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ARTICLE

Impact of postfire management on forest regeneration in a managed hemiboreal forest, Estonia[1]

Kristi Parro, Marek Metslaid, Getter Renel, Allan Sims, John A. Stanturf, Kalev Jõgiste, and Kajar Köster

Abstract: Fire is a significant agent for the development of boreal and hemiboreal forests, altering soil and light conditions, affecting seedbanks, and removing seed trees. Burned areas should be managed with care, as inappropriate techniques prolong the regeneration period and reduce the diversity and resilience of stands to disturbances. To study the effects of fire and postfire management on the successional changes in regeneration abundance, species composition and tree height sample plots were established in sandy pine forests in northwestern Estonia on areas burned 2 or 22 years ago. Five types of sample plots were established: (*i*) areas without fire damage, (*ii*) burned uncleared areas, (*iii*) burned forest areas cleared after forest fire, (*iv*) burned uncleared areas with live trees, and (*v*) burned uncleared areas with dead trees. Three main tree species common to hemiboreal forests were analyzed: *Betula* spp., *Pinus sylvestris* L., and *Populus tremula* L. Results showed that clearing burned areas after wildfire significantly reduced the abundance of regeneration compared with burned uncleared areas but favored height growth of *P. sylvestris* in later development. To regenerate and maintain mixed stands after wildfire, retaining some residual trees can facilitate regeneration compared with complete clearing, although a dense stand with live trees or a large amount of deadwood can hinder regeneration.

Key words: wildfire, salvage logging, natural regeneration, diversity, succession.

Résumé : Le feu est un agent important de développement des forêts boréales et hémiboréales; il modifie le sol et la luminosité, affecte les banques de graines et élimine les arbres semenciers. Les aires brûlées doivent être aménagées avec soin puisque des techniques inappropriées prolongent la période de régénération et réduisent la diversité et la résilience des peuplements aux perturbations. Pour étudier les effets du feu et de l'aménagement après feu sur les changements successionnels dans l'abondance de régénération, la composition en espèces et la hauteur des arbres, des placettes échantillons ont été établies dans des pinèdes sur sols sablonneux ayant brûlées 2 ou 22 ans auparavant dans le nord-ouest de l'Estonie. Cinq types de placettes échantillons ont été établies : (*i*) aires exemptes de dommage causé par le feu, (*ii*) aires brûlées avec des arbres vivants ou morts non récupérés après le feu, (*iii*) aires brûlées où tous les arbres vivants et morts ont été récoltés après le feu, (*iv*) aires brûlées avec des arbres vivants non récupérés et (*v*) aires brûlées avec des arbres morts non récupérés. Trois espèces d'arbre communes aux forêts hémiboréales ont été analysées : *Betula* spp., *Pinus sylvestris* L. et *Populus tremula* L. Les résultats montrent que les aires brûlées et récupérées après le feu étaient associées à une abondance de régénération significativement plus faible que les aires brûlées non récupérées, mais à une plus forte croissance en hauteur de *P. sylvestris* au cours des stades plus avancés de développement. Pour régénérer et maintenir des peuplements mixtes après un feu, la rétention de quelques arbres résiduels peut faciliter la régénération comparativement à une récupération complète, quoiqu'un peuplement dense avec des arbres vivants ou une grande quantité de bois mort puisse nuire à la régénération. [Traduit par la Rédaction]

Mots-clés : feu de forêt, coupe de récupération, régénération naturelle, diversité, succession.

Introduction

Fire plays an important role in the development of boreal and hemiboreal forests (Angelstam 1998) by altering physical, chemical, and biological conditions (Den Herder et al. 2009). Wildfire can have severe negative effects by removing aboveground vegetation, consuming soil organic matter, and reducing the seedbank by destroying the viability of stored seeds and removing source trees (Wang 2001). Intense fires that cause overstory mortality and alter light conditions, however, can create more diverse landscapes with new habitats by releasing growing space and favoring dispersal and establishment of shade-intolerant pioneer tree species to burned areas (Hart and Chen 2008).

The severity of wildfire affects the amount of remaining live and dead trees, which influences the susceptibility of tree seedlings to unfavorable weather and environmental conditions, as well as competition from vegetation or ungulate damage (Lilja-Rothsten et al. 2008). Standing and downed dead wood in different stages of decay provide suitable microhabitats for regeneration (Lampainen et al. 2004), and decaying trees are important nutrient sources for forests on dry infertile sites (Kuuluvainen and Rouvinen 2000).

Forest management in Estonia over the last 100 years has homogenized the landscape by planting monocultures on clearcut areas, resulting in single-species stands of uniform age over large

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K. Parro, M. Metslaid, A. Sims, and K. Jõgiste. Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Kreutzwaldi 5, 51014 Tartu, Estonia.
G. Renel. Rakvere City Government, Tallinna 5, 44306 Rakvere, Estonia.
J.A. Stanturf. Center for Forest Disturbance Science, USDA Forest Service, 320 Green Street, Athens, GA 30602, USA.
K. Köster. Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Kreutzwaldi 5, 51014 Tartu, Estonia; Department of Forest Sciences, University of Helsinki, Latokartanonkaari 7, FI-00014 Helsinki, Finland.
Corresponding author: Kristi Parro (e-mail: kristi.parro@gmail.com).

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areas. Mixed stands developed only through natural regeneration and without active management such as early cleaning and pre-commercial thinning that would have discriminated against other species. Management objectives have changed in recent years, however, and more diverse stands are desired; nevertheless, timber production remains the primary goal. In northwestern Estonia, on sandy soils, fire has been a natural disturbance for centuries. Fires that do occur are almost all caused by humans and aggressive suppression has contributed to the lack of diversity in today's landscape. Recognizing the desire for more diverse forests, different management approaches are needed to create stands that are more resilient following disturbances (Parro et al. 2009).

There has been little research in Estonia on the combination of fire and postfire forest management even though knowledge about previous fires is supposed to be included in management planning (Wallenius et al. 2004). In Estonia, the normal practice following large-scale disturbances in managed forests is to intervene immediately and clear the stand of all dead and live trees regardless of whether it will be regenerated naturally or planted. In other countries, postfire salvage logging that clears a stand of potential natural regeneration has proven controversial (Lindenmayer et al. 2004).

This study focuses on forest management after fire disturbance and offers approaches that would provide quick regeneration of burned areas and protection for soil, as well as the potential for natural regeneration to increase diversity. We examined different postfire management treatments on two areas following wildfire. We hypothesized that (1) areas without clearing regenerate more abundantly after fire, (2) immediately after wildfire, birch (*Betula* spp.) is more successful in regenerating but over time Scots pine (*Pinus sylvestris* L.) starts to dominate, and (3) height of trees is greater on areas that are cleared after wildfire than on areas with trees left on the site due to lower competition.

Materials and methods

Study site

This study was carried out in two permanent research areas in northwestern Estonia that were damaged by fire: Vihterpalu (59°13′N, 23°49′E) and Nõva (59°10′N, 23°45′E). Estonia belongs to the hemiboreal vegetation zone (Ahti et al. 1968) where the average annual temperature is +5.2 °C. The coldest month is February, with an average temperature of −5.7 °C, and the warmest month is July, with an average temperature of +16.4 °C. The average precipitation is 550–650 mm. Vihterpalu and Nõva forests belong to the *Vaccinium uliginosum* and *Calluna* site types (Lõhmus 1984), with sandy and dry soils.

The distance between the Vihterpalu and Nõva areas is around 10 km. Both sites were covered with planted or sown Scots pine (*Pinus sylvestris* L.) forests originally regenerated after heavy fires in 1940 (Nõva, 300 ha burned) and 1951 (Vihterpalu, 2000 ha burned). Productivity in these forests was low, and stands were in the lower site-quality classes. The stands had not been thinned before recent wildfires occurred. There are about 150 fires per year in Estonia, with an average size of 4 ha (1992–2012); almost all fires are ignited by humans. Fire occurred in the Vihterpalu study area in 1992 (550 ha burned), when the forest was 52 years old, and fire occurred in the Nõva area in 2008 (800 ha burned), when the forest was 70 years old.

Experimental design

We established 48 permanent sample plots (2.5 × 40 m) in fire-damaged areas to study the effects of fire and management on forest regeneration. Sample plots were established in Vihterpalu ($n = 18$) in 2002 (10 years after wildfire) and in Nõva ($n = 30$) in 2008 (immediately after fire disturbance). Plot locations were selected randomly, with a distance of at least 200 m between the plots. Fire intensity in the overstory and on the forest floor varied within and between the sample plots, creating patches with different damage levels and leaving some scattered live trees. Density of live and dead trees on plots is still changing due to dead trees falling over and live trees dying. Fire removed all ground vegetation and the entire organic layer was consumed, leaving mostly bare mineral soil. Six to 20 years after fire, the organic layer thickness on burned areas was 2.7 to 3.3 cm, whereas on control areas (where no burning had occurred in recent history), the average thickness was 4.4 cm (measured in 2013).

Three types of sample plots were set up in both study areas: (1) control (CO), areas unburned and with no harvesting carried out (six plots in Vihterpalu, stand age at the time of CO establishment was 52 years; six plots in Nõva, stand age at the time of CO establishment was 68 years); (2) burned and uncleared (BU), areas without management in which both dead and live trees were left on the plots after fire (six plots in Vihterpalu, six plots in Nõva); (3) burned and cleared with salvage logging (BC), areas in which all dead and live trees were harvested from the plot after fire (six plots in Vihterpalu, six plots in Nõva). In addition, at Nõva, we established two additional types of plots: (4) burned and uncleared areas with dead trees (BUD), all trees were dead and left on the plot after fire (six plots); and (5) burned and uncleared areas with live trees (BUA), all trees were live and left on the plot after fire (six plots). These latter plots (BUD and BUA, also CO, BU, and BC plots from the 2008 fire) in Nõva were measured twice, 2 years after the fire in 2010 and 6 years after fire in 2014. Other plots (CO, BU, and BC from the 1992 fire) in Vihterpalu were measured six times, at the end of growing season at 2-year intervals from 2004 to 2014. Abundance of natural regeneration was analyzed on all plots. All residual trees (live and standing dead) were measured for species, height, and coordinates in each 2.5 × 40 m plot. Additionally, all natural regeneration, including seedlings, vegetative sprouts, and saplings, was measured by species and height on each plot.

Data analysis

The combination of monitored and re-measured plots in Vihterpalu and Nõva, where site type and treatments were similar, allowed a chronosequence approach. Coordinates of the individual trees enabled us to follow growth dynamics. For data analysis, the statistical software R (R Core Team 2014) was used; significance level of all tests was $P < 0.05$. To study the relations between fire and forest management effect, a multifactor ANOVA was used with tree species, time since fire, regeneration abundance, and tree height growth. Normal distribution of model residuals was tested with the Shapiro–Wilk test. A generalized additive model (GAM) was used for regression (as shown on figures).

Results

In total, eight tree species were found in the study areas, including birch (*Betula* spp.), Scots pine (*Pinus sylvestris* L.), common aspen (*Populus tremula* L.), Norway spruce (*Picea abies* (L.) Karst.), willow (*Salix* spp.), bog myrtle (*Myrica gale* L.), small-leaved lime (*Tilia cordata* Mill.), and common hazel (*Corylus avellana* L.). Only three species (birch, Scots pine, and aspen) were found in sufficient number to be included in the statistical analyses.

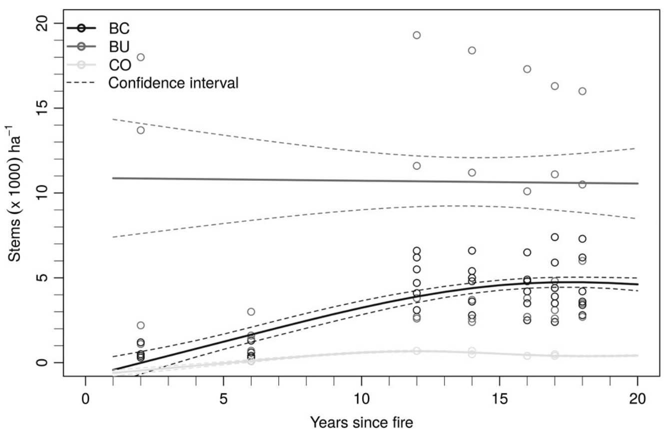
Regeneration abundance was significantly ($P < 0.05$) affected by postfire management and tree species. Postfire management, time since fire, and tree species significantly ($P < 0.05$) affected the height of trees (Table 1).

The greatest regeneration abundance was found on BU areas with no further disturbance after fire. The abundance of natural regeneration on BU plots was very diverse (Fig. 1). The average number of stems in BU areas exceeded 12 000·ha^{-1} in the early years after fire. Regeneration abundance decreased steadily throughout the study period; 20 years after fire, there were an average of 10 000 saplings and seedlings per hectare.

Table 1. The effect of time since fire, postfire management type, and tree species on regeneration abundance and tree height on burned areas according to multifactor ANOVA analysis.

Parameter	Sum of squares	Mean square	*F* value	Pr(>*F*)
ANOVA for regeneration abundance				
Time since fire	9.9×10⁶	9.9×10⁶	0.3816	0.537
Postfire management	309.3×10⁶	309.3×10⁶	11.9042	<0.001
Tree species	290.4×10⁶	145.2×10⁶	5.5890	0.004
ANOVA for height				
Time since fire	12.6×10⁶	12.6×10⁶	1517.36	<0.001
Postfire management	2.4×10⁶	2.4×10⁶	170.520	<0.001
Tree species	8.6×10⁶	4.3×10⁶	291.63	<0.001

Fig. 1. Abundance of regeneration of all species combined (stems·ha⁻¹) in fire-damaged areas according to time since fire with different management type: BU, burned and uncleared; BC, burned and cleared; CO, control areas with no fire. Each circle in the figure represents an individual plot, and the broken lines mark the confidence intervals.



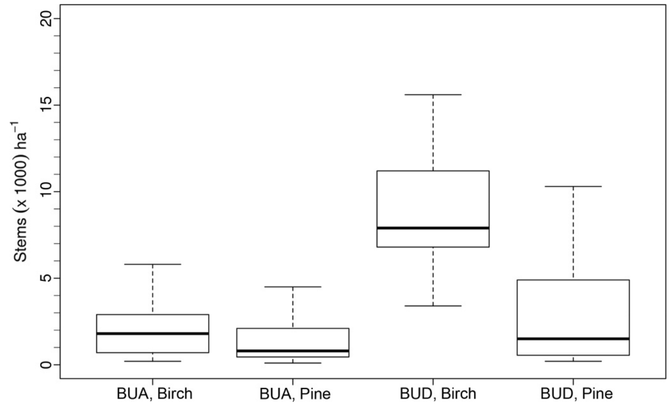
In BC areas, the abundance of trees of all sizes was lower than in BU areas throughout the study period. In the early years after fire, there was almost no regeneration present in BC areas. Regeneration increased in abundance until 13 years after fire and then plateaued at about 4000 stems·ha⁻¹. Thirteen years after fire, the number of stems in BC areas was still 2.5 times lower than in BU areas (Fig. 1). Regeneration in CO areas was very low (Fig. 1).

Six years after fire, the regeneration abundance in BUD areas was similar to BU areas, with 9000 stems·ha⁻¹. In BUA areas, the number of stems was three times lower, about 3000 stems·ha⁻¹, showing similar trends to BC areas (Fig. 1, 2).

Regeneration dynamics of the three main tree species in BC and BU areas was more abundant on the plots that were burned and uncleared (BU). Tree species changed significantly ($P < 0.05$) over time, with birch dominating BU areas in the first 12 years (Table 1; Fig. 3). Abundance of birch was already very high 2 years after fire, with almost 12 000 stems·ha⁻¹, remaining on the same level for 7 years. Twelve years after fire, abundance of birch had decreased to around 6000 stems·ha⁻¹. Two years after fire, the abundance of Scots pine was almost six times lower than the abundance of birch in BU areas. Scots pine steadily increased in abundance and dominated BU areas 15 years after fire, with more than 5000 stems·ha⁻¹. Scots pine reached a maximum level (around 7000 stems·ha⁻¹) by 20 years after fire disturbance (Fig. 3). Aspen began with low abundance in BU and BC areas and increased steadily to 1000–2000 stems·ha⁻¹ (Fig. 3).

In BUD and BUA areas, the regeneration abundance was measured only twice, 2 years after the fire and 6 years after the fire (Fig. 2). Total regeneration abundance was lower in BUA areas than in BUD areas. In BUA areas, birch and Scots pine abundance was similar (1400–2000 stems·ha⁻¹) to Scots pine abundance in BUD areas (1900 stems·ha⁻¹). Birch regeneration in BUD areas, however, was more abundant, with almost 8000 stems·ha⁻¹.

Fig. 2. Average regeneration abundance of birch (*Betula* spp.) and pine (*Pinus sylvestris*) on burned and uncleared areas with dead trees (BUD) and burned and uncleared areas with live trees (BUA) 6 years after fire. Boxplots present quartiles of the distribution of stem numbers.



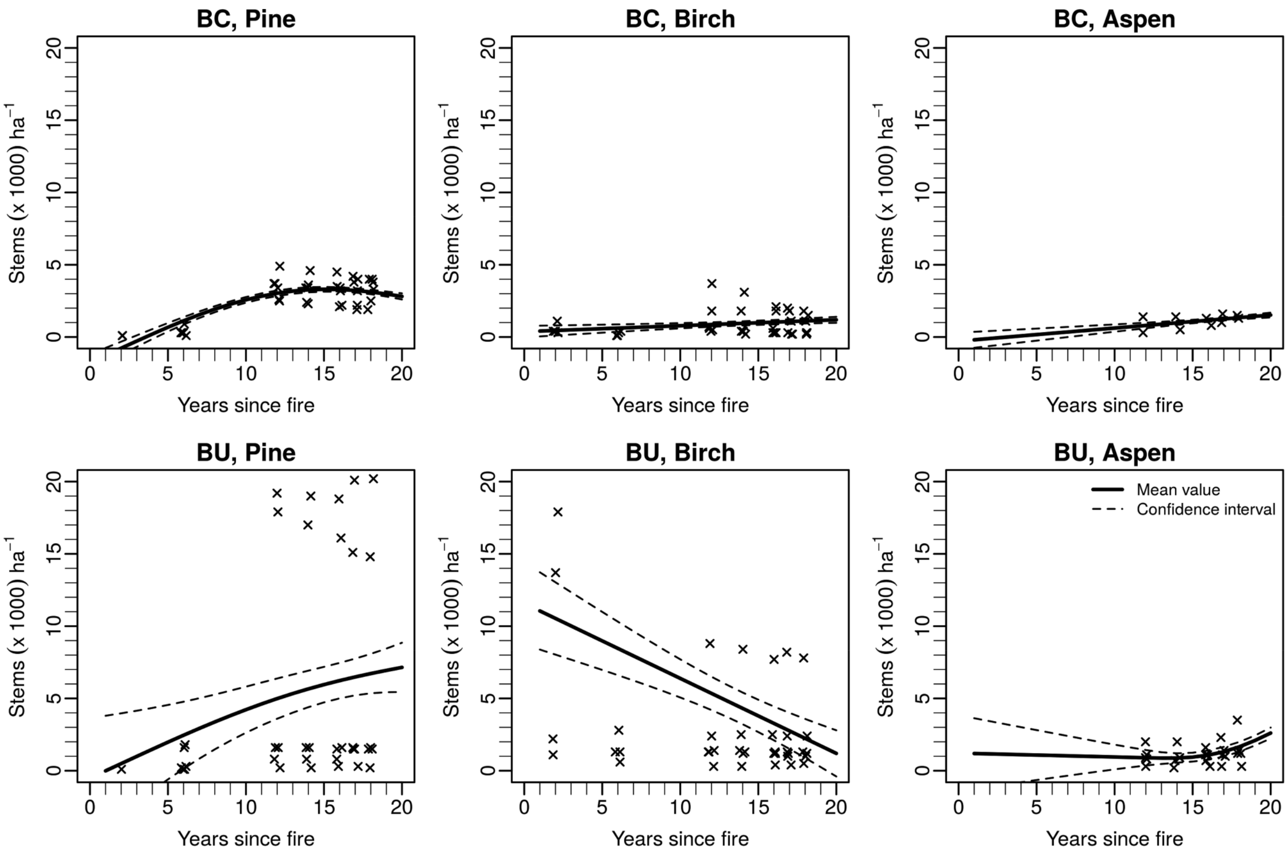
Height growth dynamics of Scots pine, birch, and aspen was followed in BU and BC areas 2 to 22 years after fire disturbance (Fig. 4). In contrast to the pattern of regeneration abundance, height was greater in the plots that were harvested after fire (BC plots) (Fig. 4). Scots pine height in BC areas exceeded the height of Scots pine in BU areas by 5 years after fire, and differences in tree heights between areas 17 years after fire were as much as 1 m (maximum 797 cm in BC areas and 529 cm in BU areas). Birch in BU areas reached a maximum average height 16 years after fire (maximum height 624 cm) and then plateaued due to abundant new regeneration decreasing the average height. In BC areas, birch reached a maximum average height 17 years after fire (maximum height 990 cm) and then began to decrease, which was also caused by the appearance of new seedlings and sprouts. Height of aspen was equivalent in BC and BU areas throughout the study period (maximum 240 cm in BC areas and 162 cm in BU areas; Fig. 4). Aspen height was probably affected by moose damage (data not shown).

Discussion

Different management approaches are needed to create diverse forest systems that are more resilient to disturbances (Vodde et al. 2011). Dry and low-productivity forests are good candidates for developing mixed forests using natural regeneration following stand-replacing disturbances such as severe wildfire. Natural regeneration reduces disturbance to soil compared with artificial regeneration, which requires site preparation. Retaining decaying wood on the site allows enrichment of the soil and regeneration of microsites (Päätalo 1998).

This study focused on natural regeneration dynamics after wildfire in managed forests in Estonia to offer solutions for fast regeneration of burned areas and protection for soil. Wildfire altered both the vegetation and soil, creating variable conditions for regeneration. Clearing burned stands was a further disturbance not only due to removal of some or all of the overstory trees, but also because logging equipment caused further soil disturbance in these dry and sandy areas. The effects of wildfire, with and without clearing, promoted or hindered natural regeneration in the first years after wildfire (Parro et al. 2009) and affected the diversity in stands as they developed.

Fig. 3. Average regeneration abundance (stems·ha^{-1}) dynamics of pine (*Pinus sylvestris*), birch (*Betula* spp.), and aspen (*Populus tremula*) according to time since fire in burned and uncleared (BU) and burned and cleared (BC) areas. Each times sign (×) in the figure represents an individual plot, and the broken lines mark the confidence interval.



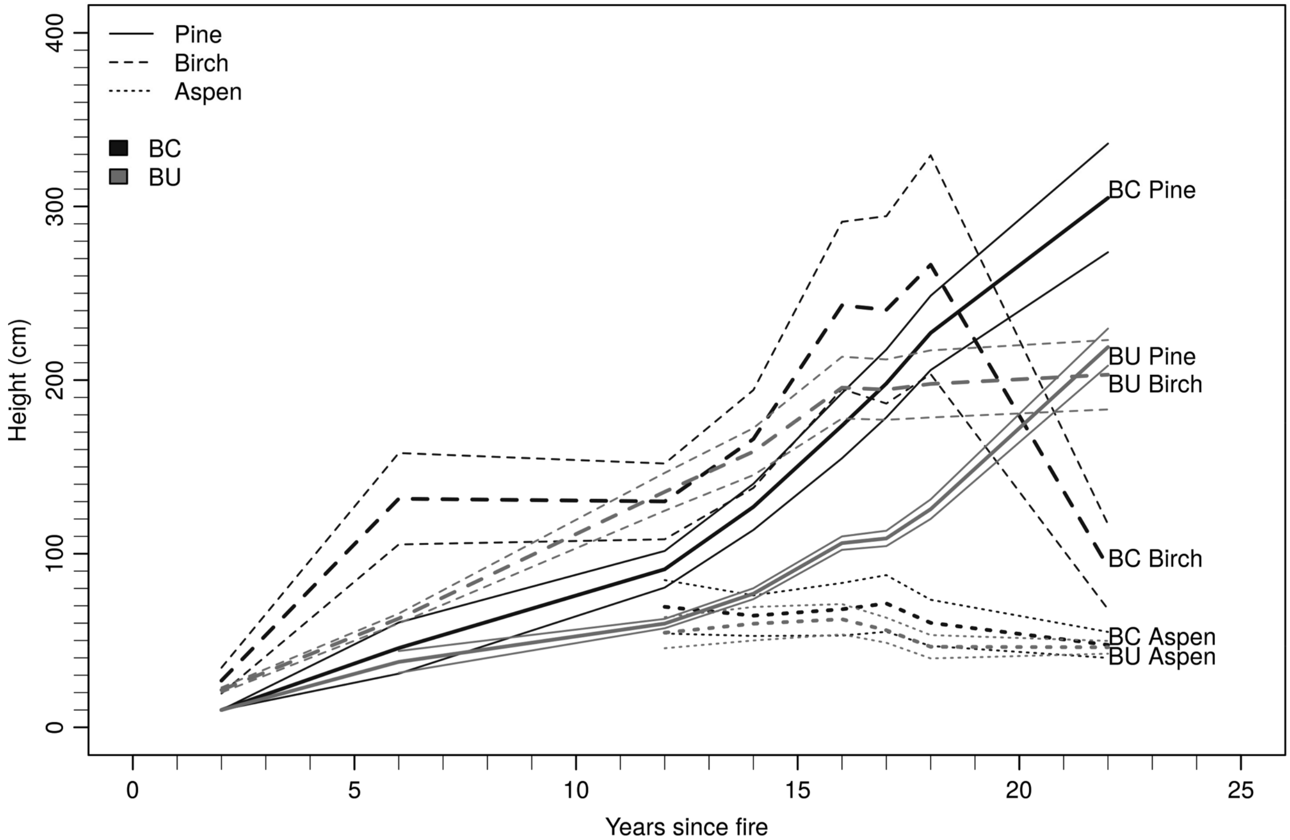
We found in our study that regeneration abundance was very low on unburned control plots and very high on burned areas. This agrees with the findings of other studies where it was reported that fire is an important factor for regeneration (Hille and Den Ouden 2004; Gärtner et al. 2014). On the other hand, both burned and cleared sites and burned sites with retained green trees regenerated slowly after fire, which shows that burning alone is not enough for regeneration development, but some limited removal of residual trees may be needed to regenerate the disturbed areas. Similarly, lower regeneration abundance in burned areas after clearing was found by Beghin et al. (2010). We found that leaving residual dead and live trees on burned sites had different effects on regeneration: retaining standing dead trees promoted natural regeneration, but live trees hindered regeneration. One the one hand, a closed canopy intercepts light, and live trees compete with regeneration for moisture and nutrients in the soil. On the other hand, dead trees allow light to penetrate and also provide shelter from wind, which reduces evaporation that often prohibits the regeneration of conifers (Moser et al. 2010). Standing dead trees may also act as seed catchers. After some years, standing dead trees fall and affect the growth of regeneration by releasing nutrients, but they may also damage young trees.

Composition of tree species on burned areas changed over time, with birch dominating initially. As a pioneer tree species, birch regenerated quickly after disturbance and was more abundant; birch also attained greater height on uncleared sites. Clearing favored pine to become the dominant tree species in the earlier stage of stand development compared with areas without clearing but showed no effect on aspen regeneration irrespective of management type. The absence of residual trees improved light conditions in burned and cleared areas but temporarily exposed soil, created conditions for erosion, and favored the spread of ericaceous species such as *Calluna* (Parro et al. 2009). This may have reduced the moisture level in the soil and created unsuitable conditions for birch in later years (Ginzburg and Steinberger 2012). Pine began to dominate burned and uncleared areas in later years (15 years after fire disturbance in our case), which is in accordance with findings elsewhere (Vanha-Majamaa et al. 1996).

At Nõva, comparison of BUD areas with BUA areas confirmed the effect of competition for light and moisture. Birch regeneration was abundant on sites with dead trees where microclimate conditions, especially for light, were better (Vanha-Majamaa et al. 2007). As also noted by Kuuluvainen and Rouvinen (2000), dead trees without needles intercept less light than live trees with full crowns, thereby providing more light to developing regeneration. Regeneration of pine in burned areas was low in the years immediately after fire, possibly because on dry sites, pine requires 3–5 years after fire to regenerate (Hancock et al. 2005). Birch, in contrast, has mast years almost annually, unlike pine (Laas 1987), and birch seeds are more resistant and have a higher germination rate (De Chantal et al. 2005). Another factor in the fast regeneration of birch after fire is distance to seed trees (Moser et al. 2010), which often also determines the success of pine regeneration (Vacchiano et al. 2014).

When intense fire removes the organic and humus layers leaving bare mineral soil, regeneration on burned areas can be hindered due to changed water regime and reduced fertility (Buhk et al. 2007). Absence of suitable growing conditions also limits the growth of ground vegetation that could facilitate stems by providing shelter from drying wind in the years immediately after fire (Päätalo 1998). On the contrary, there may be a fertilizing effect of

Fig. 4. Average height dynamics of pine (*Pinus sylvestris*; solid lines), birch (*Betula* spp.; long-dashed lines), and aspen (*Populus tremula*; short-dashed lines) in burned and uncleared (BU; grey lines) and burned and cleared (BC; black lines) areas 2 to 22 years after fire. Bold lines represent the mean height dynamics; paired lines that are not bold mark the 95% confidence intervals.



ash on burned areas (York et al. 2009). However, height growth rate of birch on burned and cleared versus burned alone sites indicates that any enrichment effect of ash immediately after fire is minimal compared with faster growth in areas with fewer standing trees and more open areas, similar to results of Den Herder et al. (2009), who noted that birch as a shade-intolerant tree species grows better on cleared areas. Later in stand development, competition further hinders the abundance and height growth of birch on uncleared areas.

In all our study areas, the overall abundance of regeneration started to decline 15 years after fire. This may have been caused by the absence of shelter from residual trees (Lampainen et al. 2004) or due to competition (Den Herder et al. 2009). Pine, which is better adapted to these dry and sandy soils (Zaidullina and Tikhodeyeva 2006), increased slightly in abundance and began to dominate by the end of the study.

Prescribed burning is often recommended for creating suitable ground for pine (Hyppönen et al. 2013), but together with postfire clearing, it may favor ericaceous species that reduce the available nitrogen of the already nutrient-stressed habitat (Mallik 2003), affecting especially pine and other conifers, and may lead to continuous cover of *Calluna* (Norberg et al. 2001). Some studies have shown that pine best regenerates 5 years after fire (Marzano et al. 2012), but it may be delayed by competing vegetation, especially the presence of *Calluna* (Mallik 2003), which may cause conversion of forestland into heathland that may persist for up to 50 years after fire (Norberg et al. 2001). Delayed regeneration of pine — more than 10 years after fire in the current study before pine noticeably increased in abundance or height growth — coincides with the results of Vacchiano et al. (2013), who found that pine regeneration was delayed up to 16 years after fire due to moisture deficit.

The question of whether to clear the forest after wildfire is probably best answered by “it depends”. Naturally regenerated stands following fire may develop into mixed forests that are more resilient to disturbances compared with monocultures. In dry pine forests, natural regeneration may be more successful in the long-term perspective compared with planting that affects the soil and water regime, creating unfavorable conditions for seedling growth due to additional disturbance caused by site preparation and reducing the adaptability of forests to climatic extremes (Thiel et al. 2012).

The decision of whether or not to clear dry sites after wildfire should be based on the amount of standing dead and live trees in burned areas and on the availability of seed trees within dispersal distance outside the burned area. Natural regeneration after fire is best without clearing in terms of abundance and diversity. Standing dead trees can provide shelter without reducing light transmission to the forest floor, facilitating growth of regeneration. Live residual trees, however, reduce light to seedlings, and trees that have survived fire often die within a few years. Immediate removal of all trees after fire to avoid insect damage or to provide material for industry may cause a delay in sufficient regeneration for up to 10 years. Nevertheless, clearing burned areas releases growing space and provides more light to regeneration, and nearby trees in unburned areas can provide seed sources. There is likely to be an optimum amount of residual trees remaining after wildfire to regenerate diverse forests on dry sites.

Although regeneration is most successful in burned areas without clearing, the question remains as to how much residual live and dead overstory to retain that would provide most diverse forests with abundant regeneration and fast height growth. Future studies in pine forests on sandy soils need not wait for wildfire to begin, however, as studies using variable retention harvesting (Gustafsson et al. 2012) would provide the answer.

Acknowledgements

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