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Scarification with surface soil replacement can promote understory reinitiation as well as the growth of a secondary birch stand

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Abstract

Soil scarification using heavy machinery has been widely used in the assisted natural regeneration of stands with a dense dwarf-bamboo understory in northern Japan. After scarification, birch forests have a high probability of growing, but dwarf-bamboos also recolonize the understory, resulting in the development of single-layered stands with lower levels of transition to the late-successional stage. In this study, we examined the long-term effects of an improved soil scarification practice called “replacement treatment,” in which the removed surface soil is returned to the scarified area. A previous study showed that the replacement treatment had a positive effect on the initial establishment and growth of birches. The site was remeasured at approximately 20 years of age, and the replaced stand, when compared with the standard scarification stand, had DBH and height values that were 1.5 times greater and stand volume that was 3 times greater. The difference in terms of height growth between the two stands widened especially during the first ten years. Additionally, in the replacement treatment stand the number of initiated saplings had more than doubled (> 100 thousand stems/ ha) and consisted of a diverse range of tree species. We have concluded that the soil replacement treatment is a suitable alternative practice that (1) significantly promotes the growth of birches and (2) promotes the reinitiation of tall-tree species in the understory and the development of the later successional stage.

Keywords; assisted natural regeneration, *Betula ermanii*, dwarf-bamboo, soil disturbance, succession.

Introduction

Natural regeneration is one of the most important strategies for sustainable forestry; as when compared with artificial planting, it has high adaptability in the *in-situ* environment and low operating costs (Schütz 1999). However, natural regeneration is generally associated with considerable uncertainty, so facilitation using an assistance practice is required to ensure its success (Löf et al. 2012). Numerous studies have been conducted to identify more effective assistance practices for various management purposes (e.g., Gastaldello et al. 2007; Shono et al. 2007; Soto et al. 2015; Reuling et al. 2019; Haeussler et al. 2021).

Scarification is the displacement of surface soil using heavy machinery to improve the substrate for successful tree regeneration via natural seeding. In many cases, scarification is an effective method by which to establish tree stands (e.g., Wurtz and Zasada 2001; Allison et al. 2003; Prévost and Dumais 2018; Haeussler et al. 2021). However, there is concern that the process will remove organic soil, which has an abundance of nutrients (Munson et al. 1995; Ozawa et al. 2001; Ito et al. 2018) and this may reduce the growth of established trees (Yoshida et al. 2005).

In northern Japan, the understory of forests is often dominated by dwarf-bamboos, which inhibit tree regeneration by limiting the availability of resources and substrates (Noguchi and Yoshida 2004). Accordingly, to enhance natural regeneration, mechanical site preparation (soil scarification) has been utilized since the 1970s (Umeki 2003; Ito et al. 2018) as an assistance practice. The entire body (including rhizomes) of dwarf-bamboos, along with the surface organic soil, is removed. The resultant stands are mostly dominated by early successional species, especially birch (*Betula*) species (Umeki 2003; Yoshida et al. 2005; Goto and Tsuda 2007. Also see Allison et al. 2003; Karlson and Nilsson 2005; Gastaldello et al. 2007; Reuling et al. 2019).

However, contrary to expectations based on the pioneer characteristics of birch species, the development of forests after scarification requires considerable time. For instance, Sano and Shibuya (2015) found that the average diameter at breast height (DBH) in a 37-year-old stand was only 8.4 cm. This was attributed to soil factors and a lack of intervention (cf. thinning) despite there being overcrowding in the stand (Umeki 2003; Ito et al. 2018). Therefore, an alternative practice, called the replacement treatment, in which the scarified organic soil is replaced intentionally, has been introduced to improve tree growth. Previous studies (Aoyama et al. 2009; Yamazaki et al. 2018; 2020) showed that this practice had remarkably positive effects on the early establishment and growth of seedlings. However, since this is a newly developed method, the impacts on long-term stand development still need to be assessed.

In this study, we examined a stand that is approximately 20 years of age, in which the replacement treatment was first performed. At approximately 5 years of age (Aoyama et al. 2009), the average regeneration density (with height > 130 cm) in this stand was 9.5 stems/m^2, which was much higher than the 0.2 saplings/m^2 reported in the control (i.e., the standard scarification stand). The first objective of this study was to determine whether these prominent growth levels had been sustained at 20 years of age. We compare the stand and tree attributes, together with the individual growth process by stem (annual ring) analysis and the current growth state by chemical analysis of leaves, between the scarification stand and the replacement stand.

In the process of stand development after a major disturbance, there is a period called the stem exclusion stage when a few pioneer species close the canopy densely not to allow the new establishment of younger trees (Oliver 1980). Over time, it shifts gradually to the understory reinitiation stage which is characterized by advanced regeneration of more shade-tolerant species. In scarified stands, the stem exclusion stage, in which birches usually occupy the overstory layer, continues for several decades (Umeki 2003; Sano and Shibuya 2015). In this period, there are few signs of understory reinitiation; the establishment of the subsequent generation including late-successional species is generally limited, because of the recolonization of dwarf-bamboos. However, the replacement treatment, which is expected to accelerate overstory growth, may also change the rate of development of the sapling layer. Consequently, we investigated the state of understory reinitiation in the scarification stand and the replacement stand, in terms of regeneration density, species composition, and species diversity. Based on the results of the current study, we discuss the applicability of the replacement treatment in silvicultural practices in this region.

Materials and methods

The study was carried out in the Uryu Experimental Forest of Hokkaido University, located in northern Japan (44˚24’N, 142˚07’E; 370 m above sea level). The mean annual temperature and precipitation for this area are 4.2°C and 1390 mm, respectively, and the maximum snow depth is > 200 cm. The forest is largely dominated by natural mixed conifer-broadleaf stands consisting mainly of *Abies sachalinensis* (Fr. Scham.) Masters, *Betula ermanii* Cham, *Quercus crispula* Blume, *Sorbus commixta* Hedl, *Acer mono* Maxim., and *Tilia japonica* (Miq.) Simonkai. The predominant soil is Inceptisol (acidic brown forest soil), and the predominant bedrock is Tertiary andesite.

We examined a 0.3 ha area of a scarification site, and this was the same area previously reported by Aoyama et al. (2009). Prior to scarification, the area was covered densely with dwarf-bamboos (*Sasa kurilensis* (Rupr.) Makino & Shibata and *S. senanensis* (Franch. & Savat.) Rehd.). In autumn of 1998, the area was scarified using a rake dozer (D60P11, Komatsu, Ltd.). The surface soil (up to 10 cm in depth) and the whole plant bodies were pushed from the site, and the resulting debris was piled outside. According to Fukuzawa et al. (2007), which reported that two-thirds of dwarf-bamboos' root biomass existed at 0-15cm depth, it is estimated that the treatment removes more than half of the root biomass. Empirically, scarification with this level of intensity was believed to hinder the recovery of dwarf-bamboos for at least several years, and has been considered sufficient for tree regeneration. In half of the scarified area, the mineral soil was left exposed, while in the other half, after one year (in autumn of 1999), the debris was replaced using a rake dozer (the replaced stand). We left the debris piled for approximately one year prior to the replacement; this has been proven to considerably reduce the recolonization of dwarf-bamboos from the rhizomes buried in the debris (Yamazaki et al. 2020). Since the replacement of the debris, the area has been untouched. Tree regeneration and soil conditions in 2004 (6 and 5 years of age respectively for the scarified- and replaced stands, as the replacement was conducted one year later) were described in Aoyama et al. (2009).

We set up 4 study plots (100 m^2), each with 4 nested subplots (4 m$^2 \times$4), in each of the scarified and replaced stands in 2020, at which point they were 20 and 19 years of age, respectively. These plots were regularly (8 m interval) located in the stands, away from the edge of the surrounding natural mixed forest (at least 10 m).

We measured the DBH and height of the overstory trees (with DBH $\geq$ 2.5 cm) and the height of the tree saplings (with DBH < 2.5 cm, except for current-year seedlings) respectively, in the study plots and subplots. For the overstory trees, stem volume was calculated from the DBH and height using the existing volume equation.

$$\text{Volume} = (\text{DBH}^{2} * \text{Height})^{0.887} * 10^{-4.089} \qquad [1]$$

The other vascular plant species were also recorded in terms of cover (the part higher than other species in the understory; %) and average height, and then summarized for each life form (tall-trees, shrubs, tall-forbs, herbs, dwarf-bamboos, and lianas). The number of species and Shannon's H' were determined to assess plant species diversity.

Three overstory birch trees were also cut down, which had an average DBH for each of the two treatments. We then took sample disks from each tree every 50 cm along its height, to reconstruct the height growth patterns. Furthermore, leaves were collected from three vertical locations within the canopy (top; leaves exposed to direct sunlight, bottom; leaves at the bottom of the canopy, middle; leaves in between them). Leave samples were then dried at 80°C for 2 days and ground to a fine powder, after which their total nitrogen content was analyzed using a differential thermal conductivity method (CHN analyzer, CE440, Exeter Analytical, Inc, Massachusetts, USA).

We tested the effects of the treatments by comparing the scarified and replaced stands using generalized linear models. We assumed a Poisson distribution with a log-link function for the stem density and number of species, and a Gaussian distribution with an identity-link function for the volume of trees, coverage of vegetation, and the Shannon diversity indices. R version 3.1.2 was used for the analyses (R Development Core Team 2019).

Results

There was no significant difference in the average overstory tree density of the scarified- and replaced stands, but the average volume in the replaced stand had more than tripled, reaching 128 m^3/ha (Table 1). *Betula ermanii* dominated the overstory in both stands, although *Salix hultenii* Floderus accounted for approximately 35% of the basal area in the replaced stand. There was no significant difference in the species diversity indices between the two stands.

The average DBH was significantly greater in the replaced stand (Table 1). In the scarified stand, the DBH distribution was biased toward smaller classes, with a maximum of 12 cm (Figure 1). While in the replaced stand, there was a wide peak at 6–12 cm and a maximum of 20 cm. Similarly, the average tree height was also significantly greater in the replaced stand; the modes of height distribution of the scarified- and replaced stands were 6m and 14m, respectively (Figure 1).

The average sapling density was nearly doubled between the two stands (Table 2). The sapling abundance for all tree species was significantly greater in the replaced stand. The most noticeable differences were seen in *T. japonica* and in the smaller class of *S. commixta* (Figure 2). Scarified stands were dominated mostly by *B. ermanii* and *A. mono* in the large and small height classes, respectively. The replaced stands had significantly higher species diversity indices (Table 2).

The coverage of the understory vegetation reached 95% in the scarified stand, the majority of which was dwarf-bamboos (Table 3). In contrast, despite the replaced stands having significantly lower coverage overall (average 58%), all species, except for the dwarf-bamboos (only 2.2%), showed significantly higher coverage. Considering each subplot (Figure 3), the average height of the dwarf-bamboos was ≥ 180 cm in the scarified stand, overwhelming all other lifeforms. In contrast, tall-trees dominated the understory in the replaced stand (21.5%) in many cases. The species diversity indices were significantly higher in the replaced stand.

The difference in tree height growth for *B. ermanii* was particularly remarkable in the first ten years (Figure 4). Thereafter, the slope of the height growth curve of the replaced stand became gentler, and it appeared parallel to that of the scarified stand.

The nitrogen content in the *B. ermanii* leaves was significantly higher in the trees grown in the replaced stand (Table 4). It is of note that the difference due to canopy position was not significant ($p < 0.05$).

Discussion

Standard scarified stands generally show the typical characteristics of the stem exclusion stage; there is strong interspecific competition among birch individuals, resulting in density-dependent high mortality and low growth rates (Umeki 2003; Sano and Shibuya 2015). In the stand we investigated, which is approximately 20 years of age, the effect of the replacement treatment was not seen for the tree density, but was extremely obvious for the individual growth and the stand volume. The replaced stand, when compared with the scarification stand, had DBH and height values that were 1.5 times greater and a stand volume that was 3 times greater (Table 1). Moreover, the effect was notable, even when compared with the volume of the scarified stands of varying ages (Aoyama et al. 2011) (Figure 5). The stand volume (128 m^3 /ha) recorded in the current study is comparable to the values previously recorded for stands that are over 30 years of age. We can thus conclude that the treatment accelerates stand development by at least 10 years.

The vigorous growth of established trees in the replaced stand (Figure 4) can be attributed to its improved soil characteristics, including nutrient content and moisture. Based on previous studies (Aoyama et al. 2009; Yamazaki and Yoshida 2018; 2020), the replacement treatment was found to produce a higher inorganic nitrogen content than the scarification treatment due to its abundance of organic matter, which is the substrate for nitrogen mineralization. The high leaf nitrogen content observed in the current study (Table 4) indicates that rich soil nutrient conditions may persist for at least 20 years in replaced stands.

However, despite this, the slope of the height growth curve in the replaced stand was gentler after approximately 10 years, and the difference with the scarified stand did not increase (Figure 4). This slowdown is thought to be due to high tree density, as shown by Sano and Shibuya (2015). Since the replaced treatment significantly enhances seedling colonization by improving soil conditions (Yamazaki and Yoshida 2018; 2020), the overcrowded tree density is to some extent an inevitable consequence.

In addition, as noticed in the previous study of the stand at 5 years age (Aoyama et al. 2009), *Salix* species was common in the replaced stand, especially in the large size classes (Table 1; Figure 1). This abundance could be attributed to a higher soil moisture content, which can result from the replacement treatment (Yamazaki and Yoshida 2020), as well as the outstanding seed-dispersal ability of this species.

The replacement treatment promoted the development of the sapling layer consisting of a diverse range of tree species (Table 3; Figure 3), showing a clear sign of transition to the understory reinitiation stage. In the scarified stand of the current study, like many existing stands (Aoyama et al. 2011), dwarf-bamboos were overwhelmingly dominant, and completely shaded the tree saplings (Figure 3). According to the previous study by Aoyama et al. (2009), the forest floor of the scarified stand at 6 years of age has only 1,700 stems/ha (trees with >130 cm height). Perhaps the length of time it took for the canopy to close led to the dwarf-bamboo's recolonization, including expansion both from the remained rhizomes and the surroundings. However, in the replaced stand, it can be considered that the extremely high initial tree density (98,600 stems/ha; Aoyama et al. 2009) prevented the recolonization.

Although we have not conducted an individual identification survey, as many as 150 to 200 thousand seedlings (except for current-year seedlings) /ha were identified in the stand at 5 years of age, so most of the saplings counted in the current study may have survived from that time. Considering that there was no significant difference in total seedling density when compared with the results at 5 years of age, the large difference seen in the current study (Table 3) suggests that survival was significantly lower in the scarified stand. This can be explained by the effect of shade provided by the dense cover of dwarf-bamboos (Figure 3). Considering the extremely low dominance of tall-trees in the scarified stand (Table 3; Figure 3), there is a possibility that the difference with the replaced stand will further increase in the future. *T. japonica* and *S. commixta* appeared frequently in the sapling layer in the replaced stand, but less so when assessed at 5 years of age (221 and 9 seedlings /100 m^2, respectively; Aoyama et al. 2009), suggesting that they colonized later. The lack of dwarf-bamboos in the understory probably promoted the colonization of these mid-successional species. Thus, we concluded that the replacement treatment has a largely positive effect on the reinitiation of the sapling layer toward an advanced successional stage.

Yamazaki and Yoshida (2018; 2020) have reported that the replacement treatment promotes the regeneration of tree species that produce buried seeds. However, the proportion of such tree species (e.g. *S. commixta*) was small (Table 2), suggesting that the contribution of buried seeds was not so important at this study site. We set the one-year deposition period prior to the replacement to delay the recovery of dwarf-bamboos (see Material and methods), and many of the buried seeds may have germinated during that period (Yamazaki et al. 2020).

The results shown here should be generalized carefully, as we have investigated only one stand without replication. As this was the first trial of the replacement treatment, there is no other long-term information available. However, following this early success, subsequent trials have also shown positive effects on natural regeneration (although see Yamazaki and Yoshida 2020 as a case of pending success). As birch wood has been used for many purposes in recent years (Shimase 2021), this replacement treatment was certainly effective for the forestry industry in the region. To further enhance the treatment usability, we believe the implementation of thinning could also be effective (Sano and Shibuya 2015). At the current study site, no human intervention has occurred after the scarification and replacement treatments. As a result, and as mentioned previously, the replaced stand was overcrowded, albeit with its initial vigorous growth. It is therefore recommended that a pre-commercial thinning be conducted prior to the 10 years age point, when tree height growth has slowed (Simard et al. 2004). The high nitrogen content of the leaves suggests that the soil nutrient level is still high at approximately 20 years of age. The replacement stand may have a further growth advantage if the thinning eliminates the negative crowding effect and provides sufficient light conditions. Furthermore, thinning is also a significant task for the purpose of ecological restoration, as it can significantly promote understory development to an advanced successional stage. As this practice is still in its trial stage, extended censuses to check the current findings are required.

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Table 1. Stand and tree properties measured in the scarified- and replaced stands. The average and the standard deviation (in parentheses) are shown.

	Treatment		Statistical difference
	Scarified	Replaced	
Density of trees (/100m^2)			
Total	39.3 (12.8)	37.5 (6.8)	ns
Betula ermanii	37.3 (13.0)	29.8 (7.0)	ns
Salix hultenii	0.5 (0.6)	7.0 (4.3)	*
Volume of trees (m^3/100m^2)			
Total	0.40 (0.10)	1.28 (0.11)	*
Betula ermanii	0.40 (0.07)	0.83 (0.41)	*
Salix hultenii	0.00 (0.10)	0.44 (0.15)	*
DBH (cm)	5.2 (2.3)	8.2 (3.4)	*
Tree height (m)	6.1 (2.3)	10.4 (3.2)	*
Species richness (/100m^2)	3.50 (0.6)	3.25 (1.0)	ns
Shannon's diversity index	0.71 (0.33)	1.19 (0.42)	ns

* $p < 0.05$. ns: not significant

Table 2. Saplings of tall-tree species measured in the scarified- and replaced stands. The average and the standard deviation (in parentheses) are shown.

	Treatment		Statistical difference
	Scarified	Replaced	
Density of saplings (/100m^2)			
Total	522.0 (207.0)	1041.4 (352.7)	*
Acer mono	339.1 (177.6)	409.4 (295.3)	*
Tilia japonica	54.4 (32.3)	306.3 (108.1)	*
Abies sachalinensis	47.5 (15.5)	83.6 (30.7)	*
Sorbus commixta	4.7 (9.4)	106.3 (84.8)	*
Species richness (/16m^2)	6.0 (1.4)	10.0 (1.8)	*
Shannon's diversity index	1.50 (0.38)	2.18 (0.39)	*

* $p < 0.05$

Table 3. Understory vegetation measured in the scarified- and replaced stands. The average and the standard deviation (in parentheses) are shown.

	Treatment		Statistical difference
	Scarified	Replaced	
Coverage (%)			
Total	94.6 (12.5)	57.5 (19.7)	*
Tall-trees	3.3 (2.9)	21.5 (10.9)	*
Shrubs	1.5 (4.0)	16.0 (14.1)	*
Tall-forbs	1.4 (1.3)	6.5 (6.7)	*
Herbs	0.0 (0.0)	0.4 (1.3)	ns
Lianas	1.9 (6.2)	11.0 (10.6)	*
Dwarf bamboos	86.6 (13.4)	2.2 (5.7)	*
Species richness (/16m^2)	11.0 (2.0)	17.8 (1.5)	*
Shannon's diversity index (H')	0.93 (0.42)	3.17 (0.13)	*

* $p < 0.05$. ns: not significant

Table 4. Leaf nitrogen contents in overstory *B. ermanii* trees grown in the scarified- and replaced stands. Leaves were collected from three different heights (top, middle, bottom) within the canopy. The average and the standard deviation (in parentheses) are shown.

	Treatment		Statistical difference
	Scarified	Replaced	
Top	1.84 (0.13)	2.11 (0.25)	*
Middle	1.98 (0.10)	2.22 (0.06)	*
Bottom	1.90 (0.20)	2.24 (0.05)	*

* $p < 0.05$

Note that the difference due to canopy position was not significant ($p < 0.05$)

Figure 1. DBH and height frequency distributions of trees grown in the scarified- and replaced stands.

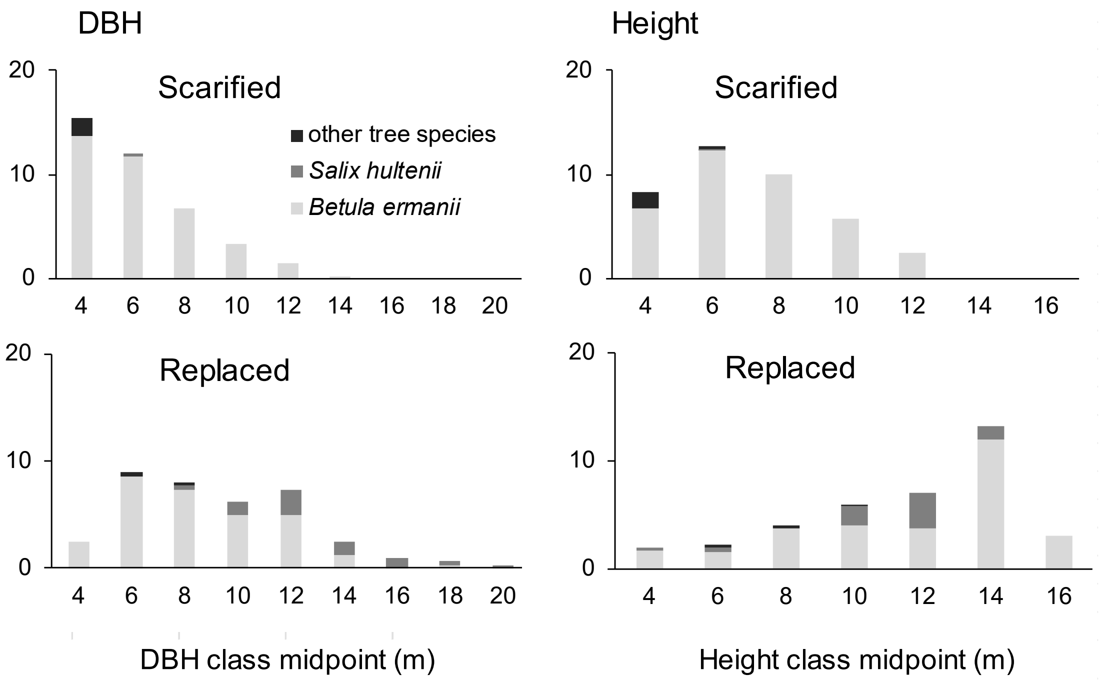

Figure 2. Height frequency distribution of seedlings grown in the scarified- and replaced stands.

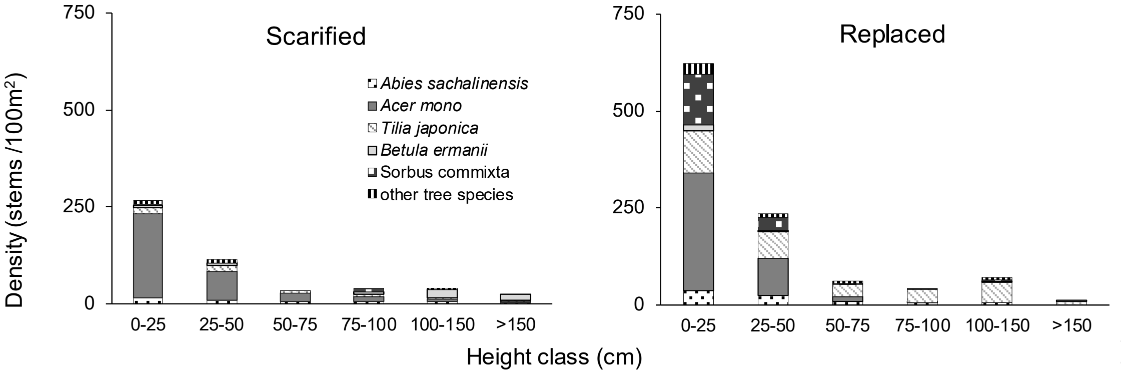

Figure 3. The average height for each life-form in each subplot. Not shown if coverage of the life-form in subplot is less than 10%.

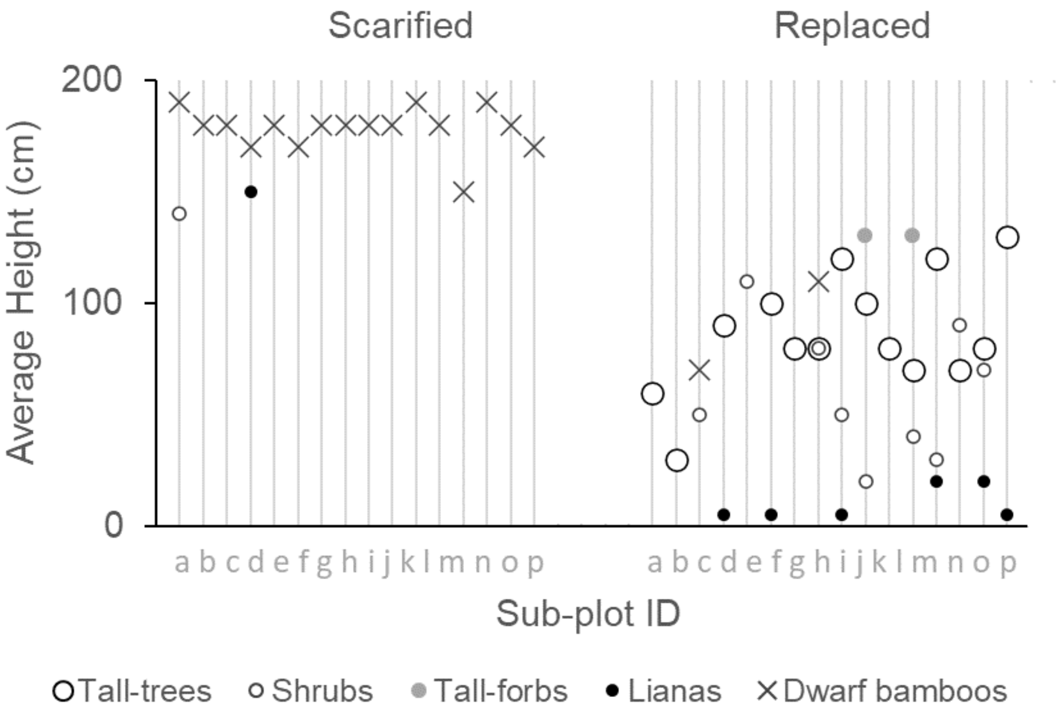

Figure 4. Height growth curves of overstory *Betula ermanii* trees sampled from the scarified- and replaced stands. Note that the age of the replaced stand was 19 years, one year younger than the scarified stand.

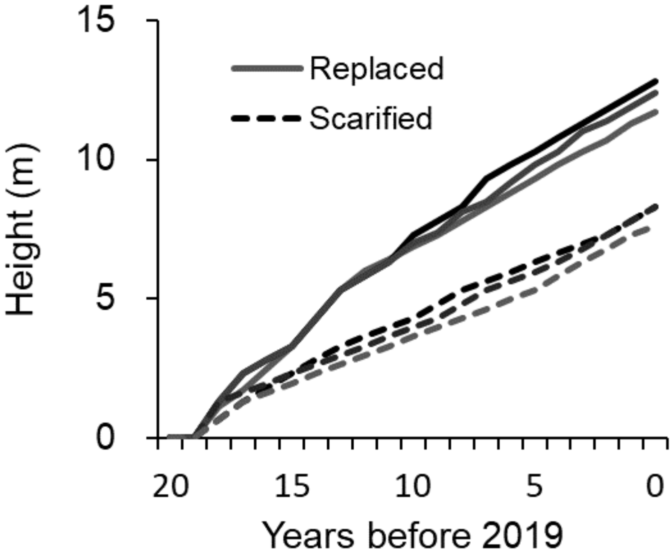

Figure 5. Stand volume by age of various scarification sites in the Uryu Experimental Forest. Bars indicate the standard deviation.