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# Carbon Stock of Larch Plantations and Its Comparison with an Old-growth Forest in Northeast China

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**Abstract:** The overall goal of this study was to understand carbon (C) stock dynamics in four different-aged Japanese larch (*Larix kaempferi*) plantations in Northeast China that were established after clear-cutting old-growth Korean pine deciduous forests. Four Japanese larch plantations which were at 10, 15, 21, and 35 years old and an old-growth Korean pine deciduous forest which was 300 years old in Northeast China were selected and sampled. We compared the C pools of biomass (tree, shrub and herb), litterfall (LF), and soil organic carbon (SOC) among them. The biomass C stock of larch plantation at 10, 15, 21, and 35 years old was 26.8, 37.9, 63.6, and 83.2 Mg/ha, respectively, while the biomass C stock of the old-growth Korean pine deciduous forest was 175.1 Mg/ha. The SOC stock of these larch plantations was 172.1, 169.7, 140.3, and 136.2 Mg/ha respectively, and SOC stock of 170.4 Mg/ha in the control of old-growth forest. The biomass C stock increased with stand age of larch plantations, whereas SOC stock decreased with age, and C stock of LF did not change significantly ($P > 0.05$). The increase of biomass C offset the decline of SOC stock with age, making total carbon stock (TCS) of larch plantations stable from stand ages of 10–35 years. The TCS in larch plantations was much smaller than that in the old-growth forest, suggesting that the conversion of old-growth forests to young larch plantations releases substantial C into the atmosphere.

**Keywords:** larch plantation; old-growth forest; biomass carbon; soil organic carbon; total carbon stocks

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## 1 Introduction

As atmospheric $CO_2$ concentrations increase and concern over climate change deepens, forests are considered to be an important means to sequestrate carbon (C) and mitigate $CO_2$ emissions (IPCC, 2000; Hu and Wang, 2008; Luyssaert *et al*., 2008; Fahey *et al*., 2009; Sommers *et al*., 2014). Forest ecosystems account for about 86% of the biomass C and 73% of soil organic carbon (SOC) of the world′s terrestrial ecosystems (Augustin *et al*., 2004). Annual C stocks in forest ecosystems equals two-thirds of the total carbon stocks (TCS) in the world′s terrestrial ecosystems, suggesting that forest ecosystems can be managed to sequester sig-

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nificant quantities of C to reduce atmospheric $CO_2$ concentration (Zhou *et al.*, 2000; Wang *et al.*, 2001; Augustin *et al.*, 2004; Chang, 2013; Shanin *et al.*, 2013). In light of the above, the Kyoto Protocol stipulated that countries should be credited for planting new forests through afforestation and reforestation (IPCC, 2007; Gren and Carlsson, 2013).

Forest ecosystem C pools are composed primarily of biomass, SOC, coarse woody debris (CWD) and litterfall (LF) (Houghton, 2005). The former two contain most of the forest ecosystem C (IPCC, 2007). The global forest biomass C is about 359 Pg, and the average biomass C stock is approximately 86 Mg/ha (Wang *et al.*, 2001). The forest soil C pool consists of soil inorganic C and SOC, with the latter distributed mainly within the top 1 m of the forest soil layer. The CWD and LF are important components that connect above- and below-ground C pools through the process of decomposition (Harmon and Chen, 1991; Zhou *et al.*, 2008). The LF combined with soil constitutes the largest C pool in forest ecosystems (Moore and Braswell, 1994). For example, mature temperate forests contain over half of their stored C in CWD, LF and SOC (Sharrow and Ismail, 2004).

Larch forests cover about $1.56 \times 10^7$ ha in China, playing a critical role in the regional C budget (Jiang and Zhou, 2002). Northeast China is the southern distribution edge of Dahurian larch (*Larix gmelinii*) plantations (Jomura *et al.*, 2010). Hollinger *et al.* (1994) investigated the C balance of a Dahurian larch forest in the eastern Siberia using an ecological model, and found that the larch forest was a C sink and sequestered C at a rate of 0.9 Mg/(ha·yr). Hirano *et al.* (2003) and Wang *et al.* (2004) investigated the C budget of a larch (*L. kaempferi*) forest in the northern Japan using eddy covariance systems, and showed that the larch forest ecosystem sequestered 1.41–2.40 Mg/ha in 2001. Li *et al.* (2005) found that a larch (*L. sibirica*) forest in the montane region of Mongolia sequestered C at a rate 0.9 Mg/(ha·yr). Based on forest inventory data, Sun *et al.* (2007) reported that the C stock of young-aged and middle-aged Dahurian larch plantations was 14.0 Mg/ha and 22.6 Mg/ha, respectively. Wang *et al.* (2008) estimated tree C stock of larch plantations in Liaoning province from 1984 to 2000 using forest inventory data. They found that the TCS of larch trees in this province was 5.7 Tg C, 6.1 Tg C, 7.5 Tg C and 8.3 Tg C in 1984, 1990, 1995 and 2000, respectively.

Old-growth Korean pine deciduous forests are the dominant primary forests in the Changbai Mountains region in Northeast China. During the latter half of the 20th century, many of these old-growth forests were cleared for agricultural lands (e.g., ginseng farms). Some of these old-growth forests were replaced by larch plantations or secondary forests (Chen and Li, 2003; Dai *et al.*, 2003). Previous studies have reported SOC declines after human disturbance of old-growth forests (Chen and Li, 2003). Harmon *et al.* (1990) found that conversion of old-growth Douglas-fir forests in the Pacific Northwest to younger plantations released significant amounts of C into the atmosphere. Qi *et al.* (2011; 2013) compared C stocks between different-aged larch (*L. gmelinii*) plantations and the local old-growth *L. gmelinii* forests in the Da Hinggan Mountains, and confirmed that biomass of larch plantations played the role of a C sink from age 10- to 61-year, whereas the SOC was C source at the ages before 26 years old. However, few studies have been conducted in northeast China to examine the C stock dynamics of different-aged larch plantations established after the clear-cutting of old-growth Korean pine deciduous forests in this region.

We hypothesized that C stock of biomass of young larch plantations would increase while SOC would decline with plantation age, but that the TCS of these young larch plantations would still be lower than TCS of the old-growth forest. The objectives of this study were: 1) to quantify C stock of vegetation biomass and soils of four different-aged larch plantations and an old-growth Korean pine deciduous forest in Northeast China; 2) to examine how forest age influences C stock distribution in these larch plantations; and 3) to discuss the implications for maximizing C stocks of larch plantations in Northeast China.

## 2 Materials and Methods

### 2.1 Study site

This work was conducted based on Forestry Standards 'Observation Methodology for Long-term Forest Ecosystem Research' of People's Republic of China (LY/T 1952–2011). This study was conducted in the Dongsheng Forest Farm of the Lushuihe Forestry Bureau (42°20′–42°40′N, 127°29′–128°02′E), which is located in the Changbai Mountains area in Jilin Province of Northeast China (Fig. 1). Scientists tend to set up random plots to avoid pseudo replication of samplings, but this method is not suitable for our study. Because most of larch plantations in the study site are at about 20 years old, and random plots can not easily include larch plantations with a great range of stand ages within limited plot numbers. Therefore, we used the typical plots method to set up sampling plots, and ensured three replications for each age class. We selected four Japanese larch (*L. kaempferi*) plantations of ages 10 years, 15 years, 21 years, and 35 years, respectively, along with an old-growth Korean pine deciduous forest (Table 1). All the larch plantations were converted after the clear-cuttings of the old-growth forests, and undergoing the same management practices. The average elevation of the study site is approximately 700 m. The region is characterized by a temperate continental climate with long winter and short cool summer (Hao *et al*., 2004). The mean annual precipitation and temperature are 894 mm and 2.9℃, respectively.

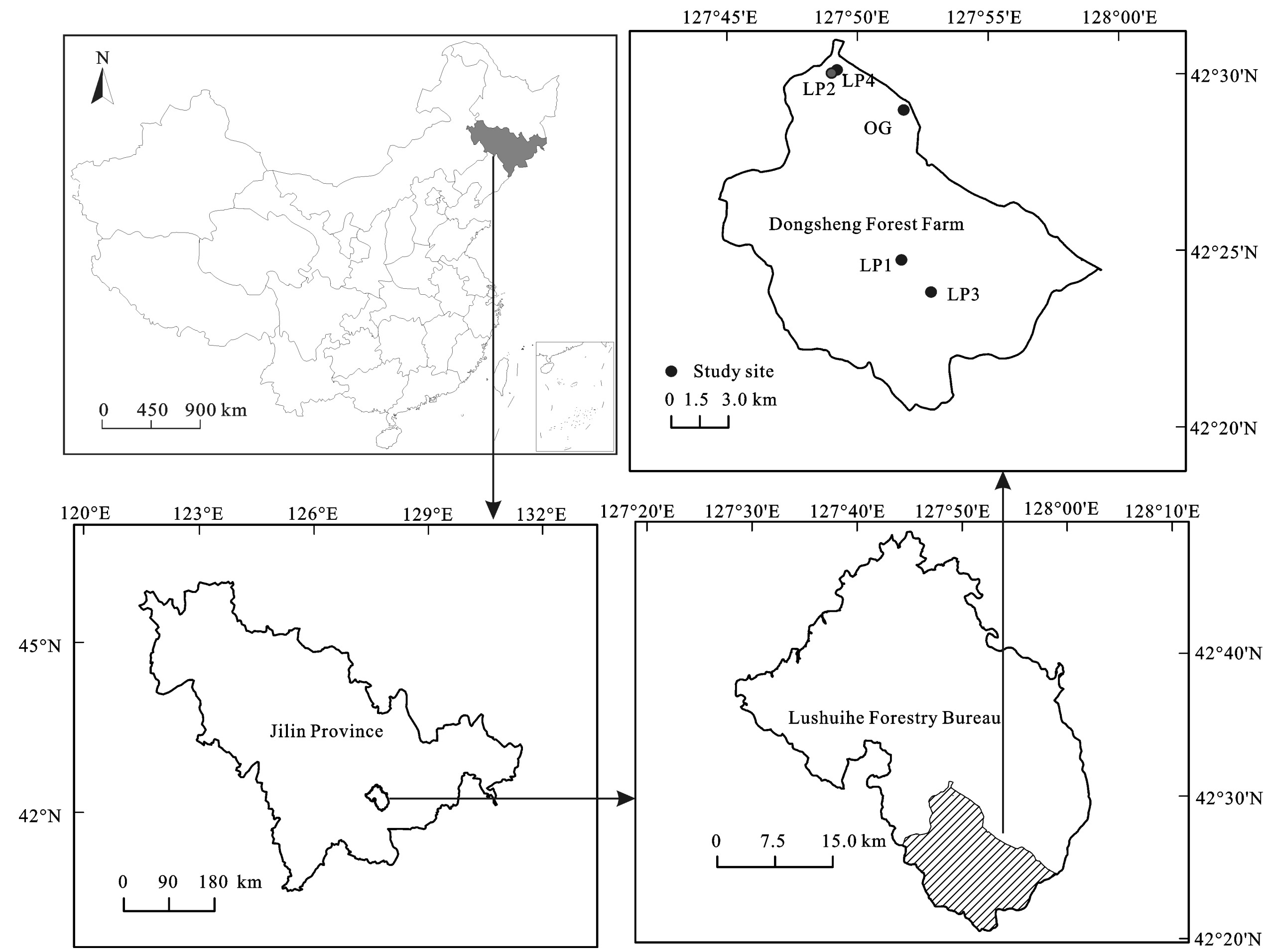


**Fig. 1** Location of five study sites. LP1–LP4 represent larch plantations aged 10-, 15-, 21-, 35-year, resectively. OG represents the old-growth Korean pine deciduous forest

**Table 1** Description of study sites

| Name of site | Stand age (yr) | Forest type | Area (ha) | Density (tree/ha) |
|---|---|---|---|---|
| OG | 300 | Old-growth Korean pine deciduous forest | 220.5 | 1064 |
| LP1 | 10 | Larch plantation | 13.8 | 2533 |
| LP2 | 15 | Larch plantation | 5.2 | 1558 |
| LP3 | 21 | Larch plantation | 21.6 | 1275 |
| LP4 | 35 | Larch plantation | 10.2 | 858 |

Notes: OG represents old-growth Korean pine deciduous forest; LP1–LP4 are larch plantations aged 10-, 15-, 21-, 35-year, respectively

The soil in this site is alfisols. The climax forest in this region is old-growth Korean pine deciduous forest. It is dominated primarily by Korean Pine (*Pinus koraiensis*), Mongolian Oak (*Quercus mongolica*), Mono Maple (*Acer mono*), Amur Linden (*Tilia amurensis*), Elm (*Ulmus propinqua*), Manchurian Ash (*Fraxinus mandshurica*), Korean Aspen (*Populus davidiana*), Japanese Birch (*Betula platyphylla*), and Manchurian Fir (*Abies holophylla*) (Yang and Xu, 2003). The main understory shrubs of the old-growth forest are Hornbeam (*Carpinus mandshurca*), Manyprickle Acanthopanax (*Acanthopanax senticosus*), Shrub Lespedeza (*Lespedeza bicolor*), Coralline Honeysuckle (*Lonicera chrysantha*), and Peking Mockorange (*Philadelphus incanus*). The main herbaceous plants in this forest include Scouring Rush (*Hippochaete hyemale*), Broad-leaf Sedge (*Carex siderotícta*), Gray-vein Sedge (*Carex appendiculata*), *Carex calltnichos*, Common Goldenrod (*Solidago virgaurea* var. *dahurica*), Nerrow-leaved Nettle (*Urtica angustifolia*), Stoneweed (*Brachybotrys paridiformis*), and Forest Horsetail (*Equisetum sylvaticum*).

The typical secondary forest after the clearing of old-growth forest in the region is Poplar/Birch forest. However, larch plantations established after old-growth forest removal have been another important and widely-distributed forest in this region (Chen and Li, 2003; Dai *et al*., 2003). Most of the plantations are established after clear-cutting old-growth Korean pine deciduous forest and removing woody debris in site preparation. The dominant tree species in larch plantations investigated in this paper, accounting for more than 90% of standing trees, is Japanese Larch (*Larix kaempferi Carr*). Other tree species that are naturally regenerated include Japanese Birch (*B. platyphylla*), Korean Aspen (*P. davidiana*), Mongolian Oak (*Q. mongolica*), Japanese Elm (*U. japonica*) and Mono Maple (*A. mono*).

### 2.2 Field method

The field investigation was conducted in the summer of 2009. The four Japanese larch plantations of the Lushuihe Forestry Bureau were established after clear cutting the old-growth Korean pine deciduous forest in 1974, 1988, 1994 and 1999, respectively (Table 1). These plantations were all planted with the same initial density of 3300 seedlings/ha. An old-growth Korean pine deciduous forest was also investigated via a method similar to that used in studying the larch plantations. All study plots were located on gentle slopes (< 5°).

We set three random 20 m × 20 m plots in each plantation, and measured the diameter at breast height (DBH) of all free-standing trees (DBH ≥ 2 cm). Within each 20 m × 20 m plot, three random 5 m × 5 m plots were established to harvest shrubs. We then set a 1 m × 1 m plot within each shrub plot to collect all herbaceous plants. A 0.2 m × 0.2 m plot within each herbaceous plot was then marked for collecting LF. After the LF was gathered, we dug 3–5 soil profiles within each 20 m × 20 m plot to sample soil at mid-depth of different layers (0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm and 60–100 cm). Each sample was placed in a separate plastic bag and transported to our laboratory at Shenyang City.

For the old-growth Korean pine deciduous forest, we established two 1 ha plots and split each into 25 small 20 m × 20 m plots, after which the five diagonal 20 m × 20 m plots were selected for field investigation. In addition, we collected CWD samples and estimated the C stock of CWD according to the method described by Zhong (2009). We did not investigate CWD in larch plantations because the CWD had been cleared by forest management practices such as forest thinning.

Individual tree biomass was calculated by employing regressed relative growth equations for organ biomass (trunk, bark, branch, leaf and root) based on DBH for different tree species in Northeast China (Chen and Zhu, 1989); and then multiplied by 0.5 to convert biomass to C content (Lamlom and Savidge, 2003). Total tree biomass for each 20 m × 20 m plot was then calculated by Equation (1).

$$B_{\mathrm{A}} = \sum_{i=1}^{n}\sum_{j=1}^{m} B_{\mathrm{S}} = \sum_{i=1}^{n}\sum_{j=1}^{m} (B_{\mathrm{T}} + B_{\mathrm{BH}} + B_{\mathrm{L}} + B_{\mathrm{R}}) \qquad (1)$$

where $B_{\mathrm{A}}$ is tree biomass of a 20 m × 20 m plot (kg); $i$ is the tress species; $j$ is the number of trees in a plot; $B_{\mathrm{S}}$ is the single tree biomass (kg); $B_{\mathrm{T}}$, $B_{\mathrm{BH}}$, $B_{\mathrm{L}}$ and $B_{\mathrm{R}}$ represent biomass of trunk, branch, leave and root of a single tree, respectively (kg) (Table 2).

The C stock for tree [$CD_{\mathrm{A}}$ (Mg/ha)] is determined by Equation (2).

$$CD_{\mathrm{A}} = (0.5 \times B_{\mathrm{A}}) / S \qquad (2)$$

where 0.5 is the coefficient of conversion from biomass to C stock; $S$ is the acreage of tree plot.

**Table 2** Relative growth equations for main tree species in larch plantations

| Tree species | Trunk | Branch | Leaf | Root |
|---|---|---|---|---|
| *Pinus koraiensis* | $0.03019 \times D^{2.67945}$ | $0.01637 \times D^{2.04518}$ | $0.07475 \times D^{1.40141}$ | $0.03459 \times D^{1.96795}$ |
| *Betula platyphylla* | $0.14622 \times D^{2.29424}$ | $0.0354 \times D^{1.96042}$ | $0.02283 \times D^{1.68044}$ | $0.03287 \times D^{2.35014}$ |
| *Abies nephrolepis* | $0.0567 \times D^{2.47523}$ | $0.0116 \times D^{2.40517}$ | $0.0083 \times D^{2.37301}$ | $0.0088 \times D^{2.58627}$ |
| *Larix* | $0.0243 \times D^{2.79542}$ | $0.0021 \times D^{2.80413}$ | $0.0012 \times D^{2.81841}$ | $0.0024 \times D^{2.80124}$ |
| *Acer* | $1.3709 \times D^{1.67134}$ | $0.05579 \times D^{1.66907}$ | $0.09056 \times D^{1.61242}$ | $0.3823 \times D^{1.60601}$ |
| *Tilia amurensis* | $0.0656 \times D^{2.39106}$ | $0.00472 \times D^{2.545627}$ | $0.00602 \times D^{2.59214}$ | $0.27040 \times D^{1.29915}$ |
| *Quercus mongolica* | $0.3049 \times D^{2.16801}$ | $0.00212 \times D^{2.95}$ | $0.00321 \times D^{2.47323}$ | $0.09017 \times D^{2.0002}$ |
| *Ulmus japonica* | $0.00432 \times D^{2.87312}$ | $0.00742 \times D^{2.67411}$ | $0.00275 \times D^{2.49603}$ | $0.03459 \times D^{1.5842}$ |
| *Populus davidiana* | $0.4573 \times D^{1.98118}$ | $0.0403 \times D^{2.04412}$ | $0.0186 \times D^{2.26703}$ | $0.2105 \times D^{1.6717}$ |
| *Populus ussuriensis* | $0.36417 \times D^{2.0048}$ | $0.03172 \times D^{2.08975}$ | $0.0149 \times D^{2.2541}$ | $0.09421 \times D^{1.64231}$ |

Notes: Unit of diameter at breast height (D) is centimeter; the equations were first reported in Chen and Zhu (1989)

We oven-dried LF, shrub, and herbage at 65 $^0$C to a constant mass and measured their plot-C-stock. The C densities were then calculated by equations (3)–(5).

$$CD_{\mathrm{FL}} = CS_{\mathrm{FL}} / A_{\mathrm{FL}} \quad (3)$$

$$CD_{\mathrm{S}} = CS_{\mathrm{S}} / A_{\mathrm{S}} \quad (4)$$

$$CD_{\mathrm{H}} = CS_{\mathrm{H}} / A_{\mathrm{H}} \quad (5)$$

where $CD_{\mathrm{FL}}$, $CD_{\mathrm{S}}$ and $CD_{\mathrm{H}}$ are C densities of litter fall, shrub and herbage, respectively (Mg/ha); $CS_{\mathrm{FL}}$, $CS_{\mathrm{S}}$ and $CS_{\mathrm{H}}$ (Mg) are C storages of litter fall, shrub and herbage in a plot, respectively; $A_{\mathrm{FL}}$, $A_{\mathrm{S}}$ and $A_{\mathrm{H}}$ are the areas of litter fall, shrub and herbage plots, respectively (ha).

The density of SOC was calculated using the method described by Yang *et al*. (2007). Soil samples were air-dried, weighed, and sieved (2 mm mesh). We oven-dried one soil sub-sample at 105℃ to a constant mass and estimated soil bulk density by oven-dry soil mass and core volume (100 cm$^3$). The other sub-sample was handpicked to remove the fine roots and then ground on a ball mill. Through wet combustion with $K_2Cr_2O_7$, we measured the SOC concentration. Finally SOC stock (SOCD) was estimated using Equation (6).

$$SOCD_{\mathrm{T}} = \sum_{i=1}^{5} SOCD_i = \sum_{i=1}^{5} C_i \times D_i \times E_i \times 10^8 \quad (6)$$

where $i$ is soil layer; $SOCD_{\mathrm{T}}$ is total SOCD within 0–100 cm (Mg/ha); $SOCD_i$ is SOCD at the $i$th layer (Mg/ha); and $C_i$, $D_i$, and $E_i$ represent SOC concentration (Mg/g), bulk density (g/cm$^3$), and soil thickness (cm) of the $i$th layer, respectively.

The C stock for the total forest ecosystem is found by summing all C pools using Equation (7).

$$CD_{\mathrm{E}} = CD_{\mathrm{A}} + CD_{\mathrm{FL}} + CD_{\mathrm{S}} + CD_{\mathrm{H}} + SOCD_{\mathrm{T}} \quad (7)$$

where $CD_{\mathrm{E}}$ is C stock of a forest ecosystem (Mg/ha).

### 2.3 Statistical analysis

One-way analysis of variance (ANOVA) followed by multiple comparisons (Duncan) were used to compare C stocks among different larch plantations, different tree components and different soil depths. The results were considered significant when $P < 0.05$. The analyses were performed using SPSS 16.0.

## 3 Results

### 3.1 Biomass carbon (C) stock of different-aged larch plantations and old-growth forest

The tree biomass C stock of four larch plantations was significantly lower than that of the old-growth forest ($P < 0.05$). However, it significantly increased with plantation age ($P < 0.05$) (Table 3). The tree biomass C stock of the four plantations ranged from 26.5 Mg/ha for the youngest larch plantation (10 years old) to 76.3 Mg/ha for the oldest plantation (35 years old), whereas tree biomass C stock of the old-growth forests was as high as 174.0 Mg/ ha.

Trunks possessed the largest biomass C pool among the different biomass pools of tree organs (Table 3, Fig. 2), accounting for an average of 72% of tree biomass C stock for the four larch plantations. This proportion tended to increase with stand age. A similar average proportion was observed in the old-growth forest. However, stand age did not significantly influence biomass C stock in other tree organs, i.e., branches, leaves

**Table 3** Carbon stock in biomass in an old-growth forest and four larch plantations of Lushuihe Forestry Bureau (Mg/ha)

| Name of site | Stand age (yr) | Trunk | Branch | Leaf | Root | Sub-total | Shrub | Herb | Total biomass |
|---|---|---|---|---|---|---|---|---|---|
| OG | 300 | 127.2±28.3d | 17.4±7.0b | 8.3±5.6 | 21.1±7.6b | 174.0±48.5c | 0.8±0.1c | 0.2±0.0a | 175.1±48.6c |
| LP1 | 10 | 17.6±2.7a | 2.9±1.6a | 2.4±1.7ns | 3.5±1.9a | 26.5±7.6a | 0.04±0.0a | 0.3±0.1a | 26.8±7.6a |
| LP2 | 15 | 25.7±5.5b | 4.0±1.6a | 3.1±1.9ns | 4.6±2.3a | 37.3±10.3a | 0.2±0.2a | 0.3±0.2ab | 37.9±10.6a |
| LP3 | 21 | 45.9±3.6c | 5.9±0.4a | 4.5±0.7ns | 6. 6±0.5a | 62.9±2.1b | 0.3±0.1a | 0.5±0.1b | 63.6±2.1b |
| LP4 | 35 | 60.8±6.8c | 5.5±0.7a | 3.3±0.5ns | 6.7±1.2a | 76.3±9.0b | 1.3±0.4b | 0.3±0.1ab | 83.2±0.1b |

Notes: OG represents old-growth Korean pine deciduous forest; LP1–LP4 are larch plantations aged 10-, 15-, 21-, 35-year, respectively. a, b and c are groups of Duncan results of tree, shrub and herb C stock; ns means the results of one-way ANOVA are not significant at the level $P < 0.05$

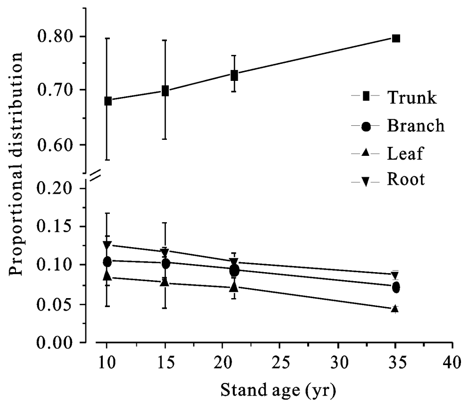


**Fig. 2** Carbon distribution in tree components of different-aged larch plantations

and roots ($P$ > 0.05). The herb C stock increased with stand age until age 21, and ultimately decreased at stand age 35.

### 3.2 Soil organic carbon (SOC) and LF carbon (C) stock of different-aged larch plantations and old-growth forest

The total SOC of the four younger larch plantations decreased with stand age (Table 4). Initially, the SOC of 10- and 15-year larch plantations were not significantly different ($P$ > 0.05) from that of the old-growth forest. The total SOC in the top 1 m of old-growth forest soil was 170.4 Mg/ha. However, SOC significantly decreased for the 21-year larch plantation. The total SOC of 35-year larch plantation was 34.2 Mg/ha less than that of the old-growth forest. The C stock of LF did not change significantly with stand age ($P$ > 0.05) for larch plantations. However, C stock of LF in the old-growth forest was significantly greater than that of the larch plantations ($P$ > 0.05).

Most SOC was distributed in the top 20 cm of these forest soils (Table 4 and Fig. 3). This study found that from 46.6% to 64.1% of the total SOC was sequestrated in the top 20 cm soil layer in the four larch plantations. Similarly, 61.4% of the total SOC was stored in the top 20 cm of the old-growth forest soil. The 60–100 cm soil layer stored only 13.1%–17.3% of the total SOC. Moreover, SOC stock in the top two soil layers (0–10 cm and 10–20 cm) did not change significantly with stand age ($P$ > 0.05) (Table 4).

## 4 Discussion

### 4.1 Biomass carbon (C) accumulation in larch plantations

Our study supports the hypothesis that biomass C stock increases with stand age for larch plantations in the Changbai Mountains area. From a 10-year old Japanese larch plantation to a 35-year old plantation, the biomass C stock has tripled. Previous studies found that the age

**Table 4** Carbon stock of soil organic carbon (SOC) and litterfall (LF) in an old-growth forest and four larch plantations of Lushuihe Forestry Bureau (Mg/ha)

| Name of site | 0–10 cm | 10–20 cm | 20–40 cm | 40–60 cm | 60–100 cm | Total SOC | LF |
|---|---|---|---|---|---|---|---|
| OG | 67.2±10.1b | 37.3±9.4ns | 27.7±2.2ab | 18.3±2.8ab | 19.9±0.6c | 170.4±13.8a | 21.0±3.4b |
| LP1 | 55.4±8.1ab | 35.0±11.5ns | 39.2±2.0a | 18.7±7.0ab | 23.9±3.4a | 172.1±18.5a | 7.3±2.1a |
| LP2 | 44.6±12.3a | 34.8±2.6ns | 38.1±6.4a | 22.9±4.1b | 29.3±1.0b | 169.7±17.5a | 7.8±2.2a |
| LP3 | 45.9±1.5a | 30.5±4.7ns | 28.2±6.2ab | 14.0±2.3a | 21.6±2.0ac | 140.3±13.2b | 6.8±1.1a |
| LP4 | 52.7±5.1ab | 35.0±11.5ns | 19.1±11.0b | 11.7±0.9a | 17.7±0.4c | 136.2±6.4b | 7.4±0.64a |

Notes: OG represents old-growth Korean pine deciduous forest; LP1–LP4 are larch plantations. a, b and c are groups of Duncan results of tree, shrub and herb C stock; ns means the results of one-way ANOVA are not significant at the level $P < 0.05$

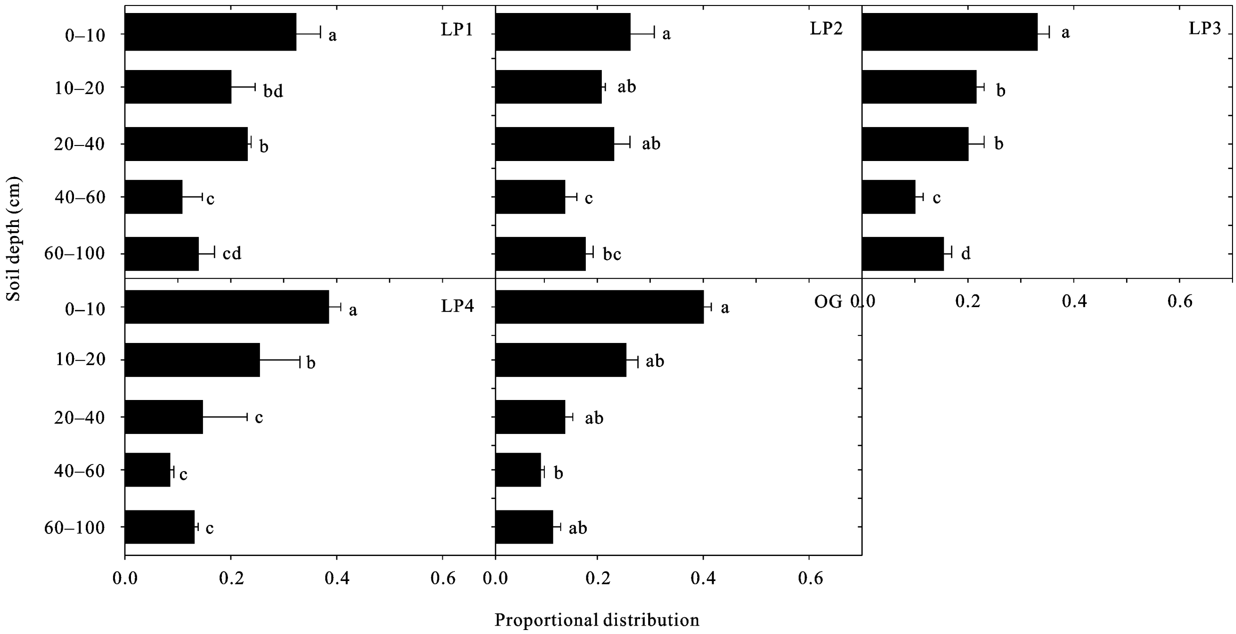


**Fig. 3** Vertical proportional distribution of soil organic carbon (SOC) in an old-growth forest and four different-aged larch plantations. OG represents old-growth Korean pine deciduous forest; LP1–LP4 are larch plantations. Black bars indicate the proportional distribution of total organic carbon in the first meter in each soil layer. Letters indicate significant differences for old-growth forest and four larch plantations at each depth interval. Error bars express one standard error of the mean

at which C stock is maximum of larch plantations in Northeast China is about 50–60 years (Yin *et al.*, 2008; Qi *et al.*, 2011). This implies that the 35-year larch plantation could continue storing considerable C as it matures. The trunk is the biggest C pool among tree components , and changes in C stock of forest biomass display the same pattern as that exhibited by trunk C stock, with both increasing with stand age (Table 3). While the proportion of biomass C stored in the trunk component increases with stand age, those for other components decrease with age (Fig. 2). This implies that C stock accumulation in the trunk increases as larch plantations mature (Qi *et al.*, 2011).

At the same time, the biomass C stock of larch plantations, which ranges from 26.8 Mg/ha to 83.2 Mg/ha, was significantly lower than 175.1 Mg/ha, the biomass C of the old-growth forest (Table 3). Harmon *et al.* (1990) found that conversion of old-growth forests to young fast-growing forests was not helpful in decreasing atmospheric $CO_2$. Chen and Li (2003) reported a decrease of SOC after the old-growth Korean pine deciduous forests in the Changbai Mountains area were converted to plantations. Although about 60 Mg C/ha is stored in timber after clear-cutting old-growth Korean pine deciduous forest, our study provides further evidence that conversion of old-growth forests to larch plantations release C ranging from 39 Mg/ha at 35 years-old larch plantation to 89 Mg/ha at 10 years-old larch plantation into the atmosphere.

### 4.2 Soil organic carbon (SOC) stock in different-aged larch plantations

In contrast to the trend of biomass C stock increasing with stand age, SOC stock decreases with stand age (Table 4), which agrees with our hypothesis. The larch plantations of the Lushuihe Forestry Bureau were established after the clear-cutting of an old-growth Korean pine deciduous forest. At early ages, SOC of larch plantations did not differ significantly from that of the old-growth forest. However, SOC levels for both 21- and 35 year-old larch plantations were significantly lower than that of the old-growth forest. We were surprised to find that SOC of plantations continued to decline from the original SOC stock equivalent to that of old-growth forests, even after 35 years. Previous studies have reported soil degradation of larch plantations (Liu and Li, 1993; Pan *et al.*, 1997), especially for second generation plantations (Pan *et al.*, 1997). Because of increases in soil acidity with stand age and the fact that the LF of larch plantations is difficult to decompose, the fertility of larch plantations was generally found to decrease with stand age (Chen and Xiao, 2006). Our results support these findings. We found that soil degradation may occur at an early stage of the mature period of larch plantations. Although fertilization with organic matter was applied to stands in this study, the SOC stock of the larch plantations still continued to decline. C stocks in the topsoil (0–10 cm and 10–20 cm) initially decreased and subsequently increased as larch plantations matured, which agrees with our hypothesis; but this pattern was not found to be significant ($P > 0.05$). This trend is similar to findings reported on the afforestation of grasslands (Chen *et al*., 2010) and larch (*L. gmelinii*) plantations in the Da Hinggan Mountains of Northeast China (Qi *et al*., 2013).

The vertical distributions of SOC indicate that SOC stock of each plantation declines with soil depth (Fig. 3). This trend agrees with the results of previous findings that most of the SOC is concentrated in the top 30 cm soil depth (Yang *et al*., 2007; Hilli *et al*., 2008; Wang *et al*., 2010; Simon *et al*., 2013; Wang *et al*., 2013). In our study, about 47%–64% of SOC was found in the top 0–20 cm of soil, and 69%–78% was stored in the top 0–40 cm (Fig. 3). The changes of vertical SOC proportions suggest that SOC accumulates mainly in the uppermost soil layer of larch plantations.

This study found that C stock of LF did not change significantly ($P > 0.05$) with stand age, a result which disagrees with previous studies (Yuan *et al*., 2009). We attribute this to the traits of larch needles, the decomposition of which is more difficult than foliage decay in other species (Yin *et al*., 2002). Moreover, the low C stock for LF in larch plantations is due to the lack of CWD, which in this region is usually removed after the clear-cutting of old-growth forests. The C stock of LF in the old growth forest in this study was 21.0 Mg/ha, much higher than the C in LF of larch plantations (Table 4).

### 4.3 Total carbon stock (TCS) in different-aged larch plantations

The C pools of forests are usually composed of biomass, SOC, and LF (Dixon *et al*., 1994). The largest C pool observed in this study was that of SOC, followed by biomass and LF, respectively (Table 3, Table 4). The TCS did not change significantly with stand age ($P > 0.05$) for the four Japanese larch plantations, implying that the increase of biomass C compensated for the decrease in SOC (Fig. 4). In contrast, the TCS of the old-growth forest was much higher than that of four young larch plantations. The CWD is an important C pool in the old-growth forests (Harmon and Chen, 1991; Gu *et al*., 2006), but management practices such as CWD elimination result in the lack of CWD in larch plantations. Therefore, we suggest that CWD should be retained in larch plantations in the process of selective harvesting.

Most previous studies have found that plantations can play an important role as a C sink (Wang *et al*., 2006; Lichter *et al*., 2008; Ren *et al*., 2010); but several studies have reported that plantations can also be a C source, especially at early stand ages (Janisch and Harmon, 2002; Chen and Li, 2003; Chen *et al*., 2005; You *et al*., 2013). However, many of these studies pay great attention to biomass C stock while ignoring another important component—SOC. Our findings show that stable TCS stock for 10- to 35-year old larch plantations results from the balance of biomass C increase and SOC decrease (Fig. 4). Although biomass C of the plantations increases during the first 35 years (Table 3), the continuous decline of SOC (Table 4) offsets the biomass C gain of the ecosystems. The lasting effect of the clear-cutting of old-growth forests on SOC stock is evident even after 35 years of plantation growth.

### 4.4 Implications for maximizing carbon (C) stocks of larch plantations in Northeast China

The old-growth forests in the Changbai Mountains area were not harvested until a century ago (Dai *et al*., 2003). Now most of primary forests have been converted to secondary forests and plantations, and the C stock has

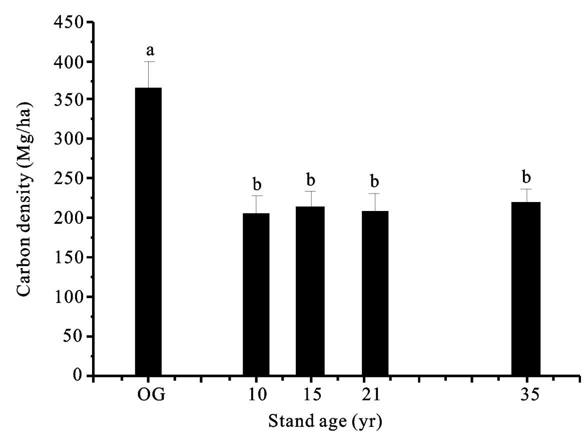


**Fig. 4** Total carbon stock (TCS) of old-growth forest and different-aged larch plantations. OG represents old-growth forest; a and b indicate significant differences of carbon densities between old-growth forest and larch plantations

declined after the conversion (Yang *et al*., 2007). Larch plantations are those most widely planted in Northeast China (Liu and Li, 1993) and are also the most extensively planted coniferous forests in the Changbai Mountains area. Thus, how to maximize C stocks of larch plantations becomes both significant and urgent given the increasing atmospheric $CO_2$ concentration and its contribution to global climate change.

Forest management is one of the key factors affecting TCS of forests (Nunery and Keeton, 2010; Schaich and Plieninger, 2013; Xie *et al*., 2014). Most previous studies have found that clear-cutting seriously impacts the C stock of forests (Smolander *et al*., 1998; Piirainen et al., 2002; Finér *et al*., 2003; Humphreys *et al*., 2006). Fortunately, selective cutting has gradually replaced clear-cutting in the Changbai Mountains area since the 1970s (Dai *et al*., 2002). Considering the rapid increase of biomass C, the intensity of selective cutting should be reduced to levels that ensure ecological health is sustained. For the sake of retaining sufficient CWD and maintaining the long-term net primary production of larch plantations, stem-only harvesting is recommended instead of whole-tree harvesting (Wei *et al*., 2003).

Our study found that the larch plantations established after the clearing of an old-growth Korean pine deciduous forest sequstrated a much smaller amount of C than did the old-growth forest, suggesting that converting old-growth forests in Northeast China to younger larch plantations releases a significant amount of C into the atmosphere. This result supports the conclusion reached by Harmon *et al*. (1990) in the U.S. Pacific Northwest. Thus, it was not reasonable to convert old-growth forests to larch plantations in order to increase C stocks in Northeast China. Larch plantations under 35 years of age in the Changbai Mountains region do have the potential for sequestrating more C over time. However, the average rotation of larch plantations in Northeast China is about 30–40 years (State Forestry Administration, 1986). We suggest that a rotation more than 35 years should be adopted to increase C stocks, the result can also be founded in Yin *et al*., (2008). In addition, we recommend that CWD be retained in larch plantations for maximizing C stock of these forests in this region.

## 5 Conclusions

We found that the larch plantations established after the clearing of an old-growth Korean pine deciduous forest sequstrated less C than did the old-growth forest, suggesting that the coversion of the old-growth forests in the Northeast China to younger larch plantations releases a significant amount of C into the atmosphere. Biomass C stock of larch plantations increases with stand age while SOC stock in such plantations simultaneously decreases with stand age up to 35 years. The TCS in larch plantations younger than 35 years of age is almost stable. The trunk component is the largest biomass C pool, and the proportion of trunk to tree biomass increases from 10- to 35-year larch plantations. The SOC stored more C than did biomass and LF tree components, and most of the SOC was distributed in the topsoil depth of 0–20 cm. The SOC in this topsoil layer did not change significantly ($P > 0.05$).

Effective forest management can make a significant contribution to the stocks of $CO_2$ from the atmosphere. To maximize forest C stocks in this area, selective cutting should be encouraged and the intensity of selective cutting should be maintained at ecologically sound levels. The CWD should be retained in larch plantations to increase TCS. Stem-only harvesting should be preferred to whole-tree harvesting. We suggest that the rotation age of larch plantations should be lengthened to at least 35 years for maximizing forest C stocks in this region.

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