
論文 (Original article)

Factors affecting multi-stem patterns of *Cercidiphyllum japonicum* trees in a broadleaf forest under selective logging in Hokkaido

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Abstract

Cercidiphyllum japonicum has high sprouting ability leading to multi-stem growth form, which may enable successful coppicing after logging. To evaluate multi-stem patterns, we measured stem sizes of *C. japonicum* trees in a broadleaf forest in central Hokkaido, where selective logging has been conducted, and obtained stem diversity (the inverse Simpson's index) in terms of their basal area proportions. In a zone (17.8 ha) where all *C. japonicum* (71 intact and 11 logged) trees were monitored, 33 (40%) trees had multiple stems. In total 123 trees monitored in the zone and sampled along a route (3.4 km), the stem diversity increased in logged trees and in trees reaching forest canopy as their size increased. In 40 logged trees of the 123 trees, we did not detect any factors, including logging conditions (stump size and age), that affected the stem diversity. These findings suggest that logging facilitates sprouting irrespective of environmental conditions, whereas bright-light conditions are responsible for sprouting of intact trees.

Key words: coppicing, inverse Simpson's index, multi-stem growth form, slope, stump

1. Introduction

Sprouting is an effective method for self-maintenance and regeneration of trees (Klimesova and Klimes 2007). Sprouting from remaining stools can extend the longevity of individual trees after main stems have been lost because of physical damage. Such self-maintenance enables the reestablishment of forests from stump sprouts after logging, called coppicing (Buckley 2020). Coppicing with harvesting in a regular rotational interval allows sustainable tree production. Sprout regeneration is effective in managing natural forests, where seedling regeneration scarcely occurs (Xue et al. 2014). Numerous tree species have the potential for coppicing, and the capacity and property of sprouting differ among tree species (Shibata et al. 2016, Umeki et al. 2018).

Sprouting depends on both internal (physiological and developmental) and external (disturbance and environmental) factors (Dinh et al. 2019). Although most factors are species specific, common factors can be found among tree species. The age and size of stools have been considered a major determinant of sprouting (Shibata et al. 2014). The number and size of sprouts are expected to increase as the age and size of stools increase because dormant buds multiply and available resources increase (Shibata et al. 2014). In old stems of large sizes beyond

a threshold, however, dormant buds tend to be buried in thick bark and senescent, resulting in decreasing sprouting ability (Vesk 2006). Physical damage due to natural disturbances, such as wildfire (Malanson and Westman 1985), heavy snowfall (Nakano and Sakio 2018), and strong winds (Bellingham et al. 1994), seem to facilitate sprouting. Frequent disturbances on unstable substrates and steep topography may also provide sprouting opportunities (Sakai et al. 1995). Artificial disturbances, such as logging and thinning, are likely to enhance sprouting, and logging conditions may affect sprouting capacity (Pyttel et al. 2013, Adamec et al. 2017). Light conditions, water availability, and soil nutrients can affect not only the survival and growth of sprouts but also resource allocation to sprouting in trees (Bellingham and Sparrow 2009, Dinh et al. 2018).

Cercidiphyllum japonicum is mainly distributed in riparian areas of the mountain regions in Japan and has high sprouting ability leading to multi-stem growth (Kubo and Sakio 2020). This species produces more sprouts in response to disturbances and increasing age and size of stools, which compensates for rare seedling regeneration (Kubo et al. 2005). In natural forests, sprouts of *C. japonicum* are often found on steep slopes, where erosion and landslides provide a sprouting stimulus (Kubo et al. 2001). Because *C. japonicum* is neither a dominant species

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in forest stands nor the main target of coppicing practice, the effects of logging disturbances on sprouting have not been sufficiently investigated.

In a valley in Kuriyama Town, Sorachi District in the National Forest in Hokkaido, we found many stumps of *C. japonicum* (Fig. 1a-c). These stumps resulted from selective logging of large trees in the natural broadleaf forest, conducted in 1924-1925, 1940, and 1956 (Hokkaido Regional Forest Office 1988). In this valley, an experimental forest for selective logging was established in 1986 and has been monitored and harvested (Ishibashi 2002). Thus, *C. japonicum* in that valley provided us with an opportunity to investigate factors affecting multi-stem growth form due to sprouting for nearly a century in the past.

We aimed to detect potential factors affecting multi-stem patterns of *C. japonicum*. This study measured the size of living stems of *C. japonicum* trees and quantified multi-stem growth form as stem diversity (the inverse Simpson's index) in terms of their basal area proportions (Fig. 1d). We measured environmental and logging conditions for each tree and verified these effects on multi-stem patterns considering tree size as a covariate of those factors.

2. Materials and methods

2.1 Monitoring zone and sampling route

We surveyed all *C. japonicum* trees in a watershed (the monitoring zone, 17.8 ha) (Nakanishi et al. 2017) of a valley

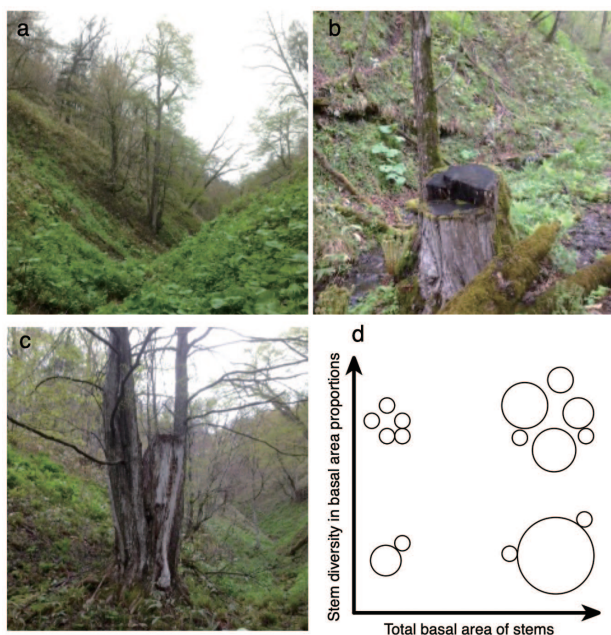


Fig. 1. *Cercidiphyllum japonicum* trees (a-c) and variables evaluating multi-stem growth form (d). Multi-stem trees on a slope of a V-shaped valley (a), a sprouting stem from a young stump (b), and sprouting stems from an old stump (c).

branch connecting to the Yubari River in central Hokkaido (42.911-42.915 ° N, 141.934-141.944 ° E, 120-240 m above sea level; Fig. 2). The downstream part of the monitoring zone is a V-shaped valley, whereas the upstream part is a flat basin surrounded by gentle ridges. The monitoring zone is located in the experimental forest (60 ha) for selective logging established by the Hokkaido Regional Forest Office (Ishibashi 2002). Intensive selective logging of large (approximately >40 cm diameter at breast height) trees in the valley was conducted in 1924-1925, 1940, and 1956 (Hokkaido Regional Forest Office 1988). The main targets of the logging were *Kalopanax septemlobus*, *Quercus crispula*, *C. japonicum*, *Magnolia obovata*, *Tilia japonica*, and *Ostrya japonica*. These trees were logged and harvested on snow in the winter, resulting in various stump heights. The maximum snow depth ranged from 0.8 to 1.8 m in typical years with light and heavy snow fall, respectively (the Mesh Climate Data 1996 compiled by

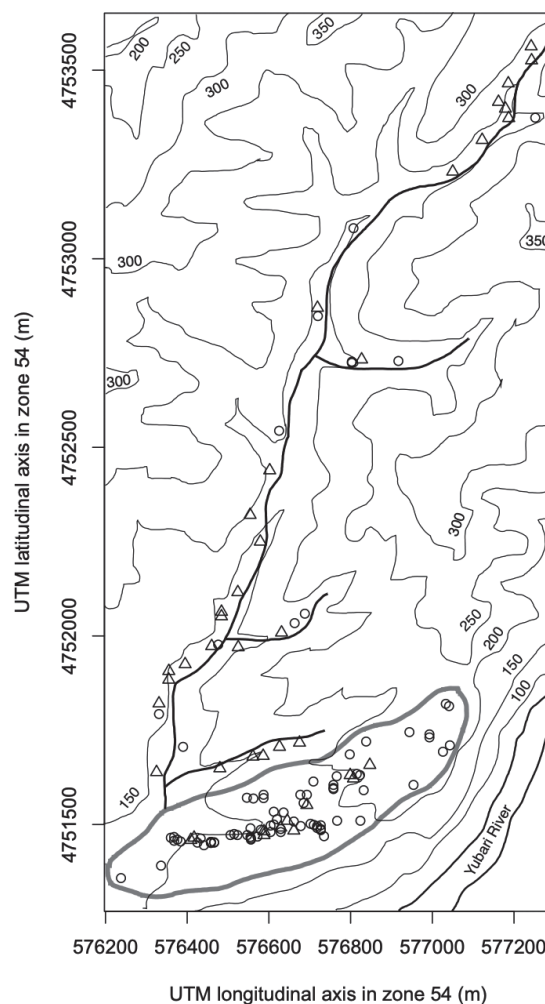


Fig. 2. Spatial distributions of *Cercidiphyllum japonicum* trees in the monitoring zone (gray envelop) and along the sampling route (thick line) in coordinates of Universal Transverse Mercator in zone 54. Circles indicate intact trees, and triangles indicate logged trees. Thin lines indicate contours.

the Japan Meteorological Agency at mesh code 64413715). Since 1986, mild selective logging has been conducted in the experimental forest for sustainable management (Ishibashi 2002).

In addition to the monitoring zone, we sampled large *C. japonicum* trees along trails in the valley (the sampling route, 3.4 km, 42.911-42.931°N, 141.935-141.947°E, 120-280 m above sea level; Fig. 2) because the number of large trees with

stumps, which had been logged in the past, in the monitoring zone was insufficient for analyses. Most sections of the sampling route were along streams, whereas some sections were on slopes on either side of streams.

2.2 Observations

We recorded tree locations in the monitoring zone and along the sampling route. The locations were transformed into

Table 1. Number of *Cercidiphyllum japonicum* trees in the monitoring zone and along the sampling route. Trees are categorized in terms of logging state, layer (trees under forest canopy or reaching it), and openness (trees surrounded by closed forest canopy and located in canopy gaps).

Logging state	Layer	Openness	Monitoring zone	Sampling route	Total
Intact	Understory	Closed	25	0	25
Intact	Understory	Gap	14	1	15
Intact	Canopy	Closed	13	3	16
Intact	Canopy	Gap	19	8	27
Logged	Understory	Closed	1	1	2
Logged	Understory	Gap	2	2	4
Logged	Canopy	Closed	5	9	14
Logged	Canopy	Gap	3	17	20
Total			82	41	123

Table 2. Parameter estimates of generalized linear model applied to all *Cercidiphyllum japonicum* trees ($n = 123$) in monitoring zone and along sampling route.

Parameter	Estimate	P value
α_0 : intercept	0.412	0.008
α_1 : intact ($x_1 = 0$) or logged ($x_1 = 1$)	0.301	0.049
α_2 : understory ($x_2 = 0$) or canopy ($x_2 = 1$)	0.367	0.012
α_3 : closed ($x_3 = 0$) or gap ($x_3 = 1$)	0.101	0.448
α_4 : slope angle a (°)	-0.001	0.725
α_5 : total basal area of stems b (m ²)	-0.579	0.298
α_6 : x_1b	0.891	0.066
α_7 : x_2b	0.165	0.906
α_8 : x_3b	0.097	0.828
α_9 : ab	0.023	0.012

Table 3. Parameter estimates of generalized linear model applied to logged *Cercidiphyllum japonicum* trees ($n = 40$) in the monitoring zone and along the sampling route.

Parameter	Estimate	P value
β_0 : intercept	0.087	0.944
β_1 : understory ($x_2 = 0$) or canopy ($x_2 = 1$)	0.120	0.839
β_2 : closed ($x_3 = 0$) or gap ($x_3 = 1$)	-0.054	0.898
β_3 : slope angle a (°)	-0.006	0.559
β_4 : total basal area of stems b (m ²)	1.888	0.722
β_5 : total basal area of stumps c (m ²)	0.873	0.452
β_6 : height of stumps h (m)	-0.016	0.977
β_7 : decay index of stumps d (0-5)	0.141	0.430
β_8 : x_2b	1.778	0.650
β_9 : x_3b	0.175	0.897
β_{10} : ab	0.020	0.594
β_{11} : cb	-2.089	0.693
β_{12} : hb	0.991	0.655
β_{13} : db	-0.704	0.177

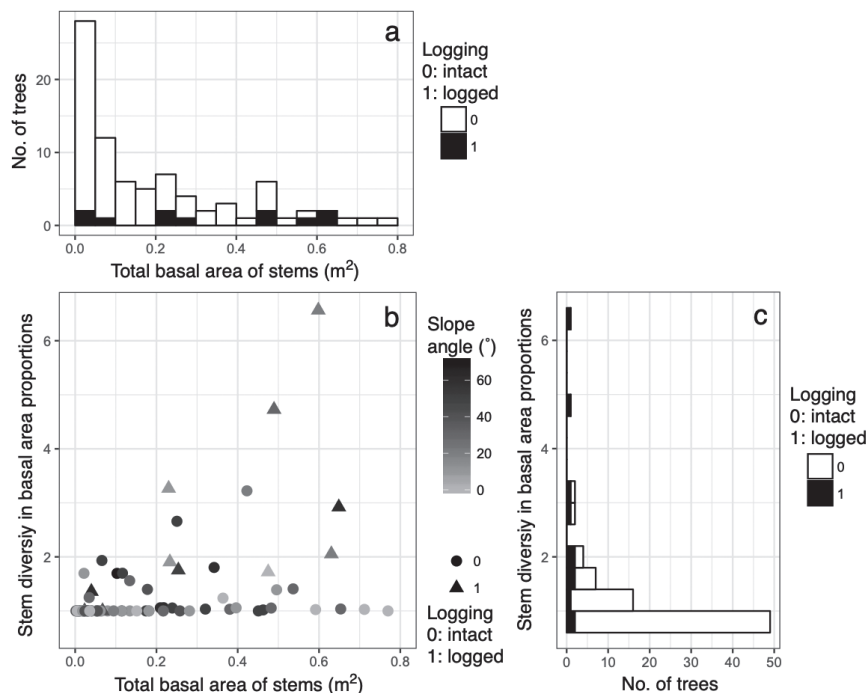


Fig. 3. Distributions of total basal area of stems and stem diversity in basal area proportions of all *Cercidiphyllum japonicum* trees ($n = 82$) in the monitoring zone. In the scatter plot (b), circles and triangles indicate intact and logged trees, respectively, and gray scales indicate slope angle ($^{\circ}$) at trees. In histograms (a, c), open and closed bars indicate intact and logged trees, respectively.

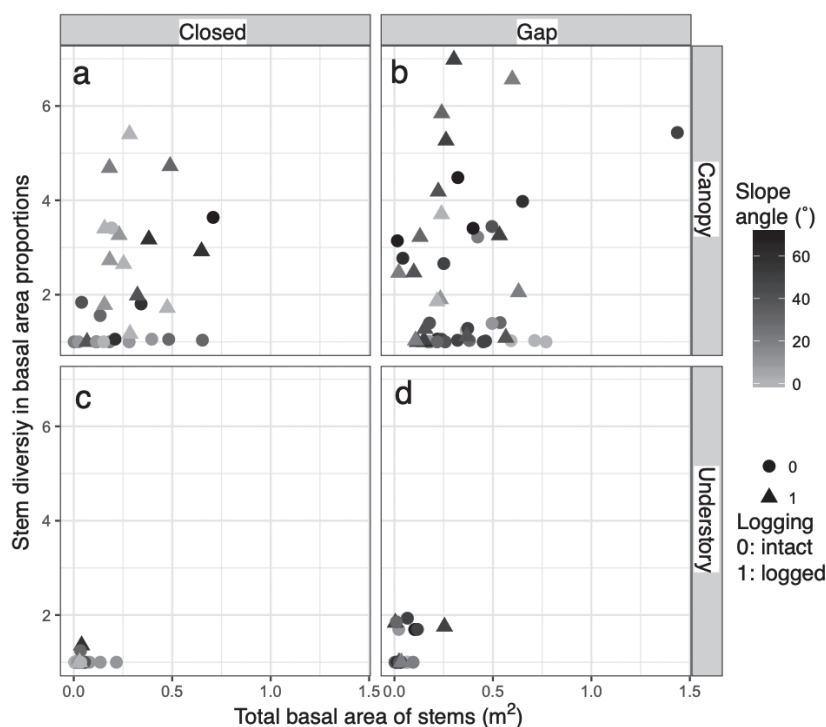


Fig. 4. Distributions of total basal area of stems and stem diversity in basal area proportions of *Cercidiphyllum japonicum* trees ($n = 123$) in the monitoring zone and along the sampling route. Trees are categorized as those under the forest canopy (lower panels: c, d) and those reaching it (upper panels: a, b), and those surrounded by the closed forest canopy (left panels: a, c) and located at canopy gaps (right panels: b, d). Circles and triangles indicate intact and logged trees, respectively, and gray scales indicate slope angle ($^{\circ}$) at trees.

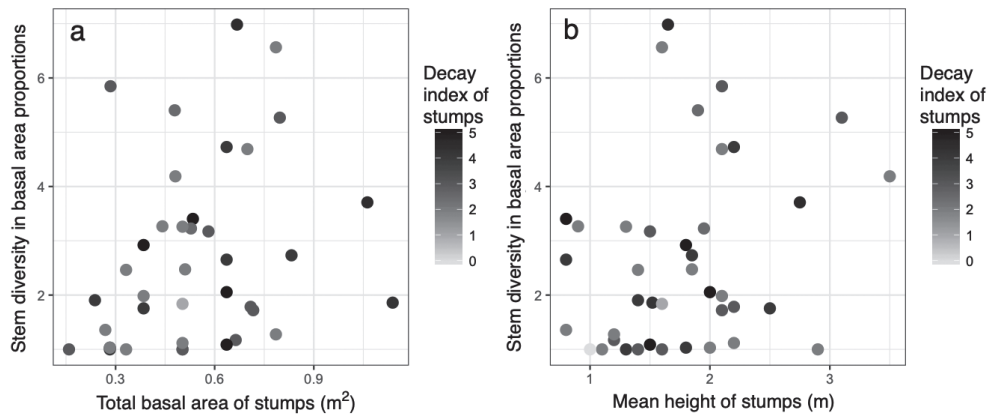


Fig. 5. Effects of total basal area (a) and mean height (b) of stumps on stem diversity in basal area proportions of logged *Cercidiphyllum japonicum* trees ($n = 40$) in the monitoring zone and along the sampling route. Gray scales indicate the mean decay index (0: youngest and 5: oldest) of stumps

longitudinal and latitudinal coordinates (m) of the Universal Transverse Mercator grid zone 54 and elevations (m) above sea level (Fig. 2). To describe environmental conditions of individual trees, we recorded the angle ($^{\circ}$) of slopes where trees were growing using a clinometer (271-3720 LandArt Inc.). Also, we categorized the layer of tree crowns into those under the forest canopy (namely understory) and those reaching it (canopy), and we categorized the forest canopy openness around tree crowns into closed and gap conditions.

We classified recorded trees as intact and logged trees, the latter of which had one or more stumps artificially logged. We measured the diameter (cm) of individual stump(s) on their upper surface using a tape measure for logged trees. We measured the height (m) of the individual stump(s) at the center from the ground surface using a measuring pole. To infer the stump age, we scored the decay index of individual stump(s) as 0 (flat surface without moss), 1 (flat surface with moss), 2 (rough surface), 3 (most surface decomposed), 4 (surface completely decomposed but most stump mass remaining), and 5 (most stump mass decomposed). The decay indices from 0 to 5 correspond from the youngest to oldest ages, respectively. To describe the logging conditions of individual trees, we calculated the total basal area (m^2), mean height (m), and mean decay index of all stump(s) of each tree.

We measured all living stems with >5 cm in the girth (cm) at breast height of each tree. To describe tree size, we calculated the total basal area b (m^2) of each tree as follows:

$$b = \sum_i a_i,$$

where a_i (m^2) is the basal area of stem i obtained from the measured girth (Fig. 1d). To quantify multi-stem patterns, we calculated the stem diversity in terms of basal area proportions for each tree as the inverse Simpson's index as follows:

$$1/\lambda = 1 / \sum_i (a_i/b)^2.$$

When a tree has a single stem, $1/\lambda = 1$, and when a tree has n stems in equal sizes, $1/\lambda = n$. When stem size greatly varies within a tree, $1/\lambda$ decreases (Fig. 1d).

2.3 Statistical analysis

The logging state $x_1 = 0$ (intact) or $x_1 = 1$ (logged) and environmental variables, including the layer $x_2 = 0$ (understory) or $x_2 = 1$ (canopy), openness $x_3 = 0$ (closed) or $x_3 = 1$ (gap), and slope angle a ($^{\circ}$), are expected to affect the stem diversity in basal area proportions $1/\lambda$ of individual trees. In logged trees, logging variables, including the total basal area c (m^2), mean height h (m), and mean decay index $0 \leq d \leq 5$ of stumps, are also expected to affect $1/\lambda$. Because sprouting capacity is likely to increase as the total basal area of stems b (m^2) increases in *C. japonicum* (Kubo et al. 2005), we considered the effects of b on $1/\lambda$. Furthermore, because the effects of environmental and logging variables on $1/\lambda$ may change with tree size, we considered interactions between these variables and b .

To examine the logging state (x_1), environmental variables (x_2 , x_3 , a), and tree size (b) and their interactions, we applied a generalized linear model to all trees in the monitoring zone and along the sampling route using the formula as follows:

$$1/\lambda \sim \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 a + \alpha_5 b + \alpha_6 x_1 b + \alpha_7 x_2 b + \alpha_8 x_3 b + \alpha_9 ab,$$

where α_0 is the intercept and α_1 - α_9 are the parameters of these effects and interactions (Table 2). In addition to this model, we applied another model to logged trees in the monitoring zone and along the sampling route using the formula as follows:

$$1/\lambda \sim \beta_0 + \beta_1 x_2 + \beta_2 x_3 + \beta_3 a + \beta_4 b + \beta_5 c + \beta_6 h + \beta_7 d + \beta_8 x_2 b + \beta_9 x_3 b + \beta_{10} ab + \beta_{11} cb + \beta_{12} hb + \beta_{13} db,$$

where β_0 is the intercept and β_1 - β_{13} are the parameters of these effects and interactions, including logging variables (c , h ,

d) because they can be examined only in logged trees (Table 3).

In these models, $1/\lambda$ followed the Gamma distribution with logarithmic link function because $1/\lambda > 0$ and its variance tended to increase as its mean increased. We fitted the models to observed variables using the function “glm” in R v.3.3.2 (R Core Team 2016). Differences in parameter estimates from 0 were verified with a t -test using the function “summary” (R Core Team 2016).

3. Results

We recorded all *C. japonicum* trees in the monitoring zone, which consisted of 71 intact and 11 logged trees (Table 1). In the 82 trees, those in the smallest size class ($b < 0.05 \text{ m}^2$) were most abundant (28 trees; Fig. 3a), and 33 (40%) trees had multiple stems ($1/\lambda > 1$; Fig. 3c). Logged trees more frequently included large and multi-stem trees compared to intact trees (Fig. 3). Stem diversity in basal area proportions ($1/\lambda$) increased as the total basal area of stems (b) increased in logged trees (Fig. 3b).

In addition to the 82 trees in the monitoring zone, we recorded 12 intact and 29 logged trees along the sampling route (Table 1). In the 123 trees in the monitoring zone and along the sampling route, tree size (b) was larger in trees reaching the forest canopy layer than in trees under it (Fig. 4). The stem diversity ($1/\lambda$) was higher in logged than in intact trees (positive α_1 of logging state x_1 , $P = 0.049$) and in canopy than in understory trees (positive α_2 of layer x_2 , $P = 0.012$; Table 2, Fig. 4). Furthermore, effects of tree size (b) on the stem diversity ($1/\lambda$) changed more positively as slope angle (a) increased (positive α_9 of interaction between a and b , $P = 0.012$; Table 2, Fig. 4), but we did not detect any other factors that affected $1/\lambda$ ($P > 0.05$; Table 2).

In 40 logged trees of the 123 trees, stumps ranged from 0.15 to 1.14 m^2 and 0.54 m^2 on average in the total basal area, from 0.80 to 3.50 m and 1.76 m on average in the mean height, and from 0.00 to 5.00 and 2.98 on average in the mean decay index (Fig. 5). These variables of logging conditions were not correlated with the stem diversity ($1/\lambda$) clearly (Fig. 5), and we did not detect any factors that affected $1/\lambda$ in the 40 logged trees ($P > 0.05$; Table 3).

4. Discussion

Scarce seedling regeneration characterizes *C. japonicum* population, which corresponds to the importance of sprout regeneration in maintaining trees and populations of this species (Kubo et al. 2005). In a riparian forest in central Honshu, saplings were uncommon. The distribution of tree sizes (the diameter of main stems) did not show a higher frequency in smaller sizes (Kubo and Sakio 2020). In contrast, the distribution of tree size (total basal area of stems) in our

monitoring zone showed higher frequency in smaller sizes, suggesting relatively frequent seedling regeneration. Although adult trees of *C. japonicum* produced seeds annually without poor crop years (Kubo and Sakio 2020), seedlings of *C. japonicum* emerged and survived at restricted habitats on bare soil, gravel, and fallen logs under bright-light conditions (Kubo et al. 2004). Thus, infrequent extensive disturbances that create bare ground and canopy gaps are likely to facilitate seedling regeneration. In the monitoring zone, selective logging that has been repeatedly conducted (Hokkaido Regional Forest Office 1988) and unstable ground substrates that occasionally induce erosion and landslides (Yamagishi and Ito 1993) may be responsible for the disturbances facilitating seedling regeneration. In comparison to that in Honshu, the abundance of *C. japonicum* tends to be high in Hokkaido, probably because of the extension of suitable habitats to lowland and the absence of competitors, such as *Pterocarya rhoifolia* (Kubo and Sakio 2020). The high abundance in Hokkaido may also result in the relatively frequent seedling regeneration observed in our monitoring zone.

Multi-stem growth form characterizes *C. japonicum* trees, which results from continuous sprouting as the age and size of trees increase (Kubo et al. 2005). On steeper slopes of V-shaped valleys, erosion and landslides tended to provide a sprouting stimulus (Kubo et al. 2001). These features are consistent with our result, which states that the effects of tree size on stem diversity changed more positively as the slope angle increased. Thus, natural disturbances seem to play an important role in sprouting. Light conditions are thought to affect not only the emergence of sprouts but also the survival and growth of sprouts in oaks (Dinh et al. 2018, 2019) and in *C. japonicum* (Kubo et al. 2005, Kubo and Sakio 2020). Although our study failed to detect the effects of the canopy gap on stem diversity, trees reaching the forest canopy had a high sprouting capacity, which is partly consistent with previous findings that sprouting was frequent and successful under bright-light conditions.

Logging of main stems often induces sprouting in *C. japonicum* (Kubo et al. 2005), which is common in various tree species under coppicing (Buckley 2020). Our study confirmed this logging effect and further explored the effects of logging conditions on sprouting using a wide variation in the age and size of stumps resulting from selective logging repeatedly conducted since 1924. Although high sprouting performance was expected in trees with old and large stumps from previous knowledge (Adamec et al. 2017, Dinh et al. 2018, 2019), any effects of logging conditions on sprouting were undetected in the model applied to logged trees. Various factors occurred in long durations after logging, reaching nearly a century, which were likely to obscure the effects of logging conditions in the past. In oak coppice forests in central Europe, harvesting

methods (manual chainsaw logging, traditional deep logging, and fully mechanized harvest) little influenced sprouting performance (Pyttel et al. 2013). These findings suggest that logging facilitates sprouting irrespective of logging conditions in some tree species with high sprouting ability.

Our study confirmed that natural disturbances and bright-light conditions facilitate sprouting, which has been found in *C. japonicum* trees in riparian forests without logging disturbances (Kubo and Sakio 2020), and further implies that logging facilitates sprouting irrespective of environmental and logging conditions. Although coppicing has scarcely been applied to *C. japonicum* owing to its low density and slow life cycle, sprout regeneration after logging contributes to sustainable selective logging in broadleaf forests, including this species. Sprouting from tall stumps may enable escaping from suppression by dwarf bamboo, which is a major obstacle of forest regeneration in Hokkaido. Protecting sprouts of oak stools using fences and enclosures effectively prevented browsing by mammals and enhanced the survival and growth of sprouts (Pyttel et al. 2013). This can be applied to selective logging forests vulnerable to browsing by sika deer in Hokkaido.

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北海道の択伐された広葉樹林におけるカツラ (*Cercidiphyllum japonicum*) の多幹性に与える要因

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要旨

カツラ (*Cercidiphyllum japonicum*) は、高い萌芽能力を持ち、複数の幹からなる樹形になりやすく、天然林での伐採後に萌芽更新が期待される。多幹性を評価するため、北海道中央部の択伐を受けている広葉樹林でカツラの幹のサイズを測り、断面積割合による幹の多様度 (シンプソン指数の逆数) を求めた。すべてのカツラの木 (非伐採木71本と伐採木11本) を観察した調査区 (17.8 ha) において、33本 (40%) の木が複数の幹からなっていた。その調査区に加えて3.4 kmの調査ルート沿いで測定した合計123本は、伐採されているか、林冠に達すると、幹の多様度が高まった。それら123本のうちの伐採木40本では、伐採の状態 (切り株の古さとサイズ) を含む要因のなかで幹の多様度に影響した要因は検出されなかった。これらの結果は、環境条件にかかわらず伐採が萌芽を促進し、明るい光環境が非伐採木の萌芽の原因となっていることを示唆する。

キーワード：萌芽更新、シンプソン指数の逆数、多幹成長型、斜面、切り株

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