especially favourable characteristics for writing paper, and is also utilised for plywood, various types of particleboards and flakeboards (von Wühlisch 2009) and is an important tree species for wood modification developments, e.g. thermowood (Homan, Jorissen 2004; Militz 2020). Aspen also plays an important role in the production of wood for renewable energy (Caudullo, de Rigo 2016). In timber production, large and healthy individual trees are of great relevance and the use of mechanical thinning in aspen stands could be economically attractive. Hence, mechanical thinning may be interesting to produce healthier wood in a short time, as we illustrated in our prediction of LMM for the proportion of rotten area (Figure 6). This concept of improving the diameter growth of selected individuals is also used in crown thinning (synonymous 'thinning from above'). According to Smith et al. (1997), in crown thinning, trees are removed from the upper crown classes in order to open up the canopy and favour the development of selected trees of these same classes. Crown thinning is also sometimes called 'low-density thinning' when selected trees are early and heavily released from competition (Guiterman et al. 2011). Because individual aspen trees react positively to thinning, we suppose that thinning from above might be more effective than mechanical thinning.

Thinning of aspen stands does not prove to be economically viable for other uses of aspen that require the whole stand to grow faster (e.g. energy or cellulose production), which was also confirmed by numerous studies (Jones et al. 1990; Bella, Yang 1991; Rice et al. 2001; Fischer 2018).

CONCLUSION

During our study, we were able to record and evaluate the thinning trial started by Baranchugov. This allowed us to expand the knowledge of management measures in rot-damaged aspen stands. Only thinning using a roller chopper has resulted in relevant faster growth of individual aspen (observed for at least 13 years). Our research shows that accelerated growth of individual trees of *P. tremula* has a direct effect on the wood quality, as the fungal rot does not grow as fast as the

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trees do. Stands with a lower rotting degree are able to produce higher volumes of healthy wood, i.e. in our case the mechanically thinned plots (roller chopper), than untreated stands in the same time. Therefore, in observed conditions, we can only recommend mechanical thinning to produce individual vital aspen trees.

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