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ORIGINAL PAPER

# Effects of silviculture treatments in a hurricane-damaged forest on carbon storage and emissions in central Hokkaido, Japan

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**Abstract**: Hurricanes cause abrupt carbon reduction in forests, but silviculture treatment can be an effective means of quickly regenerating and restoring hurricane-damaged sites. This study assessed how silviculture treatments affect carbon balance after hurricane damage in central Hokkaido, Japan. We examined carbon storage in trees and underground vegetation as well as carbon emissions from silviculture operations in 25-year-old stands, where scarification and plantation occurred just after hurricane damage. The amount of carbon stored varied according to silviculture treatment. Among three scarification treatments, a scarified depth of 0 cm (understory vegetation removal) led to the largest amount of carbon stored (64.7 t·ha$^{-1}$ C). Among four plantation treatments, the largest amount of carbon was stored in a *Larix* hybrid (*L. gmelinii* var. *japonica* × *L. kaempferi*) plantation (80.3 t·ha$^{-1}$ C). The plantation of *Abies sachalinensis* was not successful at accumulating carbon (40.5·ha$^{-1}$ C). The amount of carbon emitted from silviculture operations was 0.05–0.14 t·ha$^{-1}$ C, and it marginally affected the net carbon balance of the silviculture project. Results indicate that silviculture treatments should be performed in an appropriate way to effectively recover the ability of carbon sequestration in hurricane-damaged forests.

**Keywords**: carbon emission; carbon storage; forest restoration; hurricane damage; plantation; scarification

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## Introduction

Hurricanes (i.e., extremely violent winds, also called typhoons) can have a great impact on forests (Dale et al. 2001; Yoshida and Noguchi 2009). For example, in August 2005, Hurricane Katrina blew down 320 million trees along the Gulf Coast of the United States (Chambers et al. 2007). In central and northern Europe, severe storms felled 165 million m$^3$ and 75 million m$^3$ of timber in 1999 and 2005, respectively (The MCPFE Liaison Unit Warsaw et al. 2007). Typhoons often strike Japan, and 37 000 ha of Hokkaido's forests were severely damaged as a result of typhoons in September 2004 (Hokkaido Forest Disaster Remote Sensing Research Group 2005). Global warming may increase the frequency, intensity, and duration of hurricanes (Webster et al. 2005).

Hurricanes play a significant role in reducing carbon storage in forests (Lindroth et al. 2009; McNulty 2002). During and after a hurricane, forest biomass is converted from living to dead carbon. Although part of the biomass can be salvaged and put into long-term carbon sequestration pools (e.g., lumber), the remainder is left to decompose and eventually return to the atmosphere. Rapid regeneration and growth of deforested sites after hurricane damage is thus important to regaining the ability to sequester atmospheric carbon.

If natural tree regeneration is difficult because of competition from other vegetation, silviculture treatment can be effective for successfully regenerating and restoring hurricane-damaged forests (Dale et al. 2001; Yoshida et al. 2005). One possible measure is scarification, which is displacement of surface soil with machinery to improve the substrate, remove understory competitors, and enable successful tree regeneration (Aoyama et al. 2009). Plantation is another alternative. Such silviculture projects

may help to increase carbon storage, although their success is partly offset by the carbon emissions resulting from the operations.

Previous studies have explored the effect of silviculture treatments on carbon storage and emission. Gaboury et al. (2009) calculated carbon balance through an afforestation project in Quebec's boreal forest, where poor regeneration occurred after wildfire. Markewitz (2006) estimated fossil fuel carbon emissions associated with silviculture activities for pine plantation in the southeastern United States. Nordborg et al. (2006) determined carbon storage in Swedish plantation stands given two different site preparation treatments (deep soil cultivation and patch scarification), and Berg and Karjalainen (2003) compared greenhouse gas emissions from silviculture operations in Finland and Sweden. Although Nomoto et al. (2005) conducted a case study analyzing carbon balance in a Sugi (*Criptomeria japonica* D. Don) plantation in Japan, there are limited data on how silviculture treatments affect carbon sequestration after hurricane damage.

The purpose of this study was to assess the possible effects of silviculture treatments within a hurricane-damaged forest on carbon balance in central Hokkaido, northern Japan. A case analysis was performed on 25-year-old stands where scarification and plantation occurred just after hurricane damage. We investigated the distribution of tree and underground vegetation biomass. The general approach for estimating carbon storage was based on the national greenhouse gas inventory report of Japan (Greenhouse Gas Inventory Office of Japan 2008). We also calculated carbon emissions from silviculture operations. By comparing the carbon balance among stands with different treatments, we were able to assess effective human interventions for quickly recovering the carbon sequestration function in hurricane-damaged sites.

## Material and methods

### Study site

The study site was established as Fig. 1 within sub-compartment 97 BC at the University of Tokyo Hokkaido Forest (43°13′ N, 142°36–37′ E, 580–670 m asl). We assumed site conditions to be equal over the study site. This area is situated on a ridge with a flat or gentle slope (<15%). According to observations at the Maeyama meteorological station (43°18′ N, 142°36′ E, 610 m asl, approximately 8 km north of the study site), the mean annual temperature and precipitation in 2007 were 5.2°C and 954 mm, respectively (Tokyo University Forests 2009). The ground is covered with snow from mid-November to mid-May. The substrate is rhyolite and dacite welded tuffs (Geological Survey of Japan 2003). The soil type is dark forest soil (Asahi 1963). The dominant native tree species are *Abies sachalinensis* (Fr. Schm.) Masters, *Picea jezoensis* (Sieb. & Zucc.) Carr., *Tilia japonica* (Miq.) Simonkai, and *Betula ermanii* Cham. The forest floor is mostly occupied by dwarf bamboo *Sasa senanensis* (Franch. & Savat.) Rehd. with some *Sasa kurilensis* (Rupr.) Makino & Shibata.

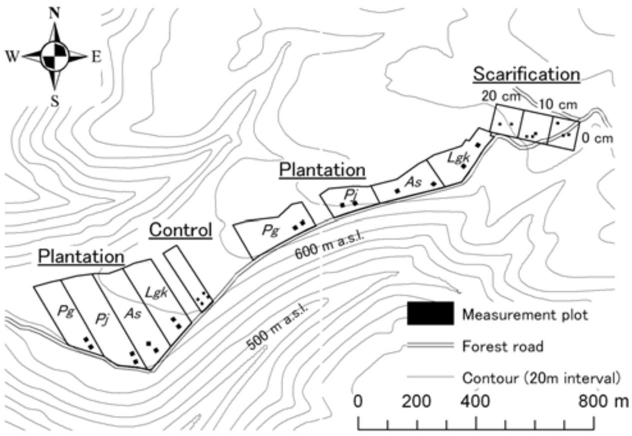


**Fig. 1 Study site.** ***Lgk*: *L. gmelinii* var. *japonica* × *L. kaempferi*, *Pg*: *Picea glehnii*, *Pj*: *Picea jezoensis*, *As*: *Abies sachalinensis*.**

In August 1981, the University Forest including the study site was heavily damaged by a typhoon. In all, 38.9% (8 735 ha) of the area was damaged, and 807 000 $m^3$ damaged trees were salvaged (Takada et al. 1986). Intensive silviculture treatments were performed just after the typhoon to quickly restore the damaged areas.

Damaged trees in the study site were salvaged in August 1982, with the exception of those in the control site. In August 1983, line scarification was performed using two bulldozers, D50A (weight = 11 t) and D60A (15 t; Komatsu, Ltd., Tokyo, Japan), both of which had a rake (width = 3.3 m) with 10 nails. The width of the scarified line was 5 m, and the interval between lines was 7 m (Kamiiizaka and Fujiwara 1986). Three scarification treatments were executed according to the depth scarified from the ground surface: 0 cm (i.e., understory vegetation removal), 10 cm (i.e., humus layer removal), and 20 cm (i.e., top soil removal). For each treatment, the scarified area was 1.00 ha (100 m × 100 m; Fig. 1).

Plantation treatments were also performed in the study site. Site preparation in August 1983 involved using bulldozers to make a scarified line of 3 m width (interval between lines = 4 m; Kamiiizaka and Fujiwara 1986). In May 1984, four coniferous tree species were planted in a total area of 20.82 ha (two duplications for each species): *Larix* hybrid (*L. gmelinii* var. *japonica* (Maxim. ex Regel) Pilg. × *L. kaempferi* (Lamb.) Carr.), *Picea glehnii* (Fr. Schm.) Masters, *Picea jezoensis*, and *Abies sachalinensis* (see Fig. 1). The seedling density was kept relatively low (a maximum of 1 500 seedlings ha) to promote succession to mixed stands with broadleaf species (Watanabe et al. 1990). Supplemental planting and management of the stands were also implemented depending upon the situation (Table 1). Rodenticide was sprayed eight times after planting the *Larix* hybrid, whereas supplemental planting and weeding occurred in *P. glehnii*, *P. jezoensis*, and *A. sachalinensis* plantations.

**Table 1. Frequency of silviculture operations performed at the study site**

| Year | Scarifi-cation | Plantation | | | | |
|---|---|---|---|---|---|---|
| | | Site preparing | Plant-ing | Supplemental planting* | Weed-ing* | Rodenticide spraying** |
| 1983 | 1 | 1 | | | | |
| 1984 | | | 1 | 1 | | |
| 1985 | | | | 2 | | 3 |
| 1986 | | | | | 1 | 1 |
| 1987 | | | | | 2 | 1 |
| 1988 | | | | | 2 | 1 |
| 1989 | | | | | 1 | 1 |
| 1990 | | | | | 1 | 1 |
| Total | 1 | 1 | 1 | 3 | 7 | 8 |

Source: Silvicultural records, The University of Tokyo Hokkaido Forest
* Not applied for *Larix* hybrid, ** Applied only for *Larix* hybrid.

### Field data collection

Field measurement was conducted in August 2008, 27 years after the hurricane damage and 25 growing years after the silviculture treatments. We established a total of 32 measurement plots in the study site (Fig. 1). The plot size was 100 $m^2$ (10 m × 10 m) for scarified/control stands and 225 $m^2$ (15 m × 15 m) for planted stands. Although the plots had to be set near the forest road because of the difficulty of walking through the dense understory vegetation, we assumed based on observations of aerial photos that trees did not have a biased distribution within each stand.

The field measurement collected data on density of above-ground vegetation, which can have a significant influence on carbon accumulated in a forest both above ground and below ground (Gaboury et al. 2009). In each plot, the species, diameter at breast height (DBH), and height were recorded for all living trees with DBH ≥ 5 cm. Snags were rarely observed in the study site. We also established 1-$m^2$ (1 m × 1 m) quadrats on the four corners of each plot and recorded the species and density of understory vegetation (i.e., *Sasa* spp.). The diameter at ground level and height of a medium-size *Sasa* culm was measured in each quadrat. In mid-September 2008, we sampled 30 culms of both *S. senanensis* and *S. kurilensis* of various heights. After taking measurements of the diameter at ground level and culm height, we dried all samples for 48 h at 80°C to measure dry weight.

### Estimation of carbon storage

Carbon storage in tree biomass (*CST*; t·$ha^{-1}$ C) was calculated using the following equation (Greenhouse Gas Inventory Office of Japan 2008):

$$CST = \sum_i [V_i \cdot D_i \cdot BEF_i \cdot (1 + R_i) \cdot cft] \quad (1)$$

where $V$ is the stem volume ($m^3 \cdot ha^{-1}$), $D$ is the basic wood density (t-dm·$m^{-3}$), *BEF* is the biomass expansion factor to convert for stem volume, $R$ is the root-to-shoot ratio, *cft* is the carbon fraction of the tree (t·t-$dm^{-1}$ C), and $i$ represents the tree species. $V$ was calculated from DBH measured using one variable volume tariff for the University Forest. Table 2 shows the values of $D$, *BEF*, and $R$ used in this study. In our calculations, we assumed the values of the *Larix* hybrid to be equivalent to those of *L. kaempferi*. The value of *cft* was assumed to be a constant of 0.5 (Greenhouse Gas Inventory Office of Japan 2008).

Carbon storage in *Sasa* biomass (*CSS*; t·$ha^{-1}$ C) was calculated using the following equation:

$$CSS = W_j \cdot (1 + R_j) \cdot cfs \quad (2)$$

where $W$ is the aboveground *Sasa* biomass (t-dm·$ha^{-1}$), $R$ is the root-to-shoot ratio, *cfs* is the carbon fraction of *Sasa* biomass (t·t-$dm^{-1}$ C), and $j$ represents the *Sasa* species.

The value of $W$ was calculated using the following equations:

$$W = (\overline{W} \cdot 10^{-6}) \cdot (N \cdot 10^4) \quad (3)$$

$$W = a \cdot (d_0{}^2 \cdot h)^b \quad (4)$$

where $\overline{W}$ is the aboveground biomass of a normal-size culm (g-dm $culm^{-1}$) and $N$ is culm density (culms·$m^{-2}$). The value of $\overline{W}$ was estimated using the allometric equation (4) where $d_0$ is diameter at ground level (cm) and $h$ is culm height (cm). The parameters $a$ and $b$ were estimated by regression analyses on data from sampled culms. The value of $\overline{W}$ in each quadrat was determined using the derived allometric equations. The values of $R$ were assumed on the basis of a thorough review of the literature (Table 3). In general, *S. senanensis* allocates more resources to belowground parts than does *S. kurilensis* (Toyooka et al. 1986; Yajima et al. 1997). This study adopted median values from previous case results: 1.17 for *S. senanensis* and 0.40 for *S. kurilensis*. The value of *cfs* was assumed to be a constant of 0.47 (Jia and Akiyama 2005).

**Table 2. Wood density (*D*), biomass expansion factor (*BEF*), and root-to-shoot ratio (*R*) for tree species.**

| Species | *D* | *BEF** | *R* |
|---|---|---|---|
| *Larix kaempferi* | 0.404 | 1.15 | 0.29 |
| *Abies sachalinensis* | 0.319 | 1.38 | 0.21 |
| *Picea jezoensis* | 0.348 | 1.46 | 0.22 |
| *Picea glehnii* | 0.364 | 1.67 | 0.21 |
| *Quercus* spp. | 0.619 | 1.26 | 0.25 |
| *Magnolia obovata* | 0.386 | 1.17 | 0.25 |
| *Acer* spp. | 0.519 | 1.17 | 0.25 |
| *Tilia japonica* | 0.369 | 1.17 | 0.25 |
| *Kalopanax pictus* | 0.398 | 1.17 | 0.25 |
| *Betula* spp. | 0.619 | 1.20 | 0.25 |
| Other broad-leaved tree spp. | 0.619 | 1.26 | 0.25 |

Source: National Greenhouse Gas Inventory Report of Japan (2008)
* *BEF*s for > 20 years of age

### Estimation of carbon emission

Because they involve the use of petroleum products (i.e., fuel and lubricants), silviculture activities produce fossil fuel carbon emissions. The amount of petroleum consumed depends on the

type and intensity of the treatment and number of interventions (Markewitz 2006). This study calculated fossil fuel carbon emissions associated with machine and automobile usage for operations and traveling. Although chemical inputs (i.e., rodenticide) directly or indirectly use fossil fuel in their production, examining this was beyond the scope of this study.

**Table 3. Root-to-shoot ratio of two *Sasa* species from the literature.**

| Species | Mean height (cm) | Mean diameter at the ground level (cm) | Density (culms·m$^{-2}$) | Aboveground biomass (g-dm·m$^{-2}$) | Belowground biomass (g-dm·m$^{-2}$) | Root-to-shoot ratio | Citation |
|---|---|---|---|---|---|---|---|
| *S. senanensis* | 113 | n.a. | 40.0 | 670 | 590 | 0.88 | Nishimura et al. (2004) |
| | 113 | n.a. | 40.0 | 640 | 590 | 0.92 | Nishimura et al. (2004) |
| | 107 | 5.2 | 149.8 | 1 672 | 1 825 | 1.09 | Yajima et al. (1997) |
| | 77 | 4.4 | 150.3 | 1 098 | 1 280 | 1.17 | Yajima et al. (1997) |
| | 117 | 6.0 | 117.0 | 1 854 | 2 175 | 1.17 | Toyooka et al. (1986) |
| | 71 | 4.1 | 159.5 | 956 | 1 165 | 1.22 | Yajima et al. (1997) |
| | n.a. | n.a. | n.a. | 966 | 1 204 | 1.25 | Matumura et al. (1988) |
| | 30 | 3.1 | 175.8 | 394 | 831 | 2.11 | Yajima et al. (1997) |
| *S. kurilensis* | 261 | 11.1 | 29.5 | 3 143 | 666 | 0.21 | Yajima et al. (1997) |
| | 320 | 12.5 | 41.0 | 7 980 | 2 330 | 0.29 | Kawahara and Suzuki (1981) |
| | 297 | n.a. | 28.0 | 8 100 | 2 720 | 0.34 | Oshima (1961b) |
| | 325 | n.a. | 29.0 | 8 075 | 2 955 | 0.37 | Oshima (1961b) |
| | 325 | n.a. | 27.0 | 7 738 | 2 984 | 0.39 | Oshima (1961a) |
| | 330 | n.a. | 28.0 | 8 266 | 3 210 | 0.39 | Oshima (1961a) |
| | 328 | n.a. | 28.0 | 7 895 | 3 150 | 0.40 | Oshima (1961b) |
| | 89 | 6.7 | 37.8 | 1 008 | 424 | 0.42 | Yajima et al. (1997) |
| | 139 | 9.0 | 24.0 | 1 411 | 595 | 0.42 | Yajima et al. (1997) |
| | n.a. | n.a. | 27.0 | 7 725 | 3 910 | 0.51 | Oshima (1961b) |
| | 330 | n.a. | 28.0 | 7 510 | 4 170 | 0.56 | Oshima (1961b) |
| | 293 | 14.4 | 28.0 | 5 941 | 4 136 | 0.70 | Toyooka et al. (1986) |
| | 59 | 5.7 | 31.3 | 509 | 408 | 0.80 | Yajima et al. (1997) |

Carbon emissions from silviculture operations ($CEM$; t·ha$^{-1}$ C) were calculated from the following equation:

$$CEM = OE \cdot (F_m \cdot EF_f + L_m \cdot EF_l) \cdot 10^{-3} \quad (5)$$

where $OE$ is the operational efficiency (h·ha$^{-1}$) and $F_m$ and $L_m$ are fuel and lubricant consumption by machine usage (l·h$^{-1}$). $EF_f$ and $EF_l$ are emission factors of fuel and lubricant (kg·l$^{-1}$ C).

Carbon emissions from traveling ($CET$; t·ha$^{-1}$ C) were calculated as follows:

$$CET = \frac{OE}{WH} \cdot \frac{DT}{VD} \cdot EF_f \cdot 10^{-3} \quad (6)$$

where $WH$ is the daily working hours (h·day$^{-1}$), $DT$ is the traveling distance (km·day$^{-1}$), $VD$ is fuel consumption by automobile (km·l$^{-1}$), and $EF_f$ is the emission factor (kg·l$^{-1}$ C).

The values of $OE$, $F_m$, $L_m$, and $VD$ were determined according to operational records at the study site (Table 4). The lower plantation density at *P. jezoensis* stands (approximately 500 seedlings ha$^{-1}$) caused by a shortage of seedlings resulted in higher operational efficiency. We measured the distance from the head office to the study site by tracking with a global positioning system receiver while driving. Emission factors of fuel and lubricant were based on the Global Environmental Bureau of the Japan Ministry of the Environment (2003).

**Table 4. Basic values used to calculate carbon emissions.**

| Factor | Symbol | Type | Value | Unit |
|---|---|---|---|---|
| Operational efficiency | $OE$ | Scarifying/site preparation | 3.6 | h·ha$^{-1}$ |
| | | Planting (*P. jezoensis*) | 18.2 | h·ha$^{-1}$ |
| | | Planting (other tree spp.) | 38.8 | h·ha$^{-1}$ |
| | | Supplemental planting | 3.6 | h·ha$^{-1}$ |
| | | Rodenticide spraying | 1.3 | h·ha$^{-1}$ |
| | | Weeding | 10.1 | h·ha$^{-1}$ |
| Petroleum consumption | $F_m$ | Bulldozer (diesel) | 18.1 | l·h$^{-1}$ |
| | | Bush cutter (gasoline) | 0.43 | l·h$^{-1}$ |
| | $L_m$ | Bulldozer (lubricant) | 0.70 | l·h$^{-1}$ |
| | | Bush cutter (lubricant) | 0.01 | l·h$^{-1}$ |
| Travelling | $DT$ | Distance | 38 | km·day$^{-1}$ |
| | $VD$ | Fuel consumption by vehicle | 8.9 | km·l$^{-1}$ |
| | $WH$ | Actual work hour | 5 | h·day$^{-1}$ |
| Emmision factor | $EF_f$ | Gasoline | 0.63 | kg·l$^{-1}$ C |
| | | Diesel | 0.72 | kg·l$^{-1}$ C |
| | $EF_l$ | Lubricant | 0.77 | kg·l$^{-1}$ C |

## Results

### Stand development in the study site

Regeneration of trees and understory vegetation (*Sasa*) in the study site 25 years after the silviculture treatments is summarized

in Table 5. Of the scarification treatments, the scarified depth of 0 cm (understory vegetation removal) led to a relatively high tree density and mean DBH, resulting in a larger stem volume (109.7 $m^3 \cdot ha^{-1}$). Tree species were mostly *Betula ermanii* in all stands with scarification (Table 6). The density and size of *Sasa* were relatively high at the scarified depth of 20 cm (top soil removal). Scarification to the depth of 10 cm (humus layer removal) led to a relatively low *Sasa* density, although the difference was not significant. *S. kurilensis* was distributed in 3 out of 12 quadrats within this treatment but was rarely found in stands with the other treatments.

**Table 5. Tree and *Sasa* regeneration 25 years after the silviculture treatments.**

| Vegetation type | Item | Unit | Scarification* | | | Plantation** | | | | Control*** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 cm | 10 cm | 20 cm | *Lgk* | *Pg* | *Pj* | *As* | | |
| Tree | Number of plot | plots | 3 | 3 | 2 | 4 | 4 | 4 | 4 | 4 | |
| | Density | $trees \cdot ha^{-1}$ | 3 400 | 2 433 | 2 000 | 1 344 | 2 256 | 1 722 | 867 | 1 225 | (350) |
| | Mean DBH | cm | 8.5 | 8.0 | 7.9 | 15.7 | 10.9 | 10.5 | 11.0 | 9.7 | (24.5) |
| | Mean height | m | 10.7 | 10.1 | 9.6 | 13.4 | 10.1 | 8.7 | 8.3 | 8.1 | (14.9) |
| | Basal area | $m^2 \cdot ha^{-1}$ | 21.4 | 13.1 | 10.7 | 29.4 | 23.9 | 16.7 | 9.8 | 10.3 | (17.0) |
| | Stem volume | $m^3 \cdot ha^{-1}$ | 109.7 | 62.3 | 53.5 | 239.6 | 147.0 | 98.7 | 63.1 | 57.3 | (134.8) |
| *Sasa* | Number of quadrat | quadrats | 12 | 12 | 8 | 8 | 16 | 16 | 16 | 16 | |
| | Density | $culms \cdot m^{-2}$ | 31.3 | 23.3 | 32.9 | 19.4 | 20.6 | 30.3 | 48.7 | 32.8 | |
| | Mean diameter at the ground level | cm | 6.2 | 6.4 | 7.1 | 5.5 | 6.4 | 5.9 | 6.2 | 5.9 | |
| | Mean height | cm | 111.1 | 113.0 | 125.0 | 79.1 | 104.3 | 103.9 | 116.5 | 109.3 | |

* Levels in scarification represent scarified soil depth from the ground surface; ** *Lgk*; *L. gmelinii* var. *japonica* × *L. kaempferi*, *Pg*; *Picea glehnii*, *Pj*; *Picea jezoensis*, *As*; *Abies sachalinensis;* *** Figures in parentheses are advanced regeneration prior to the windthrow.

**Table 6. Tree regeneration 25 years after the silviculture treatments by species (trees $ha^{-1}$).**

| Species | Scarification | | | Plantation** | | | | Control*** | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 cm | 10 cm | 20 cm | *Lgk* | *Pg* | *Pj* | *As* | | |
| *Abies sachalinensis* | | | | 11 | 33 | 67 | 478 | 200 | (150) |
| *Picea jezoensis* | | | | | | 756 | 56 | 150 | (25) |
| *Picea glehnii* | | | | | 1 011 | | | | |
| *Larix* hybrid* | | | | 1 222 | | | | | |
| *Salix* spp. | 33 | 33 | | | 11 | 156 | 22 | 150 | |
| *Betula maximowicziana* | 67 | | | 11 | 56 | 100 | | 125 | |
| *Betula platyphylla* var. *japonica* | | | | | | 11 | 11 | | |
| *Betula ermanii* | 3 300 | 2 400 | 2 000 | 56 | 944 | 622 | 178 | | |
| *Quercus crispula* | | | | | 11 | | | | |
| *Magnolia obovata* | | | | | 11 | | 22 | | |
| *Magnolia kobus* var. *borealis* | | | | | | | | 75 | |
| *Prunus* spp. | | | | | 33 | | | 50 | (50) |
| *Sorbus commixta* | | | | | 11 | | 33 | 50 | (25) |
| *Acer amoenum* | | | | | | | | | (25) |
| *Acer mono* | | | | 33 | 44 | 11 | 33 | 50 | (25) |
| *Tilia japonica* | | | | 11 | 89 | | 33 | 350 | (50) |
| *Kalopanax pictus* | | | | | | | | 25 | |
| Total | 3 400 | 2 433 | 2 000 | 1 344 | 2 256 | 1 722 | 867 | 1 225 | (350) |

* *L. gmelinii* var. *japonica* × *L. kaempferi;* ** *Lgk*; *L. gmelinii* var. *japonica* × *L. kaempferi*, *Pg*; *Picea glehnii*, *Pj*; *Picea jezoensis*, *As*; *Abies sachalinensis;* *** Figures in parentheses are advanced regeneration prior to the windthrow.

Among plantation treatments, a significant difference was observed in tree density ($p < 0.05$, Kruskal–Wallis test). *P. glehnii* plantation had the highest density (2 256 $trees \cdot ha^{-1}$), which was significantly greater than *A. sachalinensis* ($p < 0.05$, Scheffe's test). Natural regeneration of different tree species (mainly *B. ermanii*) was dominant in the *P. glehnii* plantation, and the number of planted trees accounted for less than half of the total (Table 6). Natural regeneration was relatively low in the *Larix* hybrid plantation. We found significant differences in mean DBH, height, and stem volume ($p < 0.05$), and the *Larix* hybrid plantation was significantly larger in height and volume than *A. sachalinensis* ($p < 0.05$). There were significant differences in *Sasa* density and culm height ($p < 0.01$). The *A. sachalinensis* plantation had a significantly larger *Sasa* density ($p < 0.05$) and height ($p < 0.01$) than the *Larix* hybrid plantation.

Tree regeneration in the control stand was relatively low in density and small in size after the hurricane damage (Table 5). The species composition was different from the stands that received silviculture treatments (Table 6), and more natural regeneration of two conifers (*A. sachalinensis* and *P. jezoensis*) and broadleaf trees (mainly *T. japonica*) was observed. Because salvage logging was not performed, considerable amounts of advanced regeneration prior to the hurricane existed in the control stand. When this was taken into account, the aggregated stem volume reached 192.1 $m^3 \cdot ha^{-1}$, which was the second largest among the stands investigated in this study.

### Carbon storage in tree and *Sasa* biomass

The carbon stored in tree and *Sasa* biomass was estimated for each silviculture treatment (Table 7). Prior to calculation, we derived the following allometric equations with regard to the relationship between culm size and the dry weight of the two *Sasa* species:

*S. senanensis*: $$w = 10.69 \cdot (d_0^{\,2} \cdot h)^{0.17}$$ ($r^2 = 0.78$, n = 30)

*S. kurilensis*: $$w = 0.36 \cdot (d_0^{\,2} \cdot h)^{0.57}$$ ($r^2 = 0.86$, n = 30).

The amount of carbon stored varied according to silviculture treatment. The largest amount of carbon was stored in the *Larix* hybrid plantation (80.3 $t \cdot ha^{-1}$ C), and 90% of this carbon was in tree biomass. Carbon storage in tree biomass was significantly different among plantation treatments ($p < 0.01$, Kruskal–Wallis test), and the amount of carbon in the *Larix* hybrid plantation was significantly greater than that in *A. sachalinensis* ($p < 0.05$, Scheffe's test). Carbon storage in *Sasa* biomass also differed significantly ($p < 0.01$), and the *A. sachalinensis* plantation contained the largest amount (21.5 $t \cdot ha^{-1}$ C). The *A. sachalinensis* stand stored significantly more *Sasa* carbon compared to any other plantation species ($p < 0.01$), and more than half of the biomass carbon was in the understory vegetation.

Among the scarification treatments, the 0-cm scarified depth led to the largest carbon storage (64.7 $t \cdot ha^{-1}$ C), of which 79% was stored in tree biomass. The carbon stored in tree biomass was relatively larger at the 0-cm depth compared to deeper depths. Scarification to a depth of 10 cm led to a relatively small amount of carbon in *Sasa* biomass, although the difference was not significant.

**Table 7. Carbon storage in tree and *Sasa* biomass by silviculture treatment ($t \cdot ha^{-1}$ C).**

| Treatment | Level | Tree | | | | *Sasa* | | Total | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | | SE | | Mean | SE | Mean | |
| Scarification | 0 cm | 51.0 | | 6.3 | | 13.7 | 1.7 | 64.7 | |
| | 10 cm | 29.0 | | 6.8 | | 9.8 | 1.4 | 38.7 | |
| | 20 cm | 24.8 | | n.a. | | 15.5 | 1.8 | 40.3 | |
| Plantation | *Lgk* | 72.6 | | 3.4 | | 7.8 | 1.6 | 80.3 | |
| | *Pg* | 58.6 | | 6.2 | | 9.1 | 0.9 | 67.7 | |
| | *Pj* | 37.2 | | 3.8 | | 13.3 | 2.0 | 50.4 | |
| | *As* | 19.0 | | 7.8 | | 21.5 | 2.3 | 40.5 | |
| Control* | | 21.1 | (42.5) | 2.9 | (5.5) | 14.4 | 1.9 | 35.5 | (42.5) |

* Figures in parentheses are carbon storage in advanced regeneration tree biomass；*Lgk*; *L. gmelinii* var. *japonica* × *L. kaempferi*, *Pg*; *Picea glehnii*, *Pj*; *Picea jezoensis*, *As*; *Abies sachalinensis*

Tree regeneration after the hurricane damage led to a gain of 21.1 $t \cdot ha^{-1}$ C in the control stand, whereas carbon in *Sasa* biomass amounted to 14.4 $t \cdot ha^{-1}$ C. When advanced regeneration prior to the hurricane was taken into account, the aggregated amount of carbon reached 78.0 $t \cdot ha^{-1}$ C, which was the second largest among stands investigated in this study.

### Carbon emissions from silviculture operations

Carbon emissions from silviculture operations were estimated (Table 8). Carbon emitted from scarified stands was 0.05 $t \cdot ha^{-1}$ C and that emitted from planted stands totaled 0.08–0.14 $t \cdot ha^{-1}$ C. In plantation treatments, site preparation and weeding operations were the major sources of carbon emissions, accounting for 63–88% of the carbon emitted by these operations.

**Table 8. Carbon emissions from silviculture treatments ($t \cdot ha^{-1}$ C).**

| Treatment | Level | Scarification | Plantation | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | | | Site preparing | Planting | Supplemental planting | Weeding | Rodenticide spraying | |
| Scarification | All | 0.05 | | | | | | 0.05 |
| Plantation | *Lgk* | | 0.05 | 0.02 | | | 0.01 | 0.08 |
| | *As* | | 0.05 | 0.02 | 0.004 | 0.06 | | 0.14 |
| | *Pj* | | 0.05 | 0.01 | 0.004 | 0.06 | | 0.13 |
| | *Pg* | | 0.05 | 0.02 | 0.004 | 0.06 | | 0.14 |

## Discussion

The results indicate that carbon storage varied considerably according to how the site was treated after the hurricane damage. The *Larix* hybrid plantation had the largest carbon storage of the silviculture treatments. This is consistent with Adachi et al. (1985), who reported 20 years of growth progress of 15 planted species in the University of Tokyo Hokkaido Forest. They found that the *Larix* hybrid grew relatively fast at a similar elevation (730 m a.s.l.). The survival rate of *Larix* hybrid seedlings was rather high because it was able to resist damage by rodents. Al-

though *L. gmelinii* became extinct about 8 000 years ago (Ono and Igarashi 1991) and *L. kaempferi* is an exotic species in Hokkaido, the hybrid seems well adapted to the higher elevation of the University Forest, with its harsh climatic conditions of low temperatures and deep snow.

The *P. glehnii* plantation stored the second largest amount of carbon. This result can be explained by the high survival rate of *P. glehnii* seedlings at higher elevations (Adachi et al. 1985). Adachi et al. (1985) reported that *P. jezoensis* is also very hardy, and the difference in carbon storage between these two species may simply be due to initial seedling density. In plantation stands with the two *Picea* species, natural regeneration of broadleaf trees (mainly *B. ermanii*) contributed to carbon storage. Several natural regeneration trees were also observed in the *Larix* hybrid plantation 10 years after treatment (Kurahashi, unpublished data), but these might have subsequently disappeared because of the change in light conditions associated with canopy closure.

The *A. sachalinensis* plantation was unsuccessful at increasing carbon storage in the hurricane-damaged site. *A. sachalinensis* seedlings are frequently damaged by *Scleroderris* canker at higher elevations (Adachi et al. 1985), resulting in a low rate of survival. According to Watanabe (1996), *A. sachalinensis* seedlings whose seed trees grew at low elevations were subject to high mortality and low growth when planted at high elevations. Although there are no data on the seed source, this might have affected the survival and growth of *A. sachalinensis* in the study site.

Within scarification treatments, the amount of carbon stored varied according to the intensity of soil disturbance. In this study, mild scarification that removed only underground vegetation resulted in larger carbon storage compared to heavily scarified sites. When scarification removes surface soil that contains abundant nutrients, it can potentially stunt established trees (Yoshida et al. 2005). The physicochemical properties of subsurface soil may have adversely affected the growth of natural regeneration (Yamada 1999). The scarified sites were mostly occupied by *B. ermanii*, as is frequently observed in Hokkaido (Umeki 2003). Even though a *Betula* tree is rich in carbon because of high wood density (Table 2), scarification treatments may lead to low species diversity in hurricane-damaged sites.

Our results on carbon emissions support those of Gaboury et al. (2009), showing that the amount of carbon emitted from forest operations is far less than the amount of carbon sequestered in afforested stands. Indeed, carbon emissions did not significantly affect the net carbon balance of the silviculture project. The operations and transportation involved in performing scarification and plantation do not consume much energy; therefore, the associated carbon emissions are actually rather negligible.

## Conclusions

If appropriately performed, silviculture treatment can enable hurricane-damaged forests to recover the ability to sequester carbon. However, treatments that are not suitable for a specific site may result in the loss of the carbon sequestration function. Within the present study site, the *Larix* hybrid plantation had the largest carbon storage. Even though this treatment technique enabled efficient carbon sequestration, experts need to carefully consider any side effects (e.g., genetic disturbance) before applying it to other sites.

This study was intended to objectively illustrate the effects of silviculture treatments on carbon storage and emissions in central Hokkaido, Japan. However, these results may be site specific, and site conditions may have affected the stand development and carbon storage. Future research should examine these factors under various other site conditions. Because our results are limited to 25-year-old stands, longitudinal studies within a site are needed to understand the dynamics of carbon balance in hurricane-damaged forests. In our calculations, we did not include carbon storage in woody debris, litter, or soil or carbon emissions from salvage logging operations or seed or seedling production. It is important that future studies provide for a more fully developed understanding of carbon distribution in hurricane-damaged forests.

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