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The combined effects of tree shelters, large stock and vegetation control on the early growth of conifer seedlings

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ABSTRACT

Tree shelters are effective in enhancing early survival and growth and protecting planted seedlings against herbivory by mammals; they are, however, expensive. In order to be cost-effective, we need to employ silvicultural practices that maximize the benefits of using tree shelters. Thus, this study examined whether tree shelter effects on early seedling growth are enhanced by the combination of large stock and vegetation control, based on a three factor split-plot experiment for the first three years after planting the seedlings out in a fenced plantation of Japanese cedar (*Cryptomeria japonica*). Vegetation control involved spot and strip weeding to reduce labor costs. The experiment demonstrated the great effect of tree shelters on enhancing the early height growth of seedlings. At the end of the third growing season, sheltered seedlings were 1.5 times taller than unsheltered seedlings on average, and approximately two-thirds of sheltered seedlings had exceeded the browsing height of deer, while unsheltered seedlings had not. Using large stock and employing vegetation control also positively affected seedling height. However, combining these treatments with tree shelters intensified the positive effects on seedling height, and shortened the period during which the leader shoots of seedlings would be unprotected from the browsing without fencing. The present study thus reveals that the combination of tree shelters, large stock and vegetation control is effective in maximizing the benefit of tree shelter installation.

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KEYWORDS
Conifer plantation; early seedling growth; large stock; tree shelter; vegetation control

Introduction

Tree shelters, which are translucent plastic tubes that are placed around young trees (Potter 1991), effectively protect the trees against herbivory by mammals and enhance their early survival and growth (Potter 1991). The shelters are also effective in reducing the risk of accidental cutting during any mechanical release treatments by increasing the visibility of trees (Potter 1991). The shelters are, however, expensive (Jacobson and Jackson 2004). The cost includes not only that for their purchase but also for transporting them to the field and installation (Lantagne 1997). In order to be cost effective, we need silvicultural practices that maximize the field performance of young trees equipped with the shelters.

Because silvicultural practices for reforestation and afforestation consist of several elements, appropriate coordination of these elements is the primary step to maximize the benefit of installing tree shelters. The important elements in plantation silviculture include the choice of seedling stock size (Grossnickle and El-Kassaby 2016) and vegetation control (Balandier et al. 2006). Seedling size at outplanting affects initial competitive ability (Jobidon et al. 2003). A large stock type is often recommended at sites prone to severe competition (Grossnickle and El-Kassaby 2016). Vegetation control is also critical in determining the competitive relationship between planted seedlings and the surrounding vegetation (Balandier et al. 2006; Wagner and Robinson 2006). The interactions between tree shelter effects and stock types and vegetation control are important for maximizing the benefit of the shelters. Their interactions with vegetation control have been examined in several studies (e.g. Dubois et al. 2000; Navarro Cerrillo et al. 2005). The synergistic interactions of tree shelters with both stock type and vegetation control in combination, however, have never been studied.

Clarifying the effects of tree shelter installation and its interactions with stock type and vegetation control is important in establishing how these aspects of management can be applied to maximize the positive effects of tree shelter installation. This would contribute to developing good practice that reduces vegetation control cost, herbicide use, and the risk of browsing by mammals in plantation silviculture (Thiffault and Roy 2011; Masaki et al. 2017). In the present study, therefore, the growth responses of conifer seedlings to tree shelter installation and vegetation control were compared for the first three years after the outplanting two stock types, differing in their initial height. The experiment was conducted in a fenced clear-cut in order to focus on the combined effects of tree shelters, stock types and vegetation control, excluding deer browsing effects on seedling growth.

Materials and methods

Study site

The study was conducted in a clear cut (32°09′N, 130°44′E; 530 m above sea level) on Mt. Takatsuka (624 m high), near Hitoyoshi city in Kumamoto prefecture, in the warm temperate zone of the Kyushu district, southwestern Japan. The slope of the site is approximately 30% on average, with an east to northeast aspect. The bedrock mainly consists of andesite (lava) of Tertiary age, and the soils are light colored

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andosols (Kumamoto Prefecture 1990). The mean annual temperature and precipitation are 15.8°C and 2535 mm, respectively, at the Hitoyoshi weather station (32°13′N, 130°45′E; 146 m above sea level), which is part of the Automated Meteorological Data Acquisition System (Japan Meteorological Agency) and is located about 7.1 km north-northeast of the site. The site was previously a Japanese cypress (*Chamaecyparis obtusa*) plantation planted in 1964, which was harvested in mid-2015 – early 2016. Before the experiment started in March 2018, about two years after the harvest, the site was covered by naturally regenerated vegetation. This vegetation was removed from the site with motor-manual brush saws before the seedlings were planted to start the experiment. The site was fenced against deer before the experiment started, because browsing by sika deer (*Cervus nippon*) was observed around the site. Consequently, no browsing scars caused by deer were found on the site throughout the study period.

Experimental design

The experiment was carried out with a three factor split-plot design (Doncaster and Davey 2007), where the whole-plot factor was "vegetation control (VC)" (with weeding vs. without weeding), the split-plot factor was "tree shelter (TS)" (with shelter vs. without shelter) and "large stock type (LS)" (large vs. standard), and they were arranged in nine blocks (replicates), giving a total of 18 subplots (Figure 1). That is, each of the nine blocks had two square subplots of 6 × 6 m in horizontal distance, to which different VC treatments were applied. The subplots with and without VC were laid out in checker-board fashion as far as possible, in order to minimize the difference in the surrounding vegetation conditions (i.e. the VC statuses of the surrounding subplots) among the subplots with the same VC treatment. Within each subplot, four seedlings with different combinations of TS and LS treatments were planted: i.e. a sheltered large type, a sheltered standard type, an unsheltered large type and an unsheltered standard type. They were planted according to a 2 × 2 m grid (corresponding to 2500 seedlings ha^{-1}) with 2-m buffers to the subplot margin. The seedlings were randomly assigned to each treatment, and to each subplot and to each planting location within a subplot, minimizing any imbalance in the frequencies of the four treatment combinations between the four within-subplot planting locations. A total of 72 seedlings were measured and analyzed in this study.

Stock types

Seedling stock types used in the experiment were large and standard, differing in height at the time they were planted out. They were both one-year-old container stock of the cultivar "Ayasugi" of Japanese cedar (*Cryptomeria japonica*), acquired from an unnamed commercial nursery in Kumamoto prefecture. The cultivar is clonally propagated by rooted cuttings, and therefore the stock seedlings were genetically identical. Both stock types were produced from cuttings obtained from the same scion garden of the commercial nursery.

For both stock size types, the container type used for the production was OS-300 hardwall plastic block containers (Zenbyouren, Tokyo, Japan), one of the most commonly used nursery containers in Japan. The OS-300 container has 24 (4 × 6) round cavities (5.6 cm top dia. × 15.0 cm depth, about 300 ml) per block (45 × 30 × 15 cm^3), and therefore about 178 cavities m^{-2}. All cavities have internal vertical root training ribs to prevent root spiraling by guiding plant roots to the short side slits and drainage hole at the bottom, where the roots are air-pruned. Both stock types were produced at the same nursery density of about 178 seedlings m^{-2}, using all cavities in these standard containers, with the same period spent in the nursery. The container medium that the nursery used was not disclosed, but was the

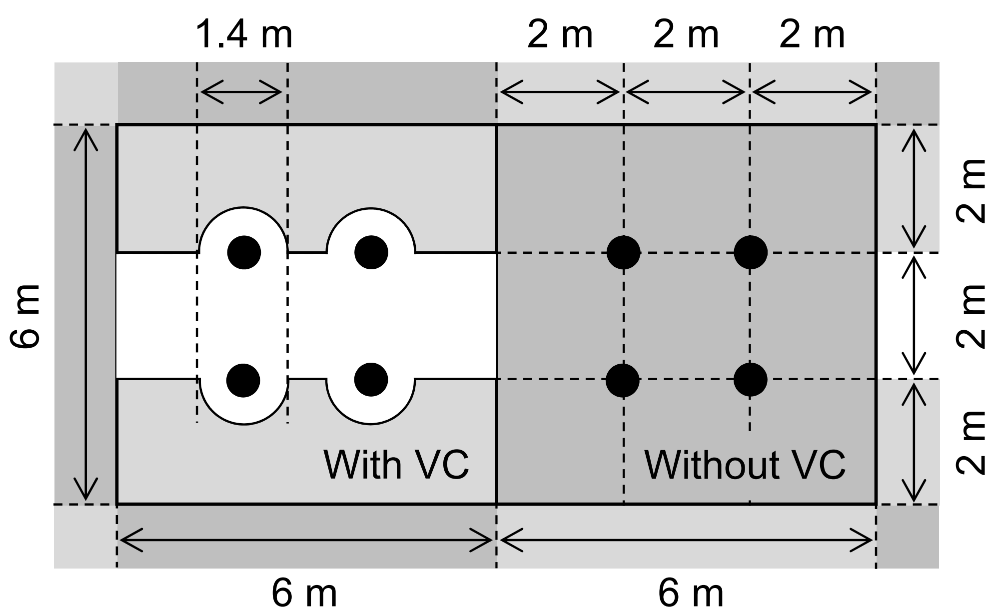

Figure 1. Schematic diagram of one block from the split-plot experimental design. Each block comprises two square subplots measuring 6 × 6 m, one with and the other without vegetation control (VC); these were laid out in checker-board fashion as far as possible. Within each subplot, four Japanese cedar seedlings were planted in a 2 × 2 m grid with 2-m buffers to the subplot margin. The four seedlings were: large stock type with and without a tree shelter, and standard stock type with and without a shelter. Each treatment combination was randomly assigned to one of the four planting spots indicated by the four black dots in each subplot. In the subplots with VC, where manual weeding was conducted once a year in summer, white areas were weeded every year, and light gray areas were weeded in the first two years in the weeding period. Dark gray areas in the subplots without VC remained intact throughout the study period.

same for both stock types. According to the nursery, the difference in height at outplanting between large and standard stock types (approximately 60–90 cm vs. 30–70 cm) was mainly attributable to the difference in fertilization. The fertilization practice, which was not disclosed, is unlikely to result in a large difference in the cost, because the price was the same for the two stock types. The large stock type was thus produced as economically as the standard stock type in the nursery.

For outplanting, seedlings of the two stock size types were acquired in February 2018. In order to cover the range of seedling trait variations within a container block, all seedlings in two container blocks were purchased for each stock type (i.e. 48 seedlings per stock type). In March 2018, 36 seedlings randomly selected for each stock type were carefully planted at the study site using a shovel. The planting practice followed Landis et al. (2010), with the planting holes deep enough to bury the plugs about 1–2 cm above the plug top. By using container stock, which is easy to plant and improves seedling establishment (Grossnickle and El-Kassaby 2016), the influences of planting technique on the results were minimized, and indeed no planted seedling died during the study period.

Tree shelters

The tree shelters used in the experiment are made from translucent white flat sheets of single-wall UV stabilized polypropylene, 0.5 mm thick, which are rolled into cylindrical tubes 140 cm tall and 10 cm in diameter, ventilated with three 2-cm-wide round holes along the length at their base (Phytoshelter S model, Phytoculture Control Co., Osaka, Japan). They are one of the most commonly used shelters in Japan. The shelters were installed around the seedlings soon after outplanting. Each shelter was staked with two 165 cm rods anchored at least 30 cm into the soil. The shelter base was not inserted into the soil, but was attached as close as possible to the soil surface.

Vegetation control

Weeding in the subplots with VC was conducted once a year in summer, using scythes and hedge shears, carefully avoiding accidental cutting. In the other areas at the study site, including the subplots without VC, the naturally regenerated vegetation remained intact after the experiment started. Any branches and foliage invading from outside the subplots with VC were trimmed off during weeding.

The weeding system employed in the subplots with VC was as follows. The weeding is conducted during the first five years after outplanting. The vegetation control method is a combination of conventional clean weeding in the first two years and then spot and strip weeding in the next three years. In the first two years, the entire area of each subplot is subjected to weeding, in order to efficiently reduce the height of competing vegetation, and establish the dominance of planted seedlings, because vegetation control at the early stage of seedling growth is critically important in establishing seedling dominance (Rosner and Rose 2006; Wagner and Robinson 2006). In the next three years, a circle of 70-cm radius around each planted seedling and the alternate strips between the planting rows (in this study, the center strip in each subplot) are weeded (Figure 1), in order to reduce the labor costs, but to ensure growth and dominance of the seedlings by removing any surrounding vegetation, including vines, and to ensure that access to the seedlings is possible for their maintenance (e.g. to address cases of trunk inclination and shelter damage; Hodge and Pepper 1998; Jacobson and Jackson 2004). For the latter three years in the weeding period, the same strips continue to be weeded every year, ensuring vegetation control in these strips. The untouched strips in between are intact and will be covered by natural vegetation. The branches and foliage invading the areas subjected to weeding (the circular areas and the strips) from the neighboring untouched strips are trimmed to ensure seedling growth. They are trimmed to eye height to provide good visibility during weeding.

During the three years of the study period, clean weeding was undertaken twice and the spot and strip weeding once. Just before the weeding in the third growing season (i.e. the first spot and strip weeding), mean vegetation height was approximately 139 cm in the subplots with VC, and the canopy was dominated by grass and fern species (mainly *Miscanthus sinensis* and *Pteridium aquilinum* var. *latiusculum*), while it was 248 cm in the subplots without VC, and the canopy was dominated by pioneer tree species (mainly *Zanthoxylum ailanthoides, Aralia elata* and *Rhus javanica* var. *roxburghii*).

In the present study, weeds (including vines) inside shelters and vines climbing on planted seedlings in both the subplots with and without VC were removed, as far as possible. For simplicity, this study did not consider the effects of weeds inside shelters or of vines on seedlings. Their effects are important but differ qualitatively from those of weeds outside shelters and of non-vine plants, respectively.

Measurements and analyses

The height (cm) and ground-level trunk diameter (cm) of each seedling were measured just before outplanting and at the end of each of the first three growing seasons (2018–2020). For each seedling, the annual absolute growth rate of seedling height (*AGRH*, cm), which equals the annual amount of height growth, was calculated for each growing season. The height/diameter ratio (*HDR*, cm cm^{-1}) of each seedling at outplanting and at the end of each growing season was also calculated as the ratio of seedling height to trunk diameter. Seedling height, *AGRH* and *HDR* were compared between treatments (i.e. TS, LS and VC) using three factor split-plot analysis of variance (ANOVA). There were no missing data because not only were there no dead seedlings, there were also no unsound seedlings (e.g. damaged seedlings or seedlings with a leaning trunk) recorded during the study period. A multiple comparison of means was performed using the Tukey method.

For each sheltered seedling, whether or not the seedling had emerged from the shelter was also recorded at the end of each growing season. The proportions (i.e. numbers) of the seedlings with protected leader shoots (i.e. within the shelter), unprotected leader shoots (i.e. out of the shelter but below deer browsing height), and escaped leader shoots (i.e. above deer browsing height) were compared between treatments (i.e. LS and VC) using Fisher's exact test. Pair-wise comparisons of the proportions between the four treatment combination types were also performed using Fisher's exact test with p-values adjusted according to Holm's method. Because the deer species at the study site was sika, the maximum browsing height of deer was assumed to be 180 cm, according to Hodge and Pepper (1998).

All statistical analyses were performed with the statistical software R version 4.0.3 (R Core Team 2020) and its packages Rcmdr version 2.7–1 (Fox and Bouchet-Valat 2020) and emmeans version 1.5.3 (Lenth 2020).

Results

Seedling height was affected by all three treatments: tree shelter (TS), large stock type (LS) and vegetation control (VC) (Table 1). The height increased with time in all treatments; the TS treatment had an especially large effect, as shown by the F-values. At outplanting, there was no difference in mean height between sheltered and unsheltered seedlings (64.4 vs. 65.4 cm, respectively). At the ends of the first, second and third growing seasons, however, mean height of sheltered seedlings was 1.3, 1.5 and 1.5 times greater than unsheltered seedlings, respectively (101.9 vs. 80.4, 151.3 vs. 100.6, and 179.1 vs. 121.6 cm). At the end of third season, a difference of approximately 50–60 cm was found in each treatment set (e.g. sheltered vs. unsheltered large type seedlings in the subplots with VC) (Table 1). In addition, the LS effect on seedling height was positive not only at outplanting but throughout the study period. The VC effect increased seedling height in the second and third seasons. The interaction between TS and VC treatments (the VC × TS factor in Table 1) was significant at the end of the second season, indicating that the VC treatment increased the TS effect on seedling height. The VC × LS interaction was significant at the end of the third season, indicating that the LS effect was greater in the plots without VC than in those with VC.

Absolute height growth rate (*AGRH*) was also affected by the TS, LS and VC treatments (Table 2). The F-values indicate that the TS effect was also greatest for *AGRH*, the mean of which was 2.5, 2.4 and 1.3 times greater in sheltered seedlings than in unsheltered seedlings in the first, second and third seasons, respectively (37.6 vs.15.1, 49.4 vs. 20.2, and 27.7 vs. 20.9 cm). In the third season, mean *AGRH* of sheltered seedlings tended to decrease from the second season, but did not become significantly smaller than that of unsheltered seedlings of the corresponding treatment (Table 2). As shown by the F-values, on the other hand, the LS effect on *AGRH* was significantly positive in the second season, while it was negative in the third season. The VC effect increased *AGRH* in the second and third seasons. With VC, in addition, the mean *AGRH* of unsheltered seedlings increased with time throughout the study period. The VC × TS interaction in the second and third seasons showed that VC significantly increased the TS effect on *AGRH* in the former season, but decreased it in the latter. The TS × LS interaction in the third season showed that the TS effect on *AGRH* was greater in the standard than in the large type seedlings.

The height/diameter ratio (*HDR*) was also affected by TS, LS and VC treatments (Table 3). The F-values indicate that the TS effect was also the most important factor for *HDR*. At outplanting, mean *HDR* did not differ between sheltered and unsheltered seedlings (94.8 vs. 92.1, respectively), but it was 1.3, 1.7 and 1.8 times greater in sheltered than in unsheltered seedlings in the first, second and third seasons, respectively (112.0 vs. 84.2, 130.0 vs. 76.0, and 119.0 vs. 67.0). In sheltered seedlings, mean *HDR* increased with time until the end of the second season, but the increase generally stopped in the third season (Table 3). In unsheltered seedlings, on the other hand, mean *HDR* generally decreased with time throughout the study period. The LS effect on *HDR* was clearly positive at outplanting but decreased with time and mostly disappeared in the second season. The VC effect decreased *HDR* in the second and third seasons, and this VC effect increased with time. The VC × TS interaction in the second season showed that the VC effect of reducing *HDR* was smaller in sheltered than in unsheltered seedlings. The TS × LS interaction in the first season showed that the positive effect of LS on *HDR* was greater in sheltered than in unsheltered seedlings.

All the treatments affected the emergence of seedlings from tree shelters and their emergence above the deer browsing height, i.e. their "exposure to browsing" status ($p < 0.001$; Table 4). At the end of the third season, approximately two-thirds of sheltered seedlings had exceeded browsing height, but none of the unsheltered seedlings had, indicating the large TS effect on exposure status. Moreover, most sheltered seedlings with LS or VC had exceeded the browsing height, but no seedlings only with TS had, indicating the importance of the LS and VC effects. At the end of the second season, however, the number of seedlings whose leader shoots were unprotected was smaller in sheltered seedlings with both LS and VC than those with only LS or VC, and more seedlings had exceeded the browsing height in the former than in the latter. Combining TS with both LS and VC was thus more effective than that with only LS or VC in shortening the period of exposure to browsing (i.e. the period during which the leader shoot of a seedling is out of the tree shelter but below browsing height).

Discussion

Tree shelters

The current study has demonstrated the great positive effect of tree shelters on the early height growth of planted conifer seedlings (Tables 1 and 2), and reinforces the results found for many other conifer and hardwood species in previous studies (e.g. Potter 1991; Ponder 1995; McCreary and Tecklin 2001). I found a substantial height difference (approximately 50–60 cm) between the sheltered and unsheltered seedlings at the end of the third growing season (Table 1). Before the end of the third growing season, the majority of the sheltered seedlings had exceeded deer browsing height, but no unsheltered seedling had (Table 4). In the third growing season, the absolute height growth rate (*AGRH*) of the sheltered seedlings greatly declined, as in other studies (Mayhead and Boothman 1997; McCreary and Tecklin 2001), but the *AGRH* was still comparable to or greater than that of the unsheltered seedlings (Table 2). A similar result was also reported by Mechergui et al. (2019). The positive effect of the shelter on early height growth was thus evident, although the future height advantage of the sheltered seedlings is uncertain (Gillespie et al. 1996; Ward et al. 2000; Ponder 2003). Their future advantage depends on

Table 1. Comparison of mean seedling height (cm) between treatments at outplanting (Yr 0) and at the end of each growing season (e.g. Yr 1 for the end of the 1st season) using three factor split-plot ANOVA, where the whole-plot factor was "vegetation control" (+, with weeding; -, without weeding) and the split-plot factor was "tree shelter" (+, with shelter; -, without shelter) and "large stock type" (+, large type; -, standard type).

Vegetation control (VC)	Tree shelter (TS)	Large stock (LS)	Yr 0	Yr 1	Yr 2	Yr 3
			Mean ± SD (n = 9 for all treatments)			
+	+	+	73.7 ± 6.4 a	120.2 ± 12.1 a	182.1 ± 16.8 a	203.3 ± 14.6 a
+	+	-	56.9 ± 3.1 b	87.6 ± 10.2 bc	148.9 ± 22.8 b	189.3 ± 14.0 a
+	-	+	74.0 ± 5.8 a	88.6 ± 7.5 bc	112.4 ± 4.1 c	142.1 ± 16.3 b
+	-	-	58.0 ± 6.0 b	75.4 ± 8.5 cd	99.1 ± 11.6 cd	129.7 ± 19.0 b
-	+	+	75.1 ± 5.8 a	111.8 ± 21.2 a	155.0 ± 29.9 b	175.9 ± 32.5 a
-	+	-	51.9 ± 12.0 b	88.2 ± 7.7 bc	119.3 ± 13.4 c	147.7 ± 23.4 b
-	-	+	77.0 ± 5.5 a	92.6 ± 7.6 b	112.7 ± 10.3 c	126.6 ± 15.2 b
-	-	-	52.4 ± 6.3 b	65.1 ± 11.4 d	78.2 ± 18.3 d	87.9 ± 20.6 c
Factors			F-values (df = 1/8 for VC, and 1/48 for the other factors)			
VC			0.57 ns	2.20 ns	30.45 ***	40.77 ***
TS			0.39 ns	75.06 ***	183.06 ***	180.94 ***
LS			166.53 ***	94.81 ***	60.53 ***	29.80 ***
VC × TS			0.03 ns	0.02 ns	5.76 *	0.47 ns
VC × LS			5.77 *	0.28 ns	2.47 ns	5.60 *
TS × LS			0.01 ns	2.49 ns	1.98 ns	0.27 ns
VC × TS × LS			0.11 ns	5.56 *	1.55 ns	0.49 ns

n (sample size) and df (numerator/denominator degrees of freedom) are the same from Yr 0 to Yr 3. Means followed by the same letters are not significantly different at $p = 0.05$ (Tukey method). Significance levels: ns, $p > 0.05$; *, $p < 0.05$; ***, $p < 0.001$.

the duration of the decrease in their *AGRH* and on the increase in *AGRH* in the unsheltered seedlings; latter of which was more clear in the subplots with VC than those without VC (Table 2).

The rapid height growth of the sheltered seedlings is attributable to the remarkable increase in their height/diameter ratio (*HDR*) (Table 3). The large *HDR*, i.e. a spindly trunk, is an adaptation to the environment inside the shelter (Mechergui et al. 2013, 2019; Mariotti et al. 2015), because the mechanical support and alleviation of desiccation by the shelter reduce the need for mechanical strength and hydraulic capacity (Holbrook and Putz 1989; Gartner 1995; Ponder 1995; Larcher 2003). The shelter allows seedlings to reduce their investment in radial growth and allocate more resources to height growth (Potter 1991; Ponder 1995; Mayhead and Boothman 1997; McCreary and Tecklin 2001; Johansson 2004; Mechergui et al. 2013, 2019; Mariotti et al. 2015). The enhanced height growth is an adaptation to the shade created by the shelter, because it speeds up access to better light conditions outside the shelter (Holbrook and Putz 1989; Henry and Aarssen 1997; Fitter and Hay 2002). After their emergence from the shelter and exposure to the external environment, however, the seedlings need to readjust their *HDR* by a resource allocation shift from height growth to radial growth (Potter 1991; Mayhead and Boothman 1997; McCreary and Tecklin 2001; Johansson 2004; Mechergui et al. 2013, 2019) and to adapt once more to the external environment imposing greater physical and physiological stresses (Holbrook and Putz 1989; Gartner 1995; Larcher 2003; Mariotti et al. 2015). In the third growing season, when the majority of the sheltered seedlings had emerged from the shelters (Table 4), the decrease in *AGRH* coincided with the cessation of the increase in *HDR* (Tables 2 and 3). This indicates the beginning of the stagnant readjustment phase, with arrested height growth. The length of this stagnant phase needs to be determined in order to evaluate the long-term overall effects of tree shelters on seedling height growth.

Stock type and vegetation control

Both large stock type and vegetation control treatments had significant effects on seedling growth. These treatments improve light availability for seedlings (Jobidon et al. 1998, 2003; Jobidon 2000; Balandier et al. 2006; Grossnickle and El-Kassaby 2016) and their effects were generally positive on both seedling height and *AGRH* in the present study (Tables

Table 2. Comparison of mean absolute height growth rate (*AGRH*, cm) between treatments in each growing season (e.g. Yr 1 for the 1st season) using three factor split-plot ANOVA, where the whole-plot factor was "vegetation control" (+, with weeding; -, without weeding) and the split-plot factor was "tree shelter" (+, with shelter; -, without shelter) and "large stock type" (+, large type; -, standard type).

Vegetation control (VC)	Tree shelter (TS)	Large stock (LS)	Yr 1	Yr 2	Yr 3
			Mean ± SD (n = 9 for all treatments)		
+	+	+	46.6 ± 9.7 a	61.9 ± 14.5 a	21.2 ± 5.4 bcd
+	+	-	30.7 ± 9.6 bc	61.3 ± 13.7 a	40.4 ± 14.8 a
+	-	+	14.6 ± 7.1 d	23.9 ± 8.0 c	29.7 ± 14.7 ab
+	-	-	17.4 ± 7.2 cd	23.7 ± 5.6 c	30.6 ± 8.7 ab
-	+	+	36.7 ± 18.3 ab	43.2 ± 15.7 b	20.9 ± 9.9 bcd
-	+	-	36.3 ± 11.8 ab	31.1 ± 8.0 b	28.3 ± 12.1 abc
-	-	+	15.6 ± 6.5 d	20.1 ± 4.6 c	13.9 ± 6.4 cd
-	-	-	12.7 ± 6.9 d	13.1 ± 8.9 d	9.7 ± 4.0 d
Factors			F-values (df = 1/8 for VC, and 1/48 for the other factors)		
VC			2.46 ns	39.30 ***	20.05 **
TS			98.43 ***	144.97 ***	9.14 **
LS			3.20 ns	4.21 *	6.77 *
VC × TS			0.00 ns	12.69 ***	7.30 **
VC × LS			1.16 ns	3.57 ns	3.55 ns
TS × LS			3.20 ns	0.32 ns	11.19 **
VC × TS × LS			5.53 *	0.24 ns	0.55 ns

n (sample size) and df (numerator/denominator degrees of freedom) are the same from Yr 1 to Yr 3. Means followed by the same letters are not significantly different at $p = 0.05$ (Tukey method). Significance levels: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Table 3. Comparison of mean height/diameter ratio (*HDR*, cm cm^{-1}) between treatments at outplanting (Yr 0) and at the end of each growing season (e.g. Yr 1 for the end of the 1st season) using three factor split-plot ANOVA, where the whole-plot factor was "vegetation control" (+, with weeding; -, without weeding) and the split-plot factor was "tree shelter" (+, with shelter; -, without shelter) and "large stock type" (+, large type; -, standard type).

Vegetation control (VC)	Tree shelter (TS)	Large stock (LS)	Yr 0	Yr 1	Yr 2	Yr 3
			Mean ± SD (*n* = 9 for all treatments)			
+	+	+	109.6 ± 10.4 a	120.7 ± 8.4 a	136.2 ± 9.5 a	108.4 ± 13.2 b
+	+	-	87.3 ± 5.4 bcd	102.8 ± 10.9 b	124.9 ± 14.0 a	118.1 ± 13.5 ab
+	-	+	107.0 ± 8.8 a	85.1 ± 8.1 c	69.7 ± 10.4 c	59.3 ± 11.2 de
+	-	-	79.6 ± 8.8 d	82.1 ± 7.1 c	65.3 ± 8.3 d	56.3 ± 6.4 e
-	+	+	101.9 ± 11.8 ab	115.2 ± 17.1 ab	132.6 ± 14.8 a	120.8 ± 12.4 ab
-	+	-	80.6 ± 16.5 d	109.5 ± 11.1 ab	126.4 ± 10.6 a	128.5 ± 11.2 a
-	-	+	98.8 ± 12.7 abc	85.8 ± 6.7 c	84.0 ± 10.6 bc	74.0 ± 7.7 cd
-	-	-	83.0 ± 9.9 cd	83.8 ± 12.5 c	86.4 ± 11.0 b	78.3 ± 6.8 c
Factors			*F*-values (df = 1/8 for VC, and 1/48 for the other factors)			
VC			1.89 ns	0.10 ns	8.05 *	26.12 ***
TS			1.38 ns	153.99 ***	459.19 ***	531.89 ***
LS			87.38 ***	10.17 **	3.73 ns	4.35 *
VC × TS			1.05 ns	0.02 ns	14.01 ***	2.40 ns
VC × LS			1.86 ns	2.17 ns	1.43 ns	0.35 ns
TS × LS			0.00 ns	4.25 *	2.42 ns	3.21 ns
VC × TS × LS			1.30 ns	1.60 ns	0.03 ns	1.09 ns

n (sample size) and df (numerator/denominator degrees of freedom) are the same from Yr 0 to Yr 3. Means followed by the same letters are not significantly different at $p = 0.05$ (Tukey method). Significance levels: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Table 4. Number of seedlings differing in the status of leader shoot protection from deer browsing (i.e. within or outside the shelter, and above or below the height of deer browsing) at the ends of the second (Yr 2) and third (Yr 3) growing seasons; proportions for different statuses were compared between treatments using Fisher's exact test.

		With vegetation control		Without vegetation control	
	Leader shoot status	Large stock	Standard stock	Large stock	Standard stock
Yr 2	Within shelter *a*	0	3	2	9
	Unprotected	3	6	7	0
	Above browsing height *b*	6	0	0	0
	$p < 0.001$	a	b	b	c
Yr 3	Within shelter	0	0	2	3
	Unprotected	1	1	0	6
	Above browsing height	8	8	7	0
	$p < 0.001$	a	a	a	b

No unsheltered seedling was analyzed because none of them had exceeded the browsing height during the study period. The proportions in the first growing season were not analyzed because emergence from the shelter was observed in only one seedling in the season (its treatment was large stock type without vegetation control). Proportions with the same letters are not significantly different at $p = 0.05$ (the pairwise p values were adjusted using Holm's method). *a* Tree shelter height = 140 cm; *b* the maximum browsing height of sika deer assumed to be 180 cm according to Hodge and Pepper (1998).

1 and 2), as found in previous studies (Jobidon 2000; Jobidon et al. 2003; Rosner and Rose 2006; Wagner and Robinson 2006; Pinto et al. 2018). The interaction between the LS and VC treatments on seedling height also shows that the advantage of LS under intense vegetative competition (Grossnickle and El-Kassaby 2016) remained even three years after outplanting. In terms of *HDR*, the initial difference associated with the LS treatment decreased rapidly and had mostly disappeared at the end of the second growing season (Table 3). This shows that the large type seedlings, which have a very spindly trunk at outplanting, acclimated successfully to the field conditions (Faure-Lacroix et al. 2013). The decrease in *HDR* by the VC treatment (Table 3), on the other hand, indicates increased allocation to radial growth and adaptation to the physical and physiological stresses caused by the vegetation removal (Jobidon et al. 1998). The surrounding vegetation would be similar to tree shelters in terms of the nurse effects alleviating these stresses (Holbrook and Putz 1989; Callaway 2007).

Moreover, the combination of the LS and VC treatments with TS had synergistic effects on seedling growth. Seedling height and *AGRH* were significantly increased by the interaction between the TS and VC treatments (Tables 1 and 2), demonstrating that VC enhances the TS effect that facilitates height growth (Dubois et al. 2000; Navarro Cerrillo et al. 2005; Chaar et al. 2008; Pinna et al. 2012; Mechergui et al. 2013). The TS effect that reduces the duration of exposure to deer browsing (McCreary and Tecklin 2001) was also increased by the combination of TS with the LS and VC treatments (see also Kittredge et al. 1992; Ward et al. 2000), which resulted in more rapid emergence of the seedlings above browsing height (Table 4). This will effectively reduce the risk of browsing by deer (McCreary and Tecklin 2001). These results were probably due to the combination of the TS, LS and VC effects on *HDR* (Table 3), because the TS effects alleviating physical and physiological stresses (Holbrook and Putz 1989; Ponder 1995) will allow the seedlings to maintain large *HDR* even in the LS and VC treatments (Kittredge et al. 1992; Chaar et al. 2008; Pinna et al. 2012; Mechergui et al. 2013, 2019), which usually require greater radial growth of the seedlings after outplanting and weeding, respectively (Jobidon et al. 1998; Faure-Lacroix et al. 2013). Consequently, the good light conditions resulting from the LS and VC treatments would have more effectively increased the height growth in the sheltered seedlings than in the unsheltered ones.

Conclusion

I found that combining tall stock with vegetation control synergistically increases the tree shelter effects on seedling height growth (Tables 1 and 2). Although a stagnant phase in height growth was observed in the sheltered seedlings, the phase began after the seedlings exceeded browsing height when TS was combined with the LS and VC treatments (Tables 2 and 4). The stagnant phase after emergence above browsing height causes no problems in terms of protection from deer browsing. In addition, the combination of TS with LS and VC greatly shortened the period during which seedlings are exposed to deer browsing (Table 4), which will also minimize the risk of browsing (McCreary and Tecklin 2001). In reducing browsing during this shortened exposure period, the spot and strip weeding method proposed in the present study would be effective, because this method leaves intact natural vegetation between the weeded rows, and the remaining natural vegetation will reduce browsing on the seedlings by providing alternative food for deer and physically impeding their approach to the seedlings (Callaway 2007; Masaki et al. 2017). The natural vegetation will also favor biodiversity, and might increase the commercial value of the timber produced and offset the vegetation control cost. Combining tree shelters with large stock and the vegetation control method used in the present study is effective in maximizing the benefit of tree shelter installation.

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Disclosure statement

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Geolocation information

The study site location: 32°9′25.22″N, 130°43′51.85″E

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