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.

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

68 al. 2005; Goto and Tsuda 2007. Also see Allison et al. 2003; Karlson and Nilsson

69 2005; Gastaldello et al. 2007; Reuling et al. 2019).

70   However, contrary to expectations based on the pioneer characteristics of birch

71 species, the development of forests after scarification requires considerable time.

72 For instance, Sano and Shibuya (2015) found that the average diameter at breast

73 height (DBH) in a 37-year-old stand was only 8.4 cm. This was attributed to soil

74 factors and a lack of intervention (cf. thinning) despite there being overcrowding

75 in the stand (Umeki 2003; Ito et al. 2018). Therefore, an alternative practice,

76 called the replacement treatment, in which the scarified organic soil is replaced

77 intentionally, has been introduced to improve tree growth. Previous studies

78 (Aoyama et al. 2009; Yamazaki et al. 2018; 2020) showed that this practice had

79 remarkably positive effects on the early establishment and growth of seedlings.

80 However, since this is a newly developed method, the impacts on long-term stand

81 development still need to be assessed.

82   In this study, we examined a stand that is approximately 20 years of age, in

83 which the replacement treatment was first performed. At approximately 5 years

84 of age (Aoyama et al. 2009), the average regeneration density (with height > 130

85 cm) in this stand was 9.5 stems/m^2, which was much higher than the 0.2

86 saplings/m^2 reported in the control (i.e., the standard scarification stand). The first

87 objective of this study was to determine whether these prominent growth levels

88 had been sustained at 20 years of age. We compare the stand and tree attributes,

89 together with the individual growth process by stem (annual ring) analysis and

90 the current growth state by chemical analysis of leaves, between the scarification

91 stand and the replacement stand.

92   In the process of stand development after a major disturbance, there is a period

93   called the stem exclusion stage when a few pioneer species close the canopy

94   densely not to allow the new establishment of younger trees (Oliver 1980). Over

95   time, it shifts gradually to the understory reinitiation stage which is characterized

96   by advanced regeneration of more shade-tolerant species. In scarified stands,

97   the stem exclusion stage, in which birches usually occupy the overstory layer,

98   continues for several decades (Umeki 2003; Sano and Shibuya 2015). In this

99   period, there are few signs of understory reinitiation; the establishment of the

100   subsequent generation including late-successional species is generally limited,

101   because of the recolonization of dwarf-bamboos. However, the replacement

102   treatment, which is expected to accelerate overstory growth, may also change

103   the rate of development of the sapling layer. Consequently, we investigated the

104   state of understory reinitiation in the scarification stand and the replacement

105   stand, in terms of regeneration density, species composition, and species

106   diversity. Based on the results of the current study, we discuss the applicability of

107   the replacement treatment in silvicultural practices in this region.

108

109   **Materials and methods**

110   The study was carried out in the Uryu Experimental Forest of Hokkaido

111   University, located in northern Japan (44˚24'N, 142˚07'E; 370 m above sea level).

112   The mean annual temperature and precipitation for this area are 4.2°C and 1390

113   mm, respectively, and the maximum snow depth is > 200 cm. The forest is largely

114   dominated by natural mixed conifer-broadleaf stands consisting mainly of *Abies*

115   *sachalinensis* (Fr. Scham.) Masters, *Betula ermanii* Cham, *Quercus crispula*

116   Blume, *Sorbus commixta* Hedl, *Acer mono* Maxim., and *Tilia japonica* (Miq.)

117   Simonkai. The predominant soil is Inceptisol (acidic brown forest soil), and the

118   predominant bedrock is Tertiary andesite.

119   We examined a 0.3 ha area of a scarification site, and this was the same area

120   previously reported by Aoyama et al. (2009). Prior to scarification, the area was

121   covered densely with dwarf-bamboos (*Sasa kurilensis* (Rupr.) Makino & Shibata

122   and *S. senanensis* (Franch. & Savat.) Rehd.). In autumn of 1998, the area was

123   scarified using a rake dozer (D60P11, Komatsu, Ltd.). The surface soil (up to 10

124   cm in depth) and the whole plant bodies were pushed from the site, and the

125   resulting debris was piled outside. According to Fukuzawa et al. (2007), which

126   reported that two-thirds of dwarf-bamboos' root biomass existed at 0-15cm depth,

127   it is estimated that the treatment removes more than half of the root biomass.

128   Empirically, scarification with this level of intensity was believed to hinder the

129   recovery of dwarf-bamboos for at least several years, and has been considered

130   sufficient for tree regeneration. In half of the scarified area, the mineral soil was

131   left exposed, while in the other half, after one year (in autumn of 1999), the debris

132   was replaced using a rake dozer (the replaced stand). We left the debris piled for

133   approximately one year prior to the replacement; this has been proven to

134   considerably reduce the recolonization of dwarf-bamboos from the rhizomes

135   buried in the debris (Yamazaki et al. 2020). Since the replacement of the debris,

136   the area has been untouched. Tree regeneration and soil conditions in 2004 (6

137   and 5 years of age respectively for the scarified- and replaced stands, as the

138   replacement was conducted one year later) were described in Aoyama et al.

139   (2009).

140   We set up 4 study plots (100 m^2), each with 4 nested subplots (4 m$^2 \times 4$), in each

141   of the scarified and replaced stands in 2020, at which point they were 20 and 19

142   years of age, respectively. These plots were regularly (8 m interval) located in the

143   stands, away from the edge of the surrounding natural mixed forest (at least 10

144   m).

145   We measured the DBH and height of the overstory trees (with DBH $\geq$ 2.5 cm)

146   and the height of the tree saplings (with DBH < 2.5 cm, except for current-year

147   seedlings) respectively, in the study plots and subplots. For the overstory trees,

148   stem volume was calculated from the DBH and height using the existing volume

149   equation.

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

151   The other vascular plant species were also recorded in terms of cover (the part

152   higher than other species in the understory; %) and average height, and then

153   summarized for each life form (tall-trees, shrubs, tall-forbs, herbs, dwarf-

154   bamboos, and lianas). The number of species and Shannon's H' were determined

155   to assess plant species diversity.

156   Three overstory birch trees were also cut down, which had an average DBH for

157   each of the two treatments. We then took sample disks from each tree every 50

158   cm along its height, to reconstruct the height growth patterns. Furthermore,

159   leaves were collected from three vertical locations within the canopy (top; leaves

160   exposed to direct sunlight, bottom; leaves at the bottom of the canopy, middle;

161   leaves in between them). Leave samples were then dried at 80°C for 2 days and

162   ground to a fine powder, after which their total nitrogen content was analyzed

163   using a differential thermal conductivity method (CHN analyzer, CE440, Exeter

164   Analytical, Inc, Massachusetts, USA).

165   We tested the effects of the treatments by comparing the scarified and replaced

166   stands using generalized linear models. We assumed a Poisson distribution with

167   a log-link function for the stem density and number of species, and a Gaussian

168 distribution with an identity-link function for the volume of trees, coverage of

169 vegetation, and the Shannon diversity indices. R version 3.1.2 was used for the

170 analyses (R Development Core Team 2019).

171

172 **Results**

173   There was no significant difference in the average overstory tree density of the

174 scarified- and replaced stands, but the average volume in the replaced stand had

175 more than tripled, reaching 128 m^3/ha (Table 1). *Betula ermanii* dominated the

176 overstory in both stands, although *Salix hultenii* Floderus accounted for

177 approximately 35% of the basal area in the replaced stand. There was no

178 significant difference in the species diversity indices between the two stands.

179   The average DBH was significantly greater in the replaced stand (Table 1). In

180 the scarified stand, the DBH distribution was biased toward smaller classes, with

181 a maximum of 12 cm (Figure 1). While in the replaced stand, there was a wide

182 peak at 6–12 cm and a maximum of 20 cm. Similarly, the average tree height was

183 also significantly greater in the replaced stand; the modes of height distribution

184 of the scarified- and replaced stands were 6m and 14m, respectively (Figure 1).

185   The average sapling density was nearly doubled between the two stands (Table

186 2). The sapling abundance for all tree species was significantly greater in the

187 replaced stand. The most noticeable differences were seen in *T. japonica* and in

188 the smaller class of *S. commixta* (Figure 2). Scarified stands were dominated

189 mostly by *B. ermanii* and *A. mono* in the large and small height classes,

190 respectively. The replaced stands had significantly higher species diversity

191 indices (Table 2).

192   The coverage of the understory vegetation reached 95% in the scarified stand,

193 the majority of which was dwarf-bamboos (Table 3). In contrast, despite the

194 replaced stands having significantly lower coverage overall (average 58%), all

195 species, except for the dwarf-bamboos (only 2.2%), showed significantly higher

196 coverage. Considering each subplot (Figure 3), the average height of the dwarf-

197 bamboos was ≥ 180 cm in the scarified stand, overwhelming all other lifeforms.

198 In contrast, tall-trees dominated the understory in the replaced stand (21.5%) in

199 many cases. The species diversity indices were significantly higher in the

200 replaced stand.

201   The difference in tree height growth for *B. ermanii* was particularly remarkable

202 in the first ten years (Figure 4). Thereafter, the slope of the height growth curve

203 of the replaced stand became gentler, and it appeared parallel to that of the

204 scarified stand.

205   The nitrogen content in the *B. ermanii* leaves was significantly higher in the trees

206 grown in the replaced stand (Table 4). It is of note that the difference due to

207 canopy position was not significant ($p < 0.05$).

208

209 **Discussion**

210   Standard scarified stands generally show the typical characteristics of the stem

211 exclusion stage; there is strong interspecific competition among birch individuals,

212 resulting in density-dependent high mortality and low growth rates (Umeki 2003;

213 Sano and Shibuya 2015). In the stand we investigated, which is approximately

214 20 years of age, the effect of the replacement treatment was not seen for the tree

215 density, but was extremely obvious for the individual growth and the stand volume.

216 The replaced stand, when compared with the scarification stand, had DBH and

217 height values that were 1.5 times greater and a stand volume that was 3 times

218 greater (Table 1). Moreover, the effect was notable, even when compared with

219 the volume of the scarified stands of varying ages (Aoyama et al. 2011) (Figure

220 5). The stand volume (128 m^3 /ha) recorded in the current study is comparable to

221 the values previously recorded for stands that are over 30 years of age. We can

222 thus conclude that the treatment accelerates stand development by at least 10

223 years.

224 The vigorous growth of established trees in the replaced stand (Figure 4) can

225 be attributed to its improved soil characteristics, including nutrient content and

226 moisture. Based on previous studies (Aoyama et al. 2009; Yamazaki and Yoshida

227 2018; 2020), the replacement treatment was found to produce a higher inorganic

228 nitrogen content than the scarification treatment due to its abundance of organic

229 matter, which is the substrate for nitrogen mineralization. The high leaf nitrogen

230 content observed in the current study (Table 4) indicates that rich soil nutrient

231 conditions may persist for at least 20 years in replaced stands.

232 However, despite this, the slope of the height growth curve in the replaced

233 stand was gentler after approximately 10 years, and the difference with the

234 scarified stand did not increase (Figure 4). This slowdown is thought to be due to

235 high tree density, as shown by Sano and Shibuya (2015). Since the replaced

236 treatment significantly enhances seedling colonization by improving soil

237 conditions (Yamazaki and Yoshida 2018; 2020), the overcrowded tree density is

238 to some extent an inevitable consequence.

239 In addition, as noticed in the previous study of the stand at 5 years age

240 (Aoyama et al. 2009), *Salix* species was common in the replaced stand,

241 especially in the large size classes (Table 1; Figure 1). This abundance could be

242 attributed to a higher soil moisture content, which can result from the replacement

243   treatment (Yamazaki and Yoshida 2020), as well as the outstanding seed-

244   dispersal ability of this species.

245   The replacement treatment promoted the development of the sapling layer

246   consisting of a diverse range of tree species (Table 3; Figure 3), showing a clear

247   sign of transition to the understory reinitiation stage. In the scarified stand of the

248   current study, like many existing stands (Aoyama et al. 2011), dwarf-bamboos

249   were overwhelmingly dominant, and completely shaded the tree saplings

250   (Figure 3). According to the previous study by Aoyama et al. (2009), the forest

251   floor of the scarified stand at 6 years of age has only 1,700 stems/ha (trees with

252   >130 cm height). Perhaps the length of time it took for the canopy to close led

253   to the dwarf-bamboo's recolonization, including expansion both from the

254   remained rhizomes and the surroundings. However, in the replaced stand, it can

255   be considered that the extremely high initial tree density (98,600 stems/ha;

256   Aoyama et al. 2009) prevented the recolonization.

257   Although we have not conducted an individual identification survey, as many

258   as 150 to 200 thousand seedlings (except for current-year seedlings) /ha were

259   identified in the stand at 5 years of age, so most of the saplings counted in the

260   current study may have survived from that time. Considering that there was no

261   significant difference in total seedling density when compared with the results at

262   5 years of age, the large difference seen in the current study (Table 3) suggests

263   that survival was significantly lower in the scarified stand. This can be explained

264   by the effect of shade provided by the dense cover of dwarf-bamboos (Figure 3).

265   Considering the extremely low dominance of tall-trees in the scarified stand

266   (Table 3; Figure 3), there is a possibility that the difference with the replaced stand

267   will further increase in the future. *T. japonica* and *S. commixta* appeared

268 frequently in the sapling layer in the replaced stand, but less so when assessed

269 at 5 years of age (221 and 9 seedlings /100 m^2, respectively; Aoyama et al. 2009),

270 suggesting that they colonized later. The lack of dwarf-bamboos in the understory

271 probably promoted the colonization of these mid-successional species. Thus, we

272 concluded that the replacement treatment has a largely positive effect on the

273 reinitiation of the sapling layer toward an advanced successional stage.

274 Yamazaki and Yoshida (2018; 2020) have reported that the replacement

275 treatment promotes the regeneration of tree species that produce buried seeds.

276 However, the proportion of such tree species (e.g. *S. commixta*) was small (Table

277 2), suggesting that the contribution of buried seeds was not so important at this

278 study site. We set the one-year deposition period prior to the replacement to delay

279 the recovery of dwarf-bamboos (see Material and methods), and many of the

280 buried seeds may have germinated during that period (Yamazaki et al. 2020).

281 The results shown here should be generalized carefully, as we have

282 investigated only one stand without replication. As this was the first trial of the

283 replacement treatment, there is no other long-term information available.

284 However, following this early success, subsequent trials have also shown positive

285 effects on natural regeneration (although see Yamazaki and Yoshida 2020 as a

286 case of pending success). As birch wood has been used for many purposes in

287 recent years (Shimase 2021), this replacement treatment was certainly effective

288 for the forestry industry in the region. To further enhance the treatment usability,

289 we believe the implementation of thinning could also be effective (Sano and

290 Shibuya 2015). At the current study site, no human intervention has occurred

291 after the scarification and replacement treatments. As a result, and as mentioned

292 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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387

388 Table 1. Stand and tree properties measured in the scarified- and replaced stands. The

389 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

390 * $p < 0.05$. ns: not significant

391

392 Table 2. Saplings of tall-tree species measured in the scarified- and replaced stands. The

393 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)	*

394 * $p < 0.05$

395 Table 3. Understory vegetation measured in the scarified- and replaced stands. The

396 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)	*

397 * $p < 0.05$. ns: not significant

398   Table 4. Leaf nitrogen contents in overstory *B. ermanii* trees grown in the scarified- and

399   replaced stands. Leaves were collected from three different heights (top, middle,

400   bottom) within the canopy. The average and the standard deviation (in parentheses)

401   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 ($p < 0.05$)

402

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

404   replaced stands.
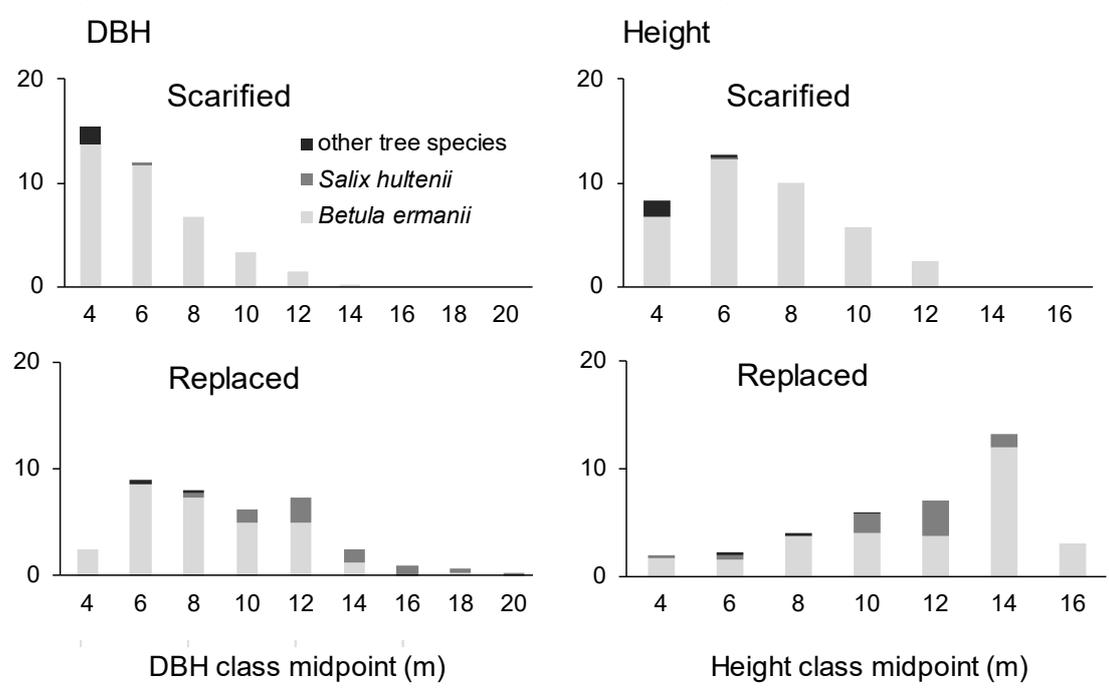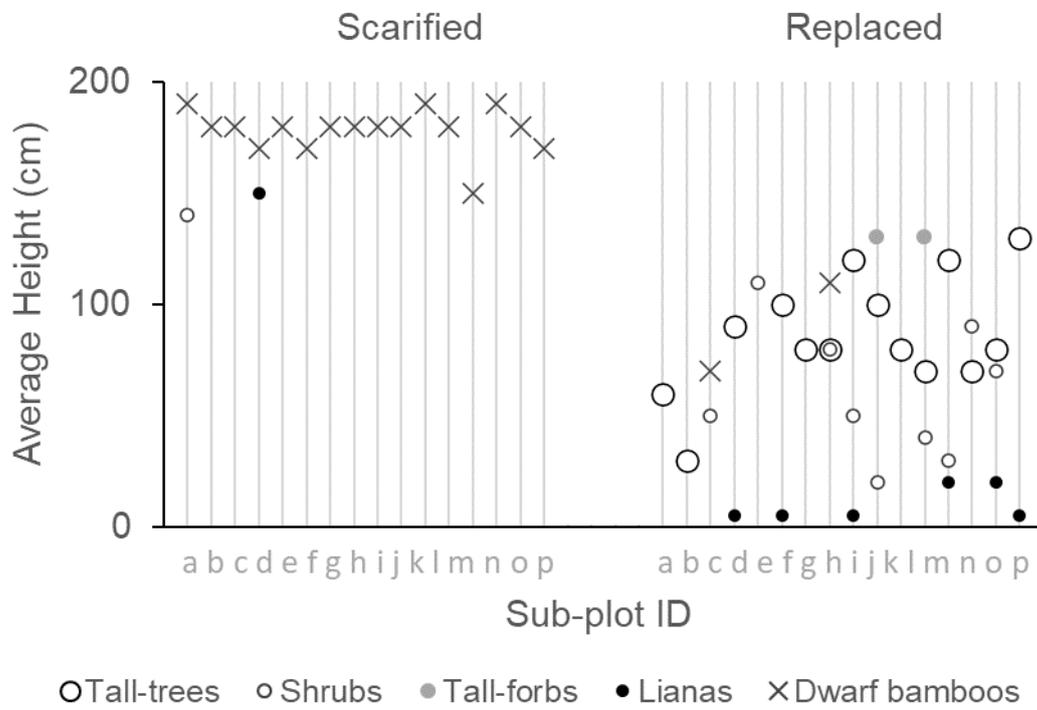

405

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

407   stands.
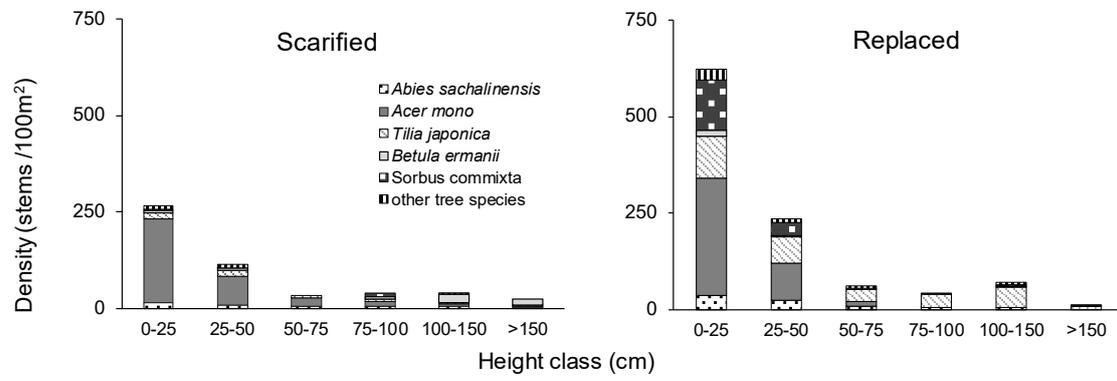
408

409   Figure 3. The average height for each life-form in each subplot. Not shown if coverage

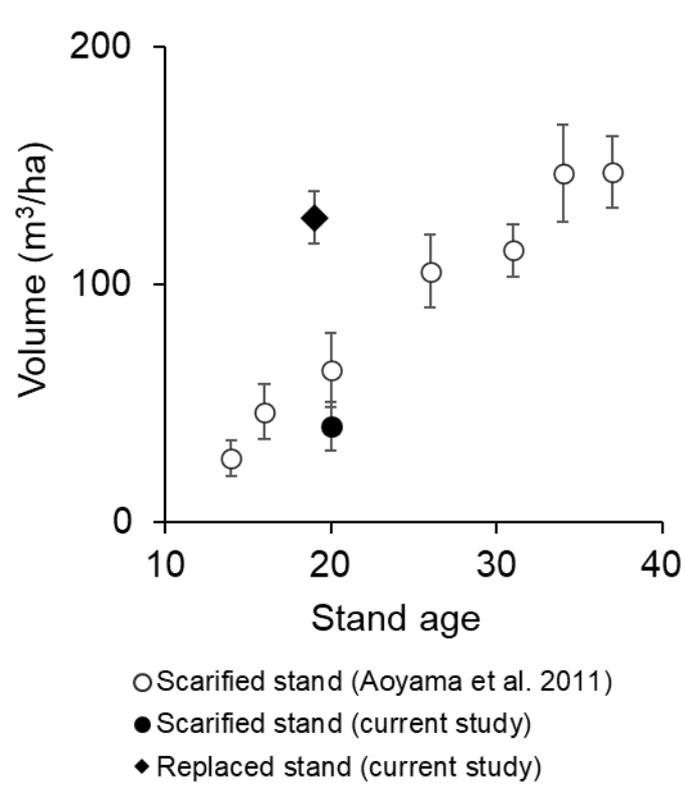410   of the life-form in subplot is less than 10%.

411

412   Figure 4. Height growth curves of overstory *Betula ermanii* trees sampled from the

413   scarified- and replaced stands. Note that the age of the replaced stand was 19 years,

414   one year younger than the scarified stand.
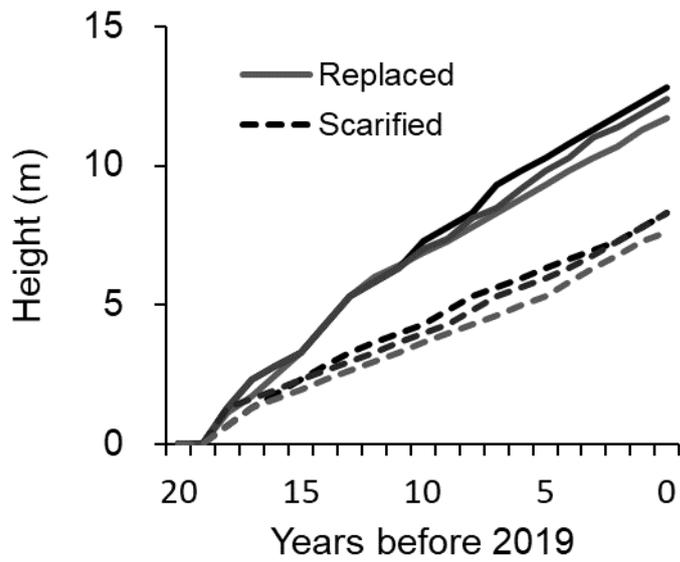
415

416   Figure 5. Stand volume by age of various scarification sites in the Uryu Experimental

417   Forest. Bars indicate the standard deviation.

418

419