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ORIGINAL ARTICLE

An alternative management regime of selection cutting for sustaining stand structure of mixed forests of northern Japan: a simulation study

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Abstract In uneven-aged conifer–broadleaved mixed forests in Hokkaido, northern Japan, single-tree selection cutting has been a common management practice since the early twentieth century. This practice is expected to produce timber without major changes in stand structure or tree species composition. The demographic response of forests to this practice has often been unexpected, and degradation of stand properties has been widely observed. We propose here a sustainable management regime of selection cutting, based on an individual-based forest dynamics simulation model, SORTIE-ND. Our simulations, based on demographic data from 15 long-term monitoring stands, suggest that selection cutting using a lower cutting intensity together with a longer rotation period and reduced removal of small trees and conifer species is more appropriate than traditional systems in terms of maintaining stand structure and tree species composition, as well as being profitable financially. Supplemental regeneration practices, which can counter accidental mortality incurred during harvesting operations, would also be necessary to ensure tree recruitment.

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Keywords Cutting intensity · Cutting rotation period · Forest modeling using SORTIE-ND · Natural uneven-aged mixed forest · Single-tree selection system

Introduction

Forest management regimes are shifting to include greater focus, not only on sustaining wood production, but also on maintaining various functions of ecosystems (Kohm and Franklin 1997; Hunter Jr 1999; Puettmann et al. 2008). Ecological based management of forests generally emphasizes the maintenance or restoration of stand structure, including tree volume, size distribution, and tree species composition, of natural forests based on an improved understanding of emulations of patterns and processes observed in the natural disturbance regime (Coates and Burton 1997; Harvey et al. 2002; Kuuluvainen 2002; Seymour et al. 2002). In this sense, relative to clear cutting, the merits of partial cutting have been recognized, notably for retaining biological legacies that can be important for biodiversity and ecosystem functions (Franklin et al. 2002; Matsuda et al. 2002).

Fine-scale gap disturbance influences the stand structure of cool–temperate conifer–broadleaved mixed forests in Hokkaido, northern Japan (Hiura and Fujiwara 1999; Kubota 2000). Single-tree selection cutting, which introduces small gaps in a stand, has been a common management practice since the early twentieth century (Matsui 1976). This practice is generally expected to promote the growth of residual trees, regardless of the tree species and size classes, and to produce timber without major changes in the stand structure or tree species composition. However, the response of forests to single-tree selection cutting in Hokkaido has often been unexpected and, to some extent, the positive effects of cutting on growth and survival of residual trees, and on regeneration, have been limited (Noguchi and Yoshida 2007, 2009; Miya et al. 2009). In effect, degradation of stand structure has been widely observed (Noguchi and Yoshida 2004; Yoshida et al. 2006). Improvement of the traditional forest management regime, to achieve harmony between resilience and preservation of the ecosystem, is therefore highly desirable. In particular, cutting intensity (the amount to be harvested) in relation to a corresponding rotation period, which essentially determines the extent of disturbance, should be reconsidered. They have traditionally been based entirely on net volume growth of the sample stands (Matsui 1976), but their long-term effects on stand structural and compositional attributes have rarely been evaluated.

The aim of this study was to explore an ecologically sound forest management regime of selection cutting for maintaining the original stand structure and species composition of a northern Japanese natural mixed forest. A field experiment involving various cutting regimes (e.g., Jalonen and Vanha-Majamaa 2001; Haeussler et al. 2007) would, in principle, be effective for this purpose; however, the time horizons necessary for determining the medium- to long-term outcomes, and the high establishment and operational costs temper interest in this option. We therefore used a simulation approach for predicting the long-term responses of a stand to various silvicultural cutting scenarios (Gratzer et al. 2004; Uriarte et al. 2009). We first estimated the parameters specifying the forest dynamics (i.e., individual growth, mortality, and recruitment) which are required by a simulator (SORTIE-ND), based on a large set of field data. Following validation of the model, we determined the effects of several selection cutting scenarios. Allowable cutting intensity, with regard to the net growth rate of sample stands in Hokkaido, is generally estimated to be approximately 1–2 % year^{-1} on average (in terms of volume; Hokkaido Prefecture 2000). Consequently, we used a 10 % cutting intensity (to living stock) with a 10-year rotation period as the standard for our study, and compared it with scenarios having different combinations of cutting intensity and rotation period. Finally, in the discussion, we propose a sustainable silvicultural regime based on the simulation results examining the effects of cutting on changes in the basal area sum, size structure, and tree species composition, as well as the financial profit.

Methods

Study sites

Our simulation was of natural conifer–broadleaved mixed forests in northern Hokkaido. The parameters required for the simulation were estimated from the data for stand structure, dynamics, and individual tree properties in 15 long-term monitoring stands in the Nakagawa (the forest office is at 44°43′N, 142°16′E) and Uryu Experimental Forest (44°22′N, 142°16′E) of Hokkaido University. The mean annual temperatures is around 5 °C, and the mean annual precipitation is about 1,400 mm, with 1.5–3 m of maximum snow cover in winter. These monitored stands, 0.5–3 ha in area, have been studied for 5–25 years at intervals of 1–10 years. For about 10,000 individual trees (consisting of 17 tree species), we measured the diameter at breast height (DBH) or diameter at the base, tree height, crown depth, crown radius, and location (X–Y coordinate) of individual trees.

The model validation and simulations were performed using the data obtained from a selection-cut stand (3.2 ha in area) in the Nakagawa Experimental Forest. The stand consists of evergreen conifers, mainly *Abies sachalinensis* (Fr. Schm.) Masters, and deciduous broadleaved species including *Quercus crispula* Bl., *Acer mono* Maxim., *Betula ermanii* Cham., and *Tilia japonica* (Miq.) Simonkai commonly in a multi-aged and uneven-sized stand structure (Yoshida et al. 2006). The forest floor in these stands is generally densely covered with dwarf bamboos, *Sasa senanensis* (Franch. et Savat.) (Rehd.) and *Sasa kurilensis* (Rupr.) Makino et Shibata (Noguchi and Yoshida 2005). In this stand single-tree selection cutting has been conducted at 9- to 10-year intervals, with harvesting intensities of around 10 % in volume (Ohgane et al. 1988; Yoshida et al. 2006). These intensities were determined in consideration of the repeated census data to maintain harvested volume equivalent to the growth increment. The harvested trees were selected from a broad range of size classes and no preference was shown for any particular tree species.

Simulator

We employed SORTIE-ND, a spatially explicit, individual-based forest dynamics model (ver 6.09; Murphy 2008; http://www.sortie-nd.org/) as the platform for the simulations. The model considers species-specific demographic parameters such as growth, death, and establishment of trees. The original SORTIE program was developed for hardwood forests in the northeastern USA (Pacala et al. 1993, 1996), and has since been improved to apply for tropical, temperate, and boreal forests (Coates et al. 2003; Uriarte et al. 2009; Thorpe et al. 2010). The latest version SORTIE-ND, with modular structure and open source code, enables us to look at spatially explicit effects of competition and disturbances including forestry activities. Details of the simulator are available in a SORTIE-ND manual (Murphy 2008).

Parameter estimations

Forest properties were updated every 5 years (basic timestep) in the simulations. ‘Trees’ in the model were assigned to one of five conditions: seed, seedling, sapling, adult, and coarse woody debris. ‘Seedling’ represents the first growing stage (defined as trees with height less than 2 m in this study) after germination of ‘seeds’, followed by ‘sapling’ (height at least 2 m and DBH less than 12.5 cm) and adult (DBH at least 12.5 cm). Adult trees were further grouped into four size-classes (DBH 12.5–22.5 cm, 22.5–32.5 cm, 32.5–42.5 cm, at least 42.5 cm). Dead trees were regarded as ‘coarse woody debris’. Trees in the SORTIE-ND were assumed to have cylindrical crowns. We estimated the tree height, crown depth, and crown radius using their species-specific allometric relations to DBH (cm), based on monitoring data.

If the sample size of a particular tree species for a particular parameter was insufficient, the parameterizations were based on species groups, according to taxonomy (conifer or broadleaved species) and shade-tolerance (tolerant and intolerant), involving shade-tolerant conifers (CF), shade-tolerant broadleaved (BT), and shade-intolerant broadleaved species (BI) (Yoshida et al. 2006).

Tree growth

The diameter growth parameters, with the assumption of light-dependency, were estimated from the long-term monitoring data. Diameter growth of individual trees was calculated at every timestep, and added to the original tree DBH. Tree height, crown depth, and crown radius were accordingly modified with the updated DBH based on allometric relations.

The amount of light available in a growing season (May–Sep) for an individual tree was calculated as the gap light index (GLI; Canham 1988; Beaudet et al. 2011), at the mid-crown of trees, taking into account the sun-track, assumption of open sky distribution, and light transmission in the crown. We referred to Pacala et al. (1996) for the light transmission of various tree species. The light model in SORTIE-ND has been evaluated and used independently by Beaudet et al. (2002, 2011) and Lefrançis et al. (2008). Because of model constraints, we did not explicitly consider topographic factors in this study.

The logistic and linear growth models (sensu SORTIE-ND; Murphy 2008), which assume light-dependent individual growth, were respectively applied for adults and saplings. Growth of seedlings was assumed to be constant in this model; most seedlings in the monitored stands were grown under a dense carpet of understory plants (dwarf bamboos), so that the growth dependency on light conditions created by overstory trees is presumably not important (Noguchi and Yoshida 2007). We applied the averages of the diameter increment at the base (height 0.1 m) observed in the monitored stands for each tree species.

Tree mortality

We considered several factors for tree mortality in our model. First, adult and sapling mortality were assumed to be dependent according to species on the estimated diameter growth; the slower the growth, the higher the probability of mortality (BC mortality in SORTIE-ND; Murphy 2008). Second, a higher mortality rate due to senescence was assumed for adult trees by considering the species-specific maximum DBH observed in the monitored stands (senescence mortality in SORTIE-ND). Third, an accidental mortality, caused by harvesting and logging operations, was set for adults and saplings at the timestep when cutting was conducted (episodic mortality in SORTIE-ND); its regression with cutting intensity was estimated. Previous studies have reported the significance of this type of mortality in managed forests of this type (Noguchi and Yoshida 2009; Miya et al., in preparation). Fourth, for seedlings, a random mortality (background mortality in SORTIE-ND) was applied based on the observations in the monitored stands.

We also allowed for mortality caused by episodic natural disturbances (storm behavior in SORTIE-ND). The historical record of wind-induced damage caused by a powerful typhoon in 1954 (Yoshida and Noguchi 2009) was taken as the most severe windthrow. Severe typhoon damage again occurred throughout the region in 2004 (Yoshida et al. 2011), so that the rotation period of the disturbance was assumed to be 50 years.

Tree establishment

Tree recruitment in the model is a function of seed dispersal and seed germination. The annual supply of seeds in the forest simulation was taken to be proportional to the basal area sum of parent trees, defined as conspecific trees larger than the minimum seed-production size (given by Koike et al. (1992)), based on the data from one of the monitored stands (Uryu Experimental Forest, unpublished data). Because we lacked reliable data on seed germination rate, parameters were set according to the density of current-year seedlings observed for each species for each substrate type (to be explained shortly) at several monitored sites (Yoshida et al. 2005; unpublished data); the rates were calculated assuming a linear correlation with the estimated seed supply.

Several substrate types (i.e., conditions of forest floor) were specified for the square grid of side 8 m, which divides the simulated stand. The standard condition is ‘forest floor’. ‘Fresh logs’ are supplied by tree death (the proportion in the grid was determined from the DBH of the dead trees); these gradually changed into ‘decayed logs’ over 25 years, in which most cut stumps moved into the third decay class (of five classes; Inoue et al., in preparation). ‘Tip-up mounds’ can be created when a live tree dies, with species- and size-specific probabilities, as presented by Yoshida and Noguchi (2009). ‘Scarified soil’ represents disturbed areas caused by tree cutting, and are assumed to appear with a certain proportion (estimated as 20 % from personal observation) in the grid after a cutting event. The durations required for the transition to ‘forest floor’ from ‘decayed log’, ‘tip-up mound’, and ‘scarified soil’ were taken as 50, 10, and 10 years, respectively (approximations based on personal observations).

Model evaluation

We evaluated the model by comparing the simulated results with actual stand dynamics from a monitored site; the changes in basal area and DBH class distributions were assessed respectively with 95 % confidential intervals and Chi-square test derived from ten simulation runs. The data observed over 20 years were obtained from the 3.2 ha of selection-cut stand (see “Study sites”), which was not used in the parameter estimations. In the simulations the initial stand condition was set as actually recorded. Because of the absence of data on seedlings, saplings, and forest floor substrate in the past data, we set their initial conditions according to values measured in a neighboring unmanaged stand (Miya et al., unpublished data). The attributes of cuttings (e.g., cutting intensity for each tree species and for each size class) were chosen to be close to the actual cutting records.

Cutting scenarios

We then simulated (ten repetitions) a series of silvicultural scenarios, with particular focus on effects of cutting intensity and rotation period. The number of repetitions was ten. As the net growth rate of natural forests in Hokkaido is estimated to be approximately 1–2 % year^{-1} on average (in terms of volume; Hokkaido Prefecture 2000), we used a 10 % cutting intensity (defined in this study as the percentage of basal area sum of cut trees to the living stock) with a 10-year rotation period as the standard for our study, and compared it with scenarios having different combinations of cutting intensity and rotation period (Table 1). Since the traditional regime has often caused stand degradation (Yoshida et al. 2006), we allowed a halved cutting intensity (relative to the standard) in the last two scenarios. Initial stand properties were set as the recent condition of the 3.2 ha area (160 m × 200 m) of the selection-cut stand (Table 2). Cutting intensity was assigned proportional to the pre-harvest basal area sum of each tree species group and each DBH class.

Table 1 Cutting scenarios examined by the simulation in this study

Scenario ID#	Cutting intensity (% to living stock)	Rotation period (years)
10–10	10	10
20–20	20	20
5–10	5	10
10–20	10	20

Cutting targets in terms of tree species and size were set proportionally to the initial stand conditions (shown in Table 2 and Fig. 1). See text for details

Table 2 Species composition of the sample stand, which corresponds to the ‘measured’ stand in Fig. 1

Species	Species group[a]	Basal area m^2 ha^{-1} (%)	Stem density ha (%)
Abies sachalinensis	CF	5.6 (48)	42 (36)
Quercus crispula	BI	1.4 (12)	11 (9)
Acer mono	BT	1.2 (10)	18 (15)
Betula ermanii	BI	1.0 (9)	12 (10)
Tilia japonica	BT	0.9 (8)	11 (10)
Other species[b]	–	1.7 (15)	24 (20)
Total	–	11.8 (100)	117 (100)
Shade-tolerant conifer	CF	5.7 (48)	43 (37)
Shade-tolerant broadleaved	BT	2.7 (23)	38 (32)
Shade-intolerant broadleaved	BI	3.4 (29)	37 (31)

Trees with DBH equal to or larger than 12.5 cm (defined as ‘adults’ in this study) were considered in this table. The condition was used for the initial state for the simulations

[a] Classification was based on Yoshida et al. (2006); *CF* conifer, *BI* shade-intolerant broadleaved species, *BT* shade-tolerant broadleaved species

[b] Other species include *Ulmus davidiana* (BT), *Kalopanax pictus* (BI), *Alnus hirsuta* (BI), *Sorbus alnifolia* (BT), *Magnolia obovata* (BI), *Phellodendron amurense* (BI), *Picea glehnii* (CF), *Sorbus commixta* (BT), *Salix hultenii* (BI), *Betula platyphylla* (BI), *Acanthopanax sciadophylloides* (BT), and *Fraxinus mandshurica* (BT) (in order of dominance)

Analyses

Results of the simulations, the averages of ten repetitions, were evaluated using three indices. Basal area recovery is expressed as a percentage of the term-end basal area sum relative to the initial value. Similarities in tree species composition and size structure are represented by the Bray–Curtis index. The statistical differences in these variables among scenarios were tested with one-way ANOVA and Tukey's HSD post hoc test.

To assess the economic feasibility of the scenarios, we estimated the potential financial profit based on income from timber sales and costs of harvesting operations. The former was calculated by multiplying the amount of merchantable trees (empirically assumed to be 65 % of cut volume, with 90 % of lower grade timber for pulp and wood chips; personal communication with Nakagawa Exp. For.) by the current timber price of each tree species (Hokkaido Prefecture 2010). Harvesting expenses included labor and machinery costs for cutting and skidding, and were estimated based on their relation to the amount of harvested trees (Nakagawa Exp. For., personal communication). Because economic conditions are volatile in the long-term, the resulting financial income and expenses are shown separately as a proportion relative to the standard scenario.

Results

The simulation reproduced the 20 years of change in the basal area sum and size structure (Fig. 1); the observed basal areas from the monitored stand were within the 95 % confidential interval derived from the ten runs for the validation exercise. Moreover, the term-end DBH class distributions were not significantly different between the model and the field data, both when considering all species ($P = 0.75$) and each species group (conifer, $P = 0.58$; shade-tolerant broadleaved, $P = 0.53$, shade-intolerant broadleaved, $P = 0.73$).

The basal area sum fell to 53.2 % of the initial value under the scenario #10–10 in 100 years (Table 3). The greatest decrease was for conifers (38.8 % of initial basal area sum), followed by shade-intolerant broadleaved (63.3 %) and shade-tolerant broadleaved species (70.7 %). The similarities of tree species composition and size structure were respectively 0.62 and 0.53 (Table 3 and Fig. 2).

Scenario #20–20, with doubled cutting intensity (20 %) and doubled rotation period (20 years), resulted in a 62.7 % recovery. Conifers again showed a drastic decrease (43.9 % of initial basal area sum), whereas shade-tolerant broadleaved species showed greater recovery (91.3 %) than in scenario #10–10. The similarities of tree species composition and size structure were respectively 0.67 and 0.62. Financial income was similar (101 %), but expenses were less than two-thirds of the scenario #10–10 (64 %).

Scenario #5–10, with halved cutting intensity (5 %) together with maintaining a 10-year rotation period, gave significantly higher recovery in basal area sum (75.3 %). Shade-intolerant broadleaved species recovered fully (96.2 %) to the initial condition, but conifers and shade-tolerant broadleaved species recovered less, at 61.0 and 78.9 %, respectively. The similarity of tree species composition was 0.75, and that of size structure was 0.60. Financial income and expenses decreased respectively to 67 and 90 % of scenario #10–10.

Scenario #10–20, with the doubled rotation period (20 years), resulted in an 83.5 % recovery, which was the highest of the scenarios considered (difference compared with scenario #10–10 was significant). This higher recovery was derived mainly from shade-intolerant to shade-tolerant broadleaved species (97.9 and 87.7 %, respectively), whereas that for conifers was still lower (71.5 %). Similarity of tree species composition was 0.78, and that of size structure was 0.63 (Table 3). Financial income fell to 70 %, but expenses also fell to 54 % relative to scenario #10–10.

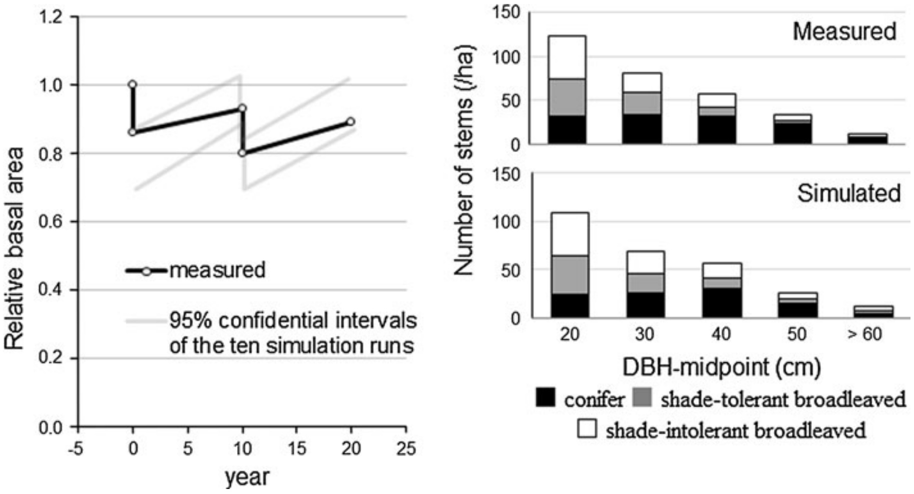

Fig. 1 Comparisons of changes in basal area (relative to initial values) (*left*) and the end-term DBH class distributions (averages of ten simulations) (*right*) predicted by the simulator with those observed in the field censuses

Table 3 Simulation results for the four cutting scenarios

Scenario ID#	Amount of cut in BA (m^2 $year^{-1}$ ha^{-1})	BA change (% of the term-end to the initial)				Similarity (index of the term-end to the initial)		Financial profit (proportion relative to scenario #10–10)	
		CF	BT	BI	Total	Species composition	DBH class distribution	Expenses	Income
10–10	0.095^{a}	38.8^{a}	70.7^{a}	63.3^{a}	53.2^{a}	0.62^{a}	0.53^{a}	1.00^{a}	1.00^{a}
	(0.008)	(10.4)	(5.6)	(12.7)	(8.2)	(0.07)	(0.03)	(0.02)	(0.16)
20–20	0.102^{b}	43.9^{a}	91.3^{b}	71.8^{a}	62.7^{a}	0.67^{a}	0.62^{bc}	0.64^{b}	1.01^{a}
	(0.006)	(11.6)	(8.1)	(10.8)	(7.3)	(0.05)	(0.02)	(0.02)	(0.12)
5–10	0.058^{c}	61.0^{b}	78.9^{a}	96.2^{b}	75.3^{b}	0.75^{b}	0.60^{b}	0.90^{c}	0.67^{b}
	(0.003)	(11.5)	(6.5)	(12.1)	(7.4)	(0.04)	(0.02)	(0.01)	(0.07)
10–20	0.061^{c}	71.5^{b}	87.7^{b}	99.9^{b}	83.5^{b}	0.78^{b}	0.63^{c}	0.54^{d}	0.70^{b}
	(0.004)	(21.4)	(6.5)	(17.1)	(14.4)	(0.07)	(0.03)	(0.01)	(0.07)

The averages (standard deviations in parentheses) of the ten simulations are shown. Different superscript letters indicate significant difference ($P < 0.05$ at one-way ANOVA, Tukey's test) between scenarios. Explanations of each scenario are provided in Table 1

BA basal area at breast height, *CF* conifer species, *BT* shade-tolerant broadleaved species, *BI* shade-intolerant broadleaved species

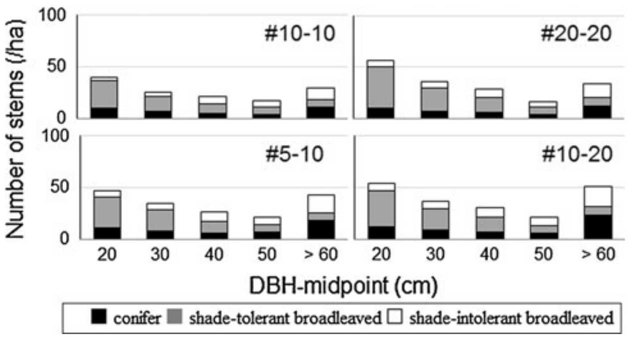

Fig. 2 Simulation results showing the end-term DBH class distributions of the four scenarios (see also Table 3). Averages of ten simulations are shown

Discussion

This work constitutes one of the first long-term simulation studies of managed mixed-species stands in Hokkaido and, as such, further studies are clearly needed to validate its assumptions and refine the simulations. SORTIE-ND is a flexible open source program, and it would be possible to include artificial regeneration options in further studies. Topographic considerations could also be integrated to reflect real site conditions of sloped sites. Also, we could increase the confidence in assumptions regarding mortality and recruitment by performing more detailed demographic studies. In particular, seedling dynamics beneath understory dwarf bamboos should be included in the subsequent models.

None of the four scenarios, especially #10–10 and #20–20, produced adequate recovery in terms of the basal area sum, tree species composition, and size structure (Table 3; Fig. 2), suggesting that these management regimes are not sustainable over the long-term. The simulated stand degradation ostensibly reflects negative factors associated with cutting. Traditional thinking concerning allowable cutting intensity, based on estimated net volume growth rate (Matsui 1976), clearly appears to fall short in terms of maintaining the forest structural attributes. It is essential to account for natural variability, notably episodic disturbances and unexpected demographic responses due to cutting, to estimate the cutting strategy.

Obviously reduction of the cutting intensity (the amount to be harvested) is necessary for a sustainable silvicultural scenario in this type of mixed forest. Even in the scenarios with halved cutting intensity (#5–10 and #10–20), the recovery in terms of basal area sum was only around 80 % (Table 3). This was due to the effects of disturbance (i.e., periodic typhoon), and the shortage of regeneration; the densities of small trees were less than 50 % in any of the scenarios (Fig. 2). The understory of forests in northern Hokkaido are generally covered with a dense dwarf bamboo carpet, and it is therefore difficult to expect a significant increase in regeneration density after a cutting (Nagaike et al. 1999; Noguchi and Yoshida 2004, 2007). Consequently, we propose that the reduction of the cutting intensity should be associated with targeting less on small trees to a maximum extent.

In addition, reducing the chance of accidental mortality induced by harvesting and skidding operations (i.e., to reduce cutting frequency) would be effective. This type of mortality is particularly significant in small trees (Noguchi

Table 4 Simulation results for the alternative cutting scenario

Scenario ID	Amount of cut in BA (m^2 $year^{-1}$ ha^{-1})	BA change (% of the term-end to the initial)				Similarity (index of the term-end to the initial)		Financial profit (proportion relative to scenario #10–10)	
		CF	BT	BI	Total	Species composition	DBH class distribution	Expenses	Income
Alternative	0.062	83.9	101.1	103.8	93.6	0.71	0.82	0.54	0.77
	(0.004)	(14.9)	(13.1)	(7.7)	(8.3)	(0.02)	(0.05)	(0.01)	(0.08)

The averages (standard deviations in parentheses) of the ten simulations are shown

BA basal area at breast height, *CF* conifer species, *BT* shade-tolerant broadleaved species, *BI* shade-intolerant broadleaved species

and Yoshida 2007), so careful attention to the conservation of those during the operations should also contribute to maintaining regeneration. In this case, we suppose that extending the rotation period is more effective than reducing each cutting intensity for enhancing recovery, because the mortality does not increase proportionally to the cutting intensity (it rather appeared to be affected by the total distance of skidding; Miya et al., in preparation). In fact, the scenario with shorter rotation (e.g., scenario #10–10) gave significantly greater size-class similarity than that with correspondent longer rotation (#20–20; Table 3).

Our model simulations also suggest that reducing the cutting intensity of conifer species is likely to have a positive effect on maintaining the initial stand properties. The basal area sum of conifers recovered only 68.5 % of maximum in these simulations (Table 3), indicating that these scenarios would be unable to maintain tree species composition. Conifer regeneration has been shown to be limited under selection cut management (Yoshida et al. 2006; Noguchi and Yoshida 2007), due apparently to increased mortality of small trees in canopy gaps created by cutting (Yoshida and Noguchi 2010). Higher mortality of adult conifers was also observed where cutting was conducted in the surrounding area, probably as a result of sudden changes in growth conditions (Noguchi and Yoshida 2009).

In summary, the necessary conditions for a selection cutting that is more likely to sustain the stand structure and dynamics of mixed forests are (1) to set a lower cutting intensity with a longer rotation period, (2) reducing the accidental mortality, and (3) targeting less on small trees and conifer components. On the basis on these, we present an alternative selection cutting regime, with the simulation set at a 10 % cutting intensity and 20-year rotation period, with more trees cut in the larger DBH classes and broadleaved species. Specifically, the cutting avoided targeting trees with DBH 12.5–22.5 cm (irrespective of species), and the cutting intensity for conifers was set at 8 %; the reduction in cutting intensity was compensated by proportionally targeting trees in the larger DBH classes and broadleaved species. At the same time, we assumed accidental mortality would be reduced by 50 %.

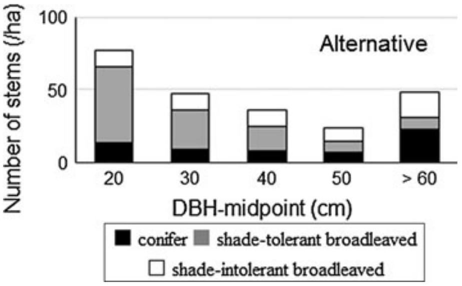

Fig. 3 Simulation results showing the end-term DBH class distributions of the alternative scenario (see also Table 4). Averages of ten simulations are shown

The simulation outcome at 100 years (Table 4; Fig. 3) showed considerable improvements; basal area sum had recovered to 93.6 % and that of conifers, shade-tolerant broadleaved, and shade-intolerant broadleaved species attained values of 83.9, 101.1, and 103.8 % respectively, relative to the initial values.

Although financial income was three-quarters (77 %) relative to the initial values, expenses fell to about half (54 %). The improved basal area recovery enabled the increase in cutting, producing better income in the period. Targeting broadleaved species, which generally have higher timber prices in the current market, also contributed to income. On the other hand, the effect of extended rotation on the expenses was also significant; as shown in the comparison between the scenario #10–20 and #10–10 (the former brought two-thirds of the income, but involved only half of the expenses), the proportion of fixed costs per cutting was considerable. The profit is particularly pronounced in the current market conditions of low timber prices and high costs of cutting.

Nevertheless, the similarity of tree species composition and size structure of the alternative scenario remained at a relatively low level (0.71 and 0.82, respectively), as a result of the reduced tree density in smaller size-classes. This effect should be countered by practicing artificial regeneration (fill planting) in zones that are poorly stocked, besides reducing accidental mortality and targeting less on small trees. Conifer plantations and soil scarification for natural regeneration are practiced in this region and it is generally recognized that plantations can improve conifer recovery whereas scarification tends to result in dominance by pioneer species (particularly *Betula* sp.; Yoshida et al. 2005). The former is more preferable with considering the decrease in conifer component, but it clearly requires more costs. The application of natural regeneration practice in combination with targeting more on broadleaved species (especially shade-intolerant ones) could be a more potent substitute for the traditional selection management system.

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