研究資料（Research record）

Retention Experiment for Plantation Forestry in Sorachi, Hokkaido (REFRESH): A large-scale experiment for retaining broad-leaved trees in conifer plantations

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Abstract

Retention forestry, a part of silvicultural system that retains important forest structures and organisms at harvest time, is a promising way to conserve biodiversity in managed forests. This harvesting method is being widely adopted in many countries and tested in field experiments. A large number of conifer plantations in Japan are reaching the planned harvest age, and their harvest is expected to help meet the domestic demand for wood. On the other hand, the restoration of conifer plantations to natural broad-leaved forests and the maintenance and enhancement of ecosystem services other than wood production are required in plantation landscapes. In this context, we launched a large-scale retention forestry experiment (the REFRESH project) in Sakhalin fir (*Abies sachalinensis*) plantations in central Hokkaido, northern Japan. The REFRESH project has six treatments (clear-cutting, three levels of dispersed retention, aggregated retention with a 0.36 ha intact patch, and gap cutting) and two controls (unharvested natural forest and unharvested plantation) with three replicates each. In dispersed retention, naturally regenerated broad-leaved trees are retained at three levels to maintain and restore elements of natural forests. After harvesting, fir seedlings are planted in the harvested area. We conducted pre- and post-harvest surveys on water and soil conservation; forestry efficiency; and the diversity of plants, arthropods, and birds. The initial surveys indicate how tree retention provides continuity in the forest structure in the harvested area, and long-term surveys until the next harvest will reveal the degree of structural and compositional enrichment of the plantations.

Key words: biodiversity conservation, forestry efficiency, planted forest, retention forestry, water and soil conservation

1. Introduction

Forests cover 31% of the earth's land surface (FAO 2015) and play significant roles in the environment (Perry 1994). Forests harbor large areas of global biodiversity and provide various indispensable ecological goods and services, e.g., wood fiber, water purification, soil conservation, recreational locations, carbon storage, and biodiversity conservation (Nelson et al. 2009, Raudsepp-Hearne et al. 2010). These ecosystem services undergo change due to anthropogenic activity in forests (Wilcove et al. 2013, Renard et al. 2015) and are likely to continue to change in the future (Bateman et al. 2013, Lawler et al. 2014). Society has therefore increasingly responded to these changes by various schemes such as sustainable forest management (Butchart et al. 2010).

In previous decades, planted forests, which are established through planting or seeding, have increased in area and now cover 7% of the world's forested area (FAO 2015). Half of all planted forests exist in Asia, particularly in East Asia (FAO 2006), where they are rapidly increasing (FAO 2015). Planted forests produce 50% of the world's wood products (FAO 2007) and are likely to increase their dominance in the near future (FAO 2015). A recently proposed concept of 'planted forest' involves fully and partially regenerating planted forests through planting and seeding; the former indicates a traditional plantation (FAO 2006), and the latter may be referred to as a semi-natural plantation. Here, plantations contain forests planted with native and introduced species, and we focus on the traditional tree (or forestry) plantation because of its potential impact on biodiversity and ecosystem services (Carnus et al. 2006, Brockerhoff et al. 2008, Paquette and Messier 2010).

Forest ecosystem services, including biodiversity conservation, depend greatly on tree species diversity (Gamfeldt

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et al. 2013, Liang et al. 2016) and vertical stratification (Franklin 1988, Hunter 1990). Plantations are typically managed to have only one or a few tree species, to have simple stand structure, and to attain high wood productivity by compromising other ecosystem services (Sedjo and Botkin 1997, Paquette and Messier 2010). Plantations can dominate the landscape by replacing the native vegetation and degrading the biota in the remnants of native vegetation (Lindenmayer et al. 2002, Yamaura et al. 2009); therefore, the reconciliation of biodiversity conservation in plantation landscapes is currently a subject of debate (Brockerhoff et al. 2008, Paquette and Messier 2010, Yamaura et al. 2012).

Japan holds a leading position in this growing era of plantation forestry, as Japanese plantations occupy the fifth-largest area (10 million ha) and the second-highest proportion (42%) of forested area in the world (FAO 2006). Although plantations are now being actively established around the world, Japanese plantations are reaching the planned harvest age since most were established after World War II (WWII) between 1950 and 1980 (Yamaura et al. 2012). In harvesting plantations, their contribution to meeting the domestic demand for wood is expected (Forestry Agency 2017), while their restoration and services other than wood production are also of social concern (Yamaura et al. 2012). Plantation landscapes are required to be multifunctional.

Retention forestry is a part of silvicultural system that retains important forest structures and organisms at harvest time and is widely practiced in many parts of the world (Gustafsson et al. 2012, Lindenmayer et al. 2012). It was developed in North America more than 25 years ago to accommodate the non-timber values of managed forests (Franklin 1989). We undertook a large-scale manipulative experiment called the Retention Experiment for Plantation Forestry in Sorachi, Hokkaido (REFRESH) to examine the efficacy of retention forestry in Sakhalin fir (*Abies sachalinensis*) plantations in central Hokkaido, northern Japan. We retained naturally regenerated broad-leaved trees at the final harvest to maintain and restore biodiversity and ecosystem services, and we planted fir seedlings in harvested areas with retained broad-leaved trees. In this paper, we offer an overview of the context, objective, experimental design, management prescriptions, and prospects of the REFRESH project.

2. Concepts and practices of retention forestry

Establishing nature reserves is insufficient to conserve biodiversity in forested landscapes (Franklin 1993, Franklin and Lindenmayer 2009); thus, biodiversity should be accommodated in managed forests (Hansen et al. 1991, Lindenmayer and Franklin 2002). Organisms, organic materials, and organically generated environmental patterns that persist through natural disturbances are called "biological legacies" and play important roles in maintaining and restoring biodiversity in disturbed areas (Franklin et al. 2000, Turner et al. 2003). However, few biological legacies can remain in harvested areas since silvicultural practices (e.g., site preparation, prescribed burning) simplify the stand structure (Franklin et al. 2000, 2002), especially in plantations. Franklin (1989) proposed an alternative to the stark choice between wood production (e.g., tree farms) and nature reserves to resolve the conflicts between timber and non-timber products, i.e., intentionally retaining biological legacies in harvested areas.

In contrast to traditional selective cutting, retention forestry selects trees (including snags and logs) with more emphasis on what is retained over the long term than what is removed (Franklin 1989). Retention forestry is highly adaptable and has great variations in its application, including the pattern and amount of retention. The practice includes retaining single trees (dispersed retention) and/or retaining small intact forest patches (aggregated retention). The important issues are therefore what structures to retain, how much of them to retain, and the spatial pattern of the retention (Franklin et al. 1997). Retention forestry can also be an effective tool for restoring impoverished or degraded forests that have few old trees via the creation of high stumps and the long-term retention of even comparatively young trees (Gustafsson et al. 2012).

Retention forestry has three major nonexclusive objectives (Franklin et al. 1997). The first is to lifeboat species and processes immediately after the harvest by providing habitat structure, ameliorating microclimates, and providing energetic substances for non-autotrophic organisms. The second is to enrich the structural complexity of regenerated forests through the next rotation. This approach is important when the rotation is shorter than the period required for some habitat structures (e.g., large old trees with hollows) to be re-created after the harvest and their retention dictates their maintenance and habitat quality in managed forests (Gibbons et al. 2010). The third is to enhance the connectivity of the harvested landscape. Dispersal is a fundamental ecological process that is likely to play an important role in the persistence of biodiversity in (unharvested) habitat remnants (cf. MacArthur and Wilson 1967, Hanski 1999); indeed, empirical studies showed that the quality of the surrounding areas (matrix) has a prominent effect on biodiversity in habitat remnants (Prugh et al. 2008, Watling et al. 2011).

Retention forestry has attracted the attention of forestry communities since its advent and is currently practiced on more than 150 million ha of boreal and temperate forests (Gustafsson et al. 2012). For example, retention forestry is practiced by all landowners in Sweden because of a stipulation of the Forestry Act and requirements for certification (Simonsson et al. 2014).

Other Fennoscandian countries, Finland and Norway, as well as Germany and Canada have widely adopted retention harvesting, which is led by forestry companies and state and federal agencies (Gustafsson et al. 2012). Certification organizations such as the Forest Stewardship Council (FSC) play an important role in the adoption of retention forestry (Gustafsson et al. 2012); for example, in the United States, FSC certification holders are required to retain large live trees, decaying trees, and snags in harvested areas (indicator 6.3.f: FSC-US 2010).

Field experiments to test the effectiveness of retention forestry are being conducted (Gustafsson et al. 2012, Lindenmayer et al. 2012, Koivula et al. 2014, Soler et al. 2016). Recent meta-analyses show that retention forestry is effective for maintaining the abundance and species richness of forest species (Fedrowitz et al. 2014) and is more effective than selective cutting (Mori and Kitagawa 2014). However, they also show strong geographical biases in studies on retention forestry. Most studies have been conducted in North America and northern Europe, and virtually none have been conducted in Asia. Furthermore, most study sites are naturally regenerated forests or those with partial plantings. Schieck and Song (2006) reviewed studies performed in western North America and found large variations in the effects of tree retention on bird communities. They supposed that differences in tree species composition and landscape structure among the studies may have been the cause of the inconsistent effects, suggesting the importance of performing studies in East Asian plantations.

3. Retention forestry and plantation

Retention forestry has been developed and basically practiced outside of tree plantations (intensive management zones) and strict nature reserves (set-aside lands) (Gustafsson et al. 2012, Lindenmayer et al. 2012). That is, areas used for retention forestry are not specialized either for wood production or biodiversity conservation and are called semi-natural forests (Lindenmayer et al. 2012) or extensively managed or ecosystem management zones (Seymour and Hunter 1999, MacLean et al. 2009). These areas are expected to perform multiple ecosystem services simultaneously, and retention forestry is an important tool of the sustainable forest management, multiple-use forestry, or balanced/ecological forestry in them.

Plantations are usually established to produce wood, and their establishment is promoted as a method to protect or spare the remaining natural forests (typically old growth) from harvesting (Brockerhoff et al. 2008, Paquette and Messier 2010). However, ecosystem services other than wood production cannot be overlooked in plantations and in landscapes dominated by plantations (Payn et al. 2015). In such cases, even landscape-level ecosystem services likely hinge on the vast plantations and their management rather than on tiny remnants of natural forests (cf. Fahrig 2001, Ruffell et al. 2017). For example, in Japan, the Forestry Agency (2016) formed a plan that 1/3 of 10 million ha of conifer plantations is to be restored to mixed forests with broad-leaved trees to enhance social values.

O'Hara et al. (1994) viewed silvicultural systems that reconcile timber and non-timber products as a structural gradient from clear-cut to single-tree selection, and O'Hara and Ramage (2013) suggested that stands with trees of more than one age and diverse trees are more resistant to and resilient against disturbances than even-aged (single-species) stands. It is also suggested that simple forests specialized for wood production cannot adapt to changes of environment, including wood markets (Puettmann et al. 2012, Messier et al. 2015). These suggestions indicate the possibility that retention forestry can be applied to plantations; indeed, retaining trees, including snags, has been suggested as an important method to conserve biodiversity in plantations (Moore and Allen 1999, Hartley 2002). Because of the increasing dominance of plantations in the United States, Demarais et al. (2017) recently suggested that the retention of habitat elements is one of the promising options for conserving vertebrate diversity in plantations. Furthermore, the FSC-US requires that in some regions, biological legacies (live trees and other native vegetation) be retained within harvested sites larger than specified areas (e.g., 4 ha in Appalachia, 0.8 ha in the Ozarks, and 8 ha in the Mississippi alluvial valley region) when even-aged management (comparable to plantation forestry) is used (indicator 6.3.g.1: FSC-US 2010).

4. Retention forestry in conifer plantations

Although plantations are established using various species, coniferous trees are important constituents of such forests, especially in temperate and boreal regions. In tropical and subtropical regions, broad-leaved species of *Eucalyptus* and *Acacia* are widely planted, while coniferous species (e.g., *Pinus*) are quite common in Europe and North America (FAO 2006). In Japan, conifer plantations are largely composed of Japanese cedar (*Cryptomeria japonica*), Japanese cypress (*Chamaecyparis obtusa*), Japanese larch (*Larix kaempferi*), and Sakhalin fir were established to meet increased wood demands. Although these coniferous species are native to Japan and can form locally dominant forests (e.g., Franklin et al. 1979, Maeda 1983), they were artificially and widely planted under intensive silvicultural practices and replaced grasslands and natural forests (Nagaike and Kamitani 1997, Miyamoto and Sano 2008). They are structurally and compositionally highly different from non-planted natural forests composed mainly of broad-leaved trees (e.g., Nagaike 2002).

Coniferous trees/forests are generally known to harbor impoverished plant (Glenn-Lewin 1977, Barbier et al. 2008) and phytophagous (plant-eating) insect communities (Ozanne 1999, Mizutani and Hijii 2002) compared to broad-leaved trees/forests, with some exceptions (Barbier et al. 2008). Harris and Skoog (1980) and Hunter (1990) raised some possible reasons that coniferous tees/forests have impoverished biota. First, conifer foliage and trunks are less palatable due to distasteful chemicals such as terpenes (Langenheim 1994, Trapp and Croteau 2001). Terpene compositions can affect the diversity and composition of phytophagous insect communities (Hatcher 1994, Ricklefs 2008), and phytophagous insects are quite important in forest biodiversity since they are major food resources for predators at higher trophic levels (Huston and Wolverton 2009). Second, the difference in branch structures and lateral branching in broad-leaved trees provide diverse foraging and nesting habitats, and self-pruning in conifers leads to fewer opportunities for cavity formation (cf. Kikuchi et al. 2013). Third, the coevolution history of angiosperms (most broad-leaved trees) means that many plant and animal species developed together through seed dispersal, pollination, and herbivory (Regal 1977).

In Japan, conifer plantations occasionally include naturally regenerated broad-leaved trees that reach the canopy layers (Yamaura et al. 2008, Yoshii et al. 2015), and thinning provides an important opportunity for regeneration (Utsugi et al. 2006, Nonoda et al. 2008, Seiwa et al. 2012). Although conifer plantations degrade the biota compared to natural forests, conifer plantations with broad-leaved trees have diverse bird (Yui and Suzuki 1987, Ohno and Ishida 1997, Yamaura et al. 2008, Yoshii et al. 2015) and beetle (Ohsawa 2007) communities, which generally is likely to occur (Bibby et al. 1989, Nájera and Simonetti 2010, Lindbladh et al. 2017). In Sweden, when possible, FSC requires forest managers to maintain at least 10% of broad-leaved trees in the production forests during the management prescription (criterion 6.3.8: FSC Sweden 2010).

Furthermore, some broad-leaved trees in conifer plantations were presumably retained when the plantations were established (Yoshida et al. 2005, Ohsawa 2007); for example, we found large broad-leaved trees in our studied plantations (Fig. S1). These trees were likely retained due to the high cutting costs and their low economic value when the plantations were established. These observations suggest that retaining broad-leaved trees in conifer plantations has already been practiced and is technically feasible. Therefore, there are opportunities to retain broad-leaved trees in conifer plantations at the final harvest, and this practice is likely to be effective in maintaining and restoring the diversity of harvested areas.

Notably, retention forestry is easy to understand and can be applied by foresters owning only small forest parcels. This advantage is particularly important since 58% of the forests in Japan are privately owned, and 88% of private foresters own <10 ha forests (Forestry Agency 2017) for historical reasons (Akao 2002). It would be more feasible in many cases for individual owners to retain these small natural features (broad-leaved trees) in conifer plantations than for aggregated owners to set aside (spare) some areas from forestry by managing intensive plantations in the other areas (cf. Hunter et al. 2017).

Although retention forestry is expected to maintain various ecosystem processes (Franklin et al. 1997, Gustafsson et al. 2012), functionally different broad-leaved trees in conifer plantations may have disproportionate effects on varied ecosystem services predicted by their amounts, as in the large old trees in repeatedly logged areas and in agricultural and urban landscapes (Lindenmayer 2017). For example, Liang et al. (2016) showed that tree species richness has concave effects on forest productivity; that is, increasing species richness has a greater role when the species richness is low. Bird abundance in plantations is similarly valued by citizens (Yamaura et al. 2016): increasing bird abundance entails higher economic values when the bird abundance is low. Therefore, retaining small amounts of broad-leaved trees may have significant returns in enhancing the ecological and social (see below as well) values of conifer plantations.

Retention forestry in plantations may also be effective for retaining carbon and alleviating landslides, as suggested in proposals for reduced impact logging and partial cutting, respectively (Dhakal and Sidle 2003, Putz et al. 2008). In landscapes dominated by plantations, other possible benefits of retention forestry for biodiversity are to capture diverse environments and spread risks (Gustafsson et al. 2012), for example, as in the benefits of establishing several small nature reserves in fragmented landscapes (Tscharntke et al. 2002, McCarthy et al. 2005). Risk spreading is an important consideration in the land-use specialization of wood production (e.g., adding other values to plantations) since wood prices can fluctuate greatly (Lindenmayer and Franklin 2002, Koh et al. 2009).

A final consideration is the social acceptability of clear-cuts. Although dispersed and aggregated retention can have contrasting values (Ribe 2005, Ford et al. 2009), citizens consistently rate harvested areas with retained trees more highly than clear-cuts as scenic and recreational sites (Brunson and Shelby 1992, Tönnes et al. 2004, Shelby et al. 2005). The visual quality of forested landscapes has been overlooked by the forestry community; however, this social dimension of forest value greatly affects the social acceptability of harvest practices (Sheppard et al. 2004). Edwards et al. (2012) showed that European people prefer forests with large trees and a number of tree species. Therefore, retained broad-leaved trees in harvested areas or, more generally, conifer plantations with broad-leaved trees may play an important role in the social acceptability of and public support for plantation forestry in Japan.

5. Experimental outline

5.1 Forests and forestry in Hokkaido

Hokkaido is the second-largest island in Japan and comprises one of the 47 prefectures in the country. The history of forestry in Hokkaido started during the Meiji Restoration (1870s) when exploitative forestry was developed with land reclamation and with commercial capital from Honshu island (the largest island in Japan) (Koseki 1962). Hokkaido had exported large amounts of coniferous and broad-leaved trees (e.g., *Picea jezoensis*, *Quercus crispula*, *Tilia japonica*, *Kalopanax septemlobus*), not only to Honshu island but also to China, Australia, North America and Europe, especially after the 1890s (*Q. crispula* was highly valued in western countries), and was known as the most important conifer-producing area in Japan (Hokkaido 1953).

The transition from exploitative to plantation forestry occurred after WWII (approximately 1950), and artificial regeneration (establishment of conifer plantations) quickly increased (Hokkaido 1983). Currently, approximately 71% of the land in Hokkaido is covered by forests (Forestry Agency 2014). Among the forests, 27% are planted (Fig. 1a), which is less than the percentage for Japan as a country (41%). However, the plantation area in Hokkaido is the largest among all the prefectures in Japan (1,494,000 ha), more than three times the area in the second-largest prefecture, Iwate (495,000 ha); indeed, 15% of the Japanese plantations are in Hokkaido, and Hokkaido has continued to produce the largest quantity of wood among all the prefectures since WWII (13-26% share of Japan's wood production from 1952 to 2014: Fig. 1b).

The native broad-leaved and mixed forests in Hokkaido were actively replaced by conifer plantations from 1950 to 1980 (Fig. 1a), and Sakhalin fir was consistently used as the main plantation species (Fig. 1c). Currently, more than half (52%) of the plantations in Hokkaido are composed of Sakhalin fir (the second-most-common plantation species is Japanese larch: 28%), and their age distribution is concentrated in the 35-55-year range (in 2012), as in other Japanese plantations. Although logs harvested from natural forests dominated until the 1980s, the volume of logs from plantations has constantly been increasing and exceeded that from natural forests in 1997 (Fig. 1d). Logs from plantations currently account for >90% of harvested logs. Since the 2000s, the volume of logs from the final harvests of plantations has reached that from thinning (Fig. 1d), suggesting that plantations in Hokkaido have entered the mature stage. Sakhalin fir trees are relatively short-lived (~200 years: Watanabe 1970, Asai et al. 1980), and old Sakhalin fir plantations are vulnerable to root rot disease (Tokuda 2005, Tokuda et al. 2007). Tokuda (2011) surveyed the infection

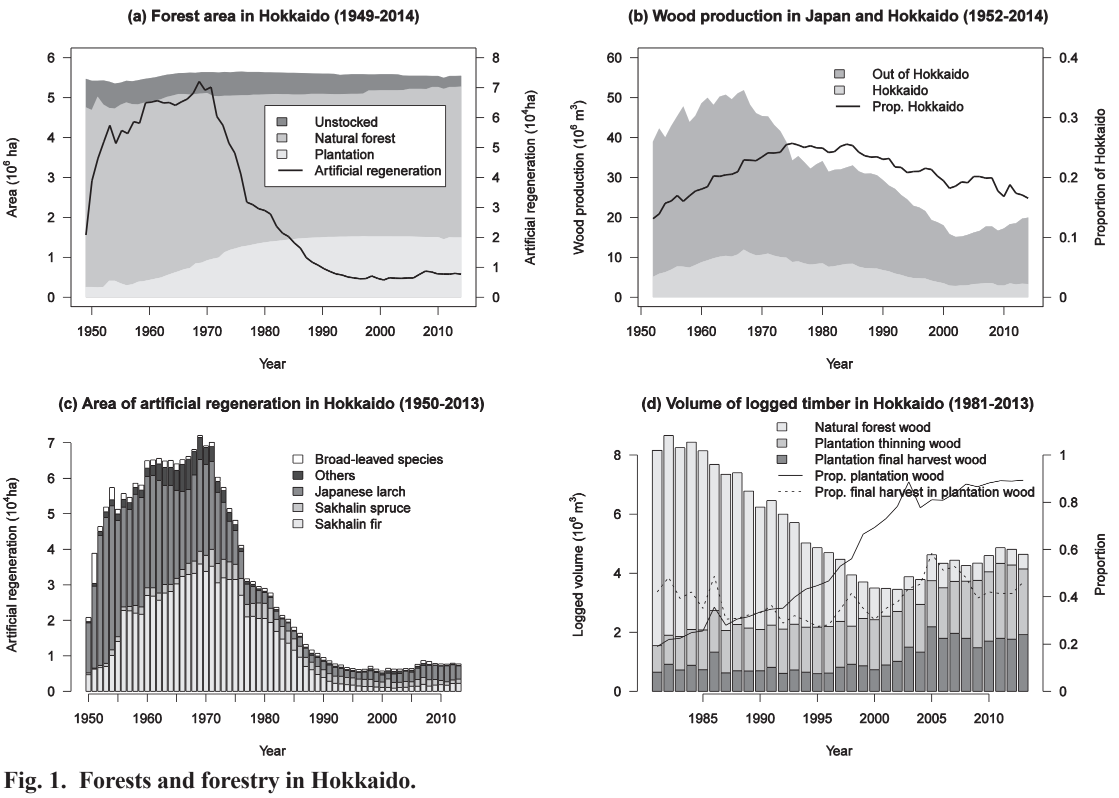

Fig. 1. Forests and forestry in Hokkaido.

All data except those for wood production (Forestry Agency 1954-2016) are from Fishery and Forestry Department (1949-2014).

rates of fir individuals from root rot disease in 51 Sakhalin fir plantations (24-72 years old) and found increasing infection rates in older plantations (the mean infection rate was 14%); therefore, long-rotation harvesting is not suitable for Sakhalin fir plantations.

The Hokkaido prefectural government administers 600,000 ha of forests. The main objective of forest management changed in 2002 from wood production to the maintenance and enhancement of ecosystem functions of public interest, such as disaster prevention, water purification, and biodiversity conservation. Since this policy change, plantations have been harvested using gap cutting of less than 1 ha, selective cutting, and long rotation (Tsuchiya 2013). However, these harvesting methods are somewhat inefficient in wood production compared to traditional clear-cutting. Thus, a harvesting method that reconciles wood production and other ecosystem services, including biodiversity conservation, is urgently needed.

5.2 Study area

Our REFRESH project is being conducted in the Irumukeppu highland area (ca. 6 km × 12 km, overlapping the municipalities of Ashibetsu, Fukagawa, and Akabira) in the Sorachi management district of the Hokkaido prefectural forest (43°34’37"-39’26"N, 142°05’27"-09’33"E). This area includes the largest spread of plantations in the prefectural forest, and we planned to locate the experimental units with replicates there (Fig. 2). Mt. Irumukeppu (864 m a.s.l.) is in the northern part of the area, and gentle slopes run eastward and southward from the mountaintop. According to the climatological normals (1981-2010) at Ashibetsu (90 m a.s.l.), the monthly mean maximum and minimum temperatures are 27.1°C (August) and −11.9 °C (January), respectively; the annual precipitation is 1,093 mm, and August has the most precipitation. Snow first falls in October, is approximately 1.5-2 m in depth during the winter, and disappears in mid-April to early May. The natural forests are composed of *Tilia japonica*, *Quercus crispula*, and other broad-leaved tree species, including *Acer pictum*, *Fraxinus mandshurica* and *Ulmus davidiana*, and *Abies sachalinensis*. The high elevation area surrounding Mt. Irumukeppu is dominated by *Betula ermanii*. The forest floor is covered by dwarf bamboos; *Sasa senanensis* and *Sasa kurilensis* are major species at lower- and higher-elevation sites, respectively. Lowlands surrounding the study area are used as cultivated land for rice paddies, crops, and pasture. Fish farms exist in the watershed, and water resources from the study area are utilized for tap and agricultural water. Many people visit the area to climb Mt. Irumukeppu for recreation, fish in the streams, and pick edible plants.

Since a large part of this area (1,930 ha) suffered from a forest fire (of unknown cause) more than 100 years ago (in 1911: Hokkaido 1956), artificial reforestation began in the 1920s. Most plantations were established during 1950-1970, and the entire planted area was prepared by clearing underbrush and artificial burning before planting the seedlings. Plantations (3,481 ha) now make up 59% of the forests (5,884 ha), and 79% of the plantations consist of Sakhalin fir (12% and 4% consist of Japanese larch and Sakhalin spruce, *Picea glehnii*, respectively). Approximately 2,165 ha (62%) of the fir plantations were planted during 1961-1980 and the number of mature stands reaching their final harvest age is increasing.

5.3 What to retain?

We will now discuss the three issues of the experiment: what structures to retain, how much of them to retain, and the spatial pattern of retention. As described above, we decided to retain broad-leaved trees to maintain and restore elements of the original broad-leaved or mixed forests in Hokkaido (Table 1). We postulated that broad-leaved canopy trees are particularly in decline for organisms dependent on forests in the plantation-dominated landscape, so broad-leaved canopy trees were selected as retained trees. In addition, Sakhalin fir may not be a suitable retention target for dispersed retention, as it is more vulnerable to wind damage than broad-leaved trees. However, we retained Sakhalin firs in the aggregated retention areas described below.

5.4 Spatial retention pattern

We used dispersed retention for the broad-leaved trees because broad-leaved trees are usually distributed in a scattered matter in conifer plantations. Although we acknowledge studies that simultaneously adopted multiple spatial patterns and the possible significance of their combinations (Aubry et al. 2009, Koivula et al. 2014, Lee et al. 2017), we could not adopt both (dispersed and aggregated) retention types for broad-leaved trees. Instead, we used aggregated retention for Sakhalin fir (Table 1). The aim of aggregated retention is to maintain an intact canopy and forest floor to provide refugia for forest-floor vegetation. We also established a gap-cutting treatment in which one-third of the experimental unit was harvested by cutting 1 ha clear-cut openings. This harvesting method has been used in the study area since 2002. The dispersed and aggregated retention areas have contrasting expected ecosystem services and management issues (Franklin et al. 1997); however, empirical evidence of the relative benefits is not sufficient or distinct (Fedrowitz et al. 2014). Aggregated retention likely provides fewer operational constraints (Franklin et al. 1997); i.e., the harvesting costs are expected to be lower in those areas than in dispersed retention areas. However, the effects of dispersed retention are generalized over the total harvested area, which may be meaningful for the large harvest

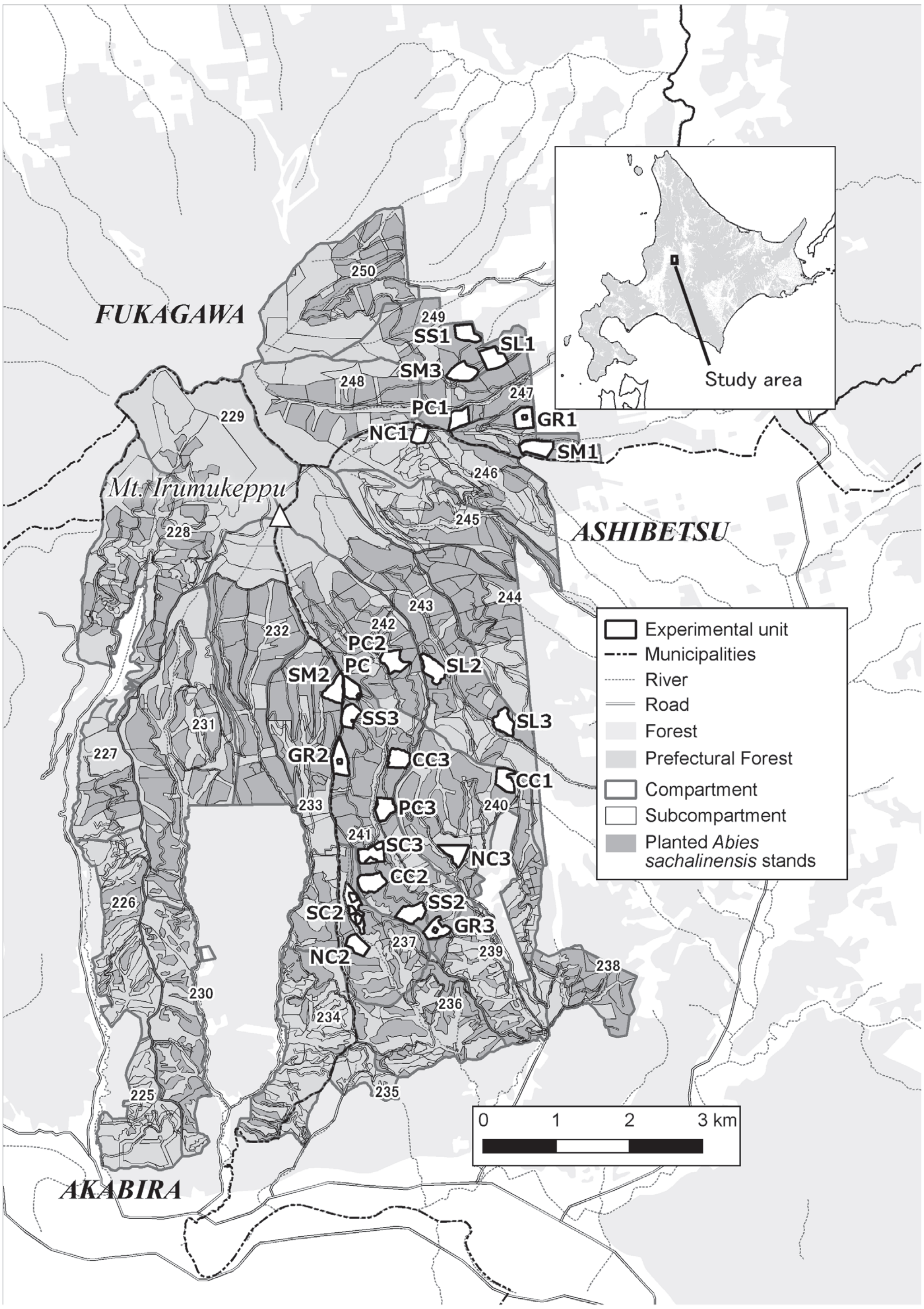

Fig. 2. Study area and experimental units of the REFRESH project.

See Table 1 for the control/treatment abbreviations. Numbers (225-250) represent the compartment. “PC” denotes the control site without harvesting in the planted stand used for watershed monitoring only.

areas. In sum, we placed a higher research priority on dispersed retention. Nevertheless, we established an aggregated retention treatment because of the likely high acceptance by foresters (cf. Neyland et al. 2012) and because retention patches of Sakhalin fir can be established even when few broad-leaved trees are present in conifer plantations.

5.5 How much to retain?

The final item of consideration is the amount of retention. In their meta-analysis, Fedrowitz et al. (2014) found that retention levels were 2%-88% (mean ± SD: 36.4% ± 25%), and a positive relationship existed between the proportion of retained trees and forest species richness. In contrast, Mori and

Table 1. Controls and treatments of REFRESH project

Control/treatment	Description
Unharvested natural forest (NC)	Reference
Unharvested plantation (PC)	Control
Clear-cutting (CC)	No retained trees
Small amount of dispersed retention (SS)	10 broad-leaved trees (/ha) are retained
Medium amount of dispersed retention (SM)	50 broad-leaved trees (/ha) are retained
Large amount of dispersed retention (SL)	100 broad-leaved trees (/ha) are retained
Aggregated (or group) retention (GR)	A 0.36 ha (60 m × 60 m square) undisturbed patch composed mostly of Sakhalin fir is retained at the center of the experimental unit
Gap cutting (or group selection cutting: SC)	1/3 of the experimental unit is harvested by clear-cutting 1 ha openings*

*Only two replications are available.

Kitagawa (2014) observed few effects of retention level on the species richness of various taxa in a meta-analysis. Gustafsson et al. (2012) suggested that retention levels of 5-10% are a strict minimum to achieve the objective of retention forestry, and Hunter (1990) and Newton (1994) suggested retaining 5-10 snags per ha to maintain populations of cavity users. These figures (5%-10%, or 5-10 trees/ha) may represent feasible targets to reconcile production and conservation. From these suggestions, we adopted three retention levels for dispersed retention: small, medium, and large amounts of retention corresponding to 10, 50, and 100 retained trees/ha, respectively (Table 1). These levels correspond to 2-18% and 1-27% on a number and basal area basis, respectively (Fig. 3). We established a 0.36 ha (60 m × 60 m) undisturbed forest patch at the center of the experimental unit as the aggregated retention area. The maximum tree height of Sakhalin fir was 28 m in this region, and the distance from the edge of the retention patch was more than one tree length at the center.

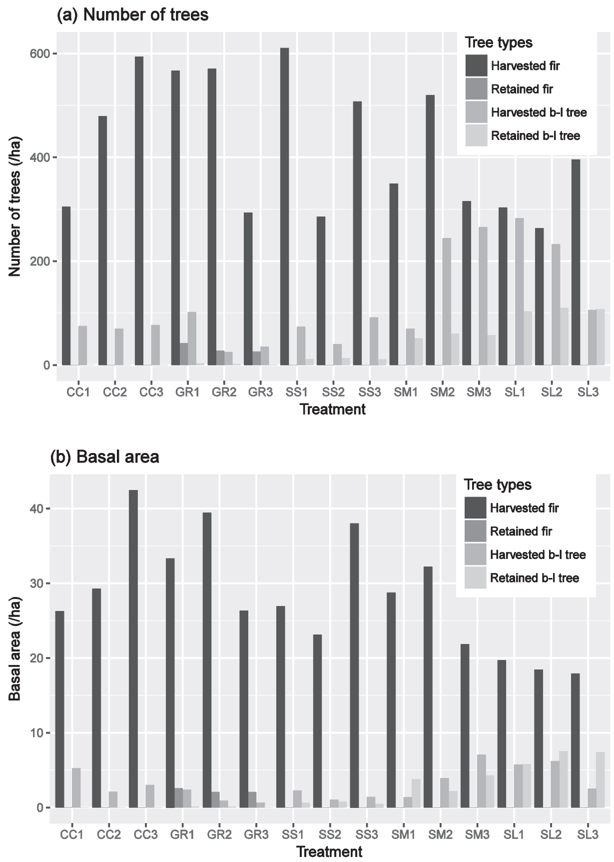

Fig. 3. (a) Number (/ha) and (b) basal area (m^2/ha) of harvested and retained trees in the 15 major treatment units.

See Table 1 for unit name abbreviations. Data were based on a field survey that measured all harvested and retained trees (≥ 5 cm DBH) and on Akashi et al. (2017). Sakhalin fir and broad-leaved trees are shown separately.

5.6 Control and replicates

We established three control types: unharvested natural forest, unharvested plantation, and clear-cutting. The first control was a natural reference, indicating a possible target of biodiversity conservation. The latter two controls were established to directly assess the treatment effects. Following the terminology of Bennett and Adams (2004), the natural forest and unharvested plantation controls in our experiment were a reference and a control, respectively. Replication and control are the most important features of harvest experiments to adequately test and infer the treatment effects (Johnson 2002, Bennett and Adams 2004); in our case, each treatment has three replicates (first-third set) except gap cutting, which had two replicates in the second and third sets (Fig. 2).

5.7 Site selection and experimental schedule

We selected experimental units (5-8 ha) from large stands that had reached harvest age. The experimental units were set at >5 ha to avoid edge effects and were spaced at least 200 m apart to prevent a pseudo-replication problem (Hurlbert 1984). However, two pairs of treatments (SM2-SS3 and CC2-SC2; see Table 1 for the abbreviations of the treatments) had an edge-to-edge distance of only ~150 m (Fig. 2). Seven experimental units (CC2, SS2, SM2, SL2, GR3, SS3, and SM3) included small watersheds to evaluate the effects of retention harvesting on water quality and quantity and stream macro-invertebrates. The pre-harvest basal area in each experimental unit was 24-45 m^2/ha (Akashi et al. 2017). Broad-leaved trees occupied 2%-

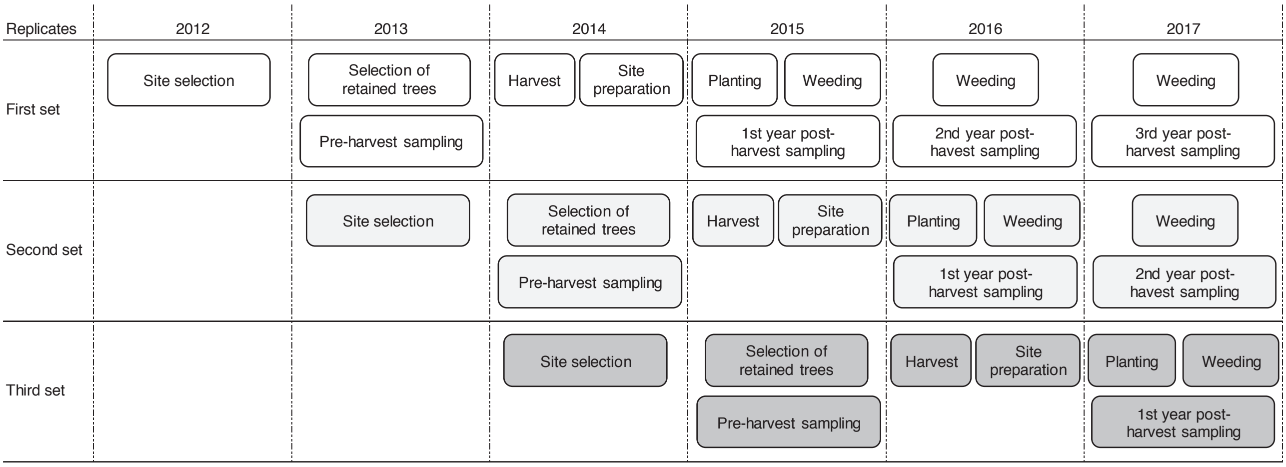

Fig. 4. Treatment and experimental schedule for the REFRESH project.

43% of this basal area, and abundant broad-leaved trees were probably retained at the time of the stand establishment and/or regenerated (and retained afterward) where planted fir trees had died due to canker diseases.

We selected the broad-leaved trees to retain 1 year before harvest. Because most of the naturally regenerated broad-leaved trees in conifer plantations were early-successional species, such as birch, late-successional species (e.g., *Quercus crispula* and *Tilia japonica*) were prioritized during the selection of retained trees. Trees were harvested from spring to summer by being felled with chain saws, delimbed and cut with harvesters, and transported using forwarders. The harvested areas were prepared for tree planting until winter (snowfall). Logging slash was piled along some of the skidding trails (Fig. S2). Sakhalin fir seedlings were planted the next spring in rows at 3 m intervals (2,400-2,700 trees/ha), and weeding was conducted during the summer. Areas 1.5-2 m wide along the planting rows were weeded (Fig. S2), which is a typical weeding practice for Sakhalin fir plantations in Hokkaido (in a larch plantation, the entire area is usually weeded). Weeding is conducted once or twice annually, depending on the growth of herbs and shrubs. Tree harvesting occurred during different years for each replicate (2014 for the first set, 2015 for the second set, and 2016 for the third set: Fig. 4). We established a staircase experimental design (Walters et al. 1988) so that each replicate reflected different starting conditions to control time-treatment interactions.

We conducted the field survey 1 year before harvest (pre-harvest sampling). Most field surveys (other than harvesting efficiency and stream survey) were not conducted during the harvest year to ensure operational safety. As our experimental design has replicates and includes pre- and post-harvest surveys, it was described as multiple samplings before and after the harvests in more than one harvested and control stands design (Bennett and Adams 2004). We aim to continue the experiment until the next final harvest (50 years). On May 2013, the Hokkaido government, the Hokkaido University Department of Forest Science, Forestry and Forest Products Research Institute Hokkaido Research Center, and Hokkaido Research Organization Forestry Research Institute implemented the REFRESH project.

6. Field survey

6.1 Biodiversity

Plants build physical habitat structures for organisms. Evergreen conifers and deciduous broad-leaved trees form quite different environments under their canopies, which affect the understory plants (Barbier et al. 2008). We established 20 m × 20 m plots to survey trees with a diameter at breast height ≥1 cm, with 5 m × 5 m quadrats at the center of each plot to survey the understory plants. We placed 4-8 plots at 50 m intervals at every site except the aggregated retention sites. At some sites, one plot was placed outside the harvest area to examine edge effects. Five or six plots were placed in the harvest area of the aggregated retention sites, and nine were arranged to cover the retention area (60 m × 60 m). Species of vascular plants were identified for each 1 m × 1 m section of each quadrat. We have completed pre-harvest surveys for three replicates and will conduct post-harvest surveys at the same plots every few years.

Arthropods comprise a large proportion of forest biodiversity. In particular, deadwood-associated (or saploxylic) species, which play important roles in nutrient cycling, are sensitive to forest harvesting (Siitonen and Martikainen 1994). Forest harvesting also changes the soil-litter interface, which reveals the assemblage structure, abundance, and diversity of litter-dwelling arthropods (Spence et al. 2008). We have collected saploxylic arthropods, such as longicorn beetles, with Malaise traps and litter-dwelling arthropods with pitfall traps. We also have surveyed arthropods in tree canopies using aerial Malaise traps because tree retention provides refugia for arthropods inhabiting tree canopies.

Birds are dependent on the forest structure and composition (MacArthur and MacArthur 1961, Brokaw and Lent 1999) and have long been studied in relation to forestry harvest; indeed, they were included as a separate taxon in the abovementioned retention forestry meta-analyses. We have surveyed birds using the standard census techniques of line census and point count in all treatment and control stands. The line census covers the entire area of the stand, and both techniques required visiting each stand six times during the breeding season per year. We have completed the pre-harvest surveys for three replicates and will conduct post-harvest surveys for at least 3 years in the short term.

6.2 Water and soil conservation

Water and soil conservation are of great concern to forest managers and citizens, in part because of biodiversity conservation issues. We established 16 small watershed monitoring sites (with 6-10 ha areas), including the seven experimental units described before, and are monitoring water discharge, water quality, and stream macro-invertebrates. We also established four water sampling points with 200-1,000 ha catchment areas to evaluate the downstream effects of forest practices. The seven experimental units were selected within the second and third sets because we needed pre-harvest data for more than 1 year. Continuous water levels have been recorded using a data logger since the summer of 2013, and water samples have been collected every 2 weeks and analyzed for major anions, cations, and dissolved organic carbon. Hydrological, physical, and biogeochemical changes caused by harvesting are expected to affect riparian ecosystems. We have also surveyed streambed conditions (substrates, organic materials, water velocity, etc.) and macro-invertebrates every autumn since 2013 to evaluate the effects of the retention harvest on riparian biota.

6.3 Forestry efficiency

The increase in silvicultural costs for tree retention is relevant in relation to the feasibility of retention forestry (Yamaura et al. 2016). Our primary interest at this harvesting stage is the possible increase in the cost of harvesting operations. We have surveyed productivity using daily reports of operations and analyzed production time by video recording harvesting operations. All tree harvesting occurred after snowmelt (May) and until September (i.e., the snow-free season). Most trees were felled manually with chain saws (partially with a feller buncher) and bunched with a grapple loader. Then, the trees were processed on a strip road, loaded on a rubber-track forwarder (without a knuckle-boom loader), transported, and unloaded and piled at the landings. As described above, the retained trees were marked using flagging tape before the harvest, and the operators harvested or retained trees based on the tape.

7. Discussion

7.1 Development of retention forestry in plantations

REFRESH seeks a way to reconcile wood production, other ecosystem services and biodiversity conservation in plantations using a globally featured harvesting practice - retention forestry (Fig. 5). The issues to resolve before practicing retention forestry are the services to be maintained, the types of tree to be retained (e.g., the retention target, its amount, and its spatial pattern), and whether the opportunity cost (economic costs required to achieve retention forestry) can be offset by the benefits. The responses of individual ecosystem services to the retention level would help identify the adequate retention level. If there is a clear threshold in the response form (cf. Ellis and Betts 2011), it would be a candidate for the possible lower limit of the retention level (Gustafsson et al. 2012).

However, many studies suggest that retention forestry is not a panacea. For example, species that are highly sensitive to harvesting would not be conserved even with high retention levels, and their conservation would require strict uncut reserve areas (Vanderwel et al. 2007). Mori et al. (2017) recently used a meta-analysis to show that the effectiveness of retention forestry can depend on the surrounding landscape structure. Early-successional species can be effectively conserved in a harvested area with fewer retained trees (Fedrowitz et al. 2014). Plantation landscapes in varied ecological and social contexts may require a hybrid of intensive plantations (no retention), semi-natural plantations (plantations with retained or regenerated broad-leaved trees), and old-growth natural forests to enhance multiple ecosystem services (Koh et al. 2009, Butsic and Kuemmerle 2015, Law et al. 2017, Triviño et al. 2017). This idea is parallel to the TRIAD zoning system developed in North America (Seymour and Hunter 1999, MacLean et al. 2009, Côté et al. 2010).

Nevertheless, we note that retention forestry is adopted in all managed forests in Sweden, and these forests are mostly plantations with native tree species (L. Gustafsson, pers. commu.). This simple adoption of retention forestry would help increase its feasibility. In addition, although retention of many trees unlikely contributes to the conservation of early-successional species (Fedrowitz et al. 2014), Viljur and Teder (2016) found 81% of regional (=65 species) and 79% of grassland butterfly species (=26 species) in 35 harvested areas with dispersed retention (2-10 years old with 0.3-2.5 ha).

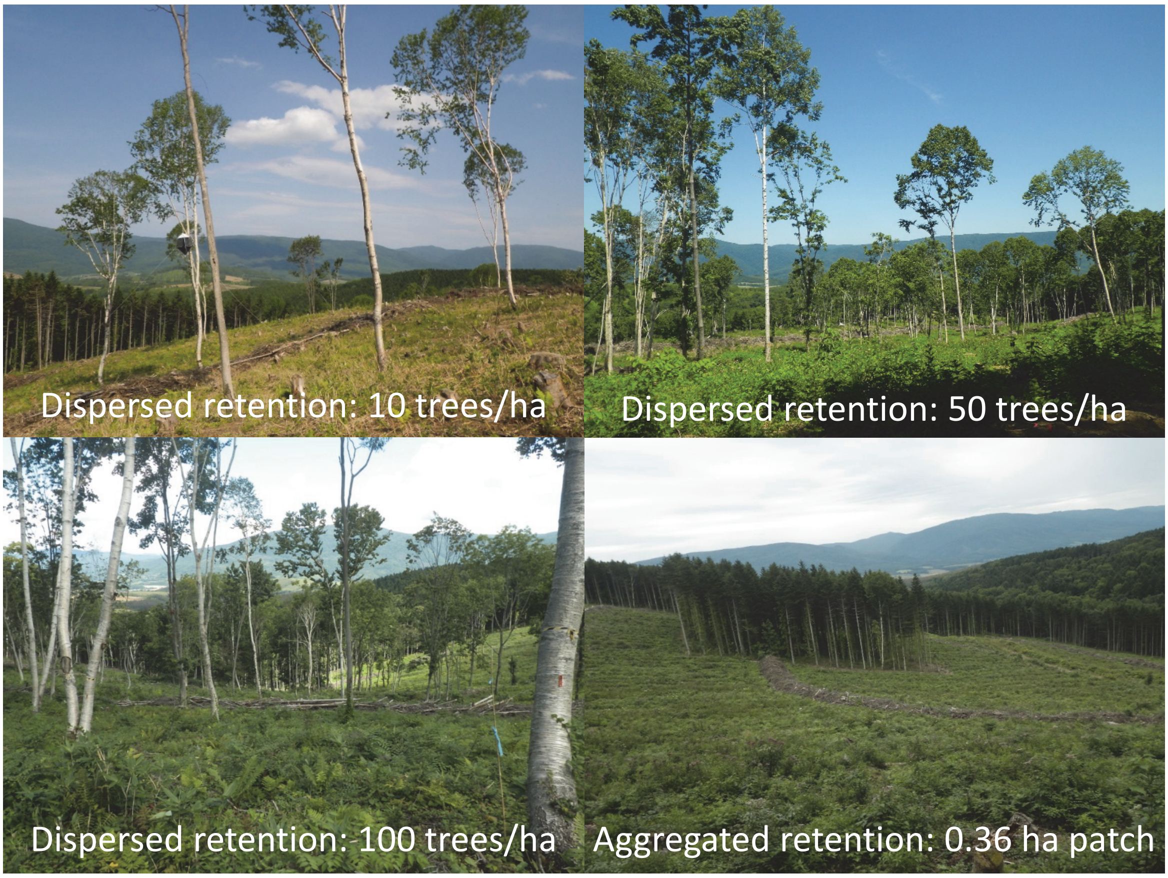

Fig. 5. Post-harvest experimental units of the first set.

This result suggests that retention forestry can conserve early-successional and forest species simultaneously in harvested areas. Furthermore, Lindbladh et al. (2017) recently showed that small increases of broad-leaved trees (<15%) in Norway spruce (*Picea abies*) production forests increase bird species richness, indicating the feasibility and benefits of retaining broad-leaved trees in conifer plantations.

7.2 Prospects of the REFRESH project

The collection of the pre-harvest REFRESH data was completed in 2015, and the initial post-harvest assessments will be completed within 2-3 years after the harvest. Future surveys will be conducted at several 10-year intervals until the next final harvest to fully understand the potential effects of retention forestry on the plantations. Initial surveys up to 10 years after the harvest will indicate how tree retention provides continuity in the forest structure in the harvested area, and long-term surveys until the next harvest will show how tree retention increases the structural and compositional complexity and restores the native biota in the plantations.

In this respect, the continuity of the project is the most important. Broad-leaved trees are retained in the harvested area in an isolated manner and will grow in an environment different from that before harvest. Light conditions will be greatly improved, but other physiological pressures will be stronger, which may lead to the loss of retained trees (McComb and Lindenmayer 1999, Hämäläinen et al. 2016). Retention levels at harvest time can be determined by accounting for the subsequent loss (Gibbons et al. 2010). On the other hand, trees that survive the stressful period will become irreplaceable components of the forests - large old trees (Lindenmayer et al. 2014, Lindenmayer and Laurance 2017), especially in plantations; retained trees may also increase plant diversity by increasing seed dispersal by birds (Yoshida et al. 2005). These expectations can be tested only by future work. The overall efficacy of the retention method will be revealed when the plantations mature.

Cooperation among researchers and forest managers is the core of REFRESH. In this project, forest managers are the forestry officials of the Hokkaido prefectural government, and regular contact among researchers and officials will be indispensable for planning and implementing the project. REFRESH represents the first opportunity for most of them to participate in such a large-scale harvest experiment. These collaborations have presented some challenges because of different objectives and approaches among researchers and managers, and some compromises were required in the number and assignment of experimental units. Fortunately, the managers understood the purpose of the experiment and have been willing to implement rigid treatments in most cases. The harvest units are larger and the silvicultural practices are more rigid and systematic than in ordinary implementations. We believe both researchers and managers will benefit from direct involvement in the REFRESH project, and the research results will be transferred directly from researchers to managers. The researchers understand the constraints under which the managers must work, and the experiences gained from this project will help them to understand the information needs of managers. This sharing of knowledge and the close working relationships are important for developing new silvicultural systems in plantations.

7.3 Concluding remarks

Vast plantations in Japan are now maturing and reaching the planned harvest age. To be socially supported, plantation landscapes ideally are multifunctional. They are desired to perform possibly conflicting ecosystem services - producing wood with economic efficiency and maintaining or enhancing other ecosystem services via the restoration of conifer plantations. Given the continuity of plantation forestry, there are not many options to achieve these objectives, and the adoption of retention forestry, especially the retention of broad-leaved trees at the final harvest, is promising. We hope that this cooperative large-scale replicated and manipulative experiment can contribute to the world's knowledge of sustainable forest management in this plantation era.

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Fig. S1. Post-harvest experimental units.

Abbreviations: SM (medium amount of dispersed retention); GR (aggregated retention); CC (clear-cutting). Numbers (1 or 2) in abbreviated names indicate that they are experimental units of the first or second set, respectively. The last inset figure (d) indicates the large broad-leaved trees presumed to have been retained when the first-generation fir plantation was established (1940-1960).

Fig. S2. Preparation, tree planting, and weeding in the REFRESH project

北海道空知地方における人工林での保持林業：針葉樹人工林の主伐時に広葉樹を残す大規模野外操作実験

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要旨

主伐の際に重要な森林の構造などを残す施業は保持林業と呼ばれ、木材生産を行なう森林で生物多様性を保全するための有望な方法の一つである。この伐採手法は多くの国で採用され、野外実験により検証が行なわれている。日本では、戦後造成された針葉樹人工林が伐期を迎えつつあり、主伐することにより木材自給へ貢献することが期待されている。一方で、針葉樹人工林の広葉樹天然林への再生や木材生産以外の生態系サービスの維持や向上も人工林が広がる景観では求められている。このような状況で、私たちは北海道のトドマツ *Abies sachalinensis* 人工林で保持林業の大規模操作実験（REFRESH プロジェクト）を立ち上げた。本プロジェクトは 6 つの処理区（皆伐、3 つのレベルの単木保持、0.36 ha の非伐採区を有する群状保持、受光伐）と伐採を行なわない 2 つの対照区（天然林対照区、人工林対照区）を有しており、各処理区・対照区はそれぞれ 3 つの繰り返しがある。単木保持では、天然更新由来の広葉樹を 3 つの異なる量（10 本/ha、50 本/ha、100 本/ha）で保持し、天然林要素の維持と再生を目指している。処理区では伐採後に再度トドマツを植林し、通常の造林作業を行なっている。伐採前と伐採後に、私たちは以下の項目を調べている : 水土保全機能、林業生産性、植物、節足動物、鳥類の多様性。伐採前後の調査により、樹木の保持が伐採地で森林の構造の連続性をいかに提供するのか、そして次の伐期までの長期的な調査により、人工林の構造と組成がどの程度豊かになるのかが示されるだろう。

キーワード：生物多様性保全、林業生産性、人工林、保持林業、水土保全

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