Environ Earth Sci (2013) 69:1559–1570
DOI 10.1007/s12665-012-1990-7

ORIGINAL ARTICLE

# Concurrent changes in soil inorganic and organic carbon during the development of larch, *Larix gmelinii*, plantations and their effects on soil physicochemical properties

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Received: 23 September 2011 / Accepted: 11 September 2012 / Published online: 10 October 2012


**Abstract** Soil inorganic carbon (SIC) and organic carbon (SOC) levels can change with forest development, however, concurrent changes in soil carbon balance and their functional differences in regulating soil properties are unclear. Here, SIC, SOC, and other physicochemical properties of soil (N, alkali-hydrolyzed N, effective Si, electrical conductivity, pH, and bulk density) in 49 chronosequence plots of larch plantation forests were evaluated, by analyzing the concurrent changes in SIC and SOC storage during growth of plantation and the functional difference of these levels in maintaining soil sustainability. These soils had characteristically high SOC (15.34 kg $m^{-2}$) and low SIC storage (83.38 g $m^{-2}$ on average). Further, 28 of 30 linear regressions between SIC and SOC storage and larch growth parameters (age, tree size, and biomass density) were not statistically significant ($p > 0.05$). However, significant changes were observed in ratios of SIC and SOC with these growth parameters (between 0–40 cm and 40–80 cm, respectively; $p < 0.05$). These results were more useful for determining the changes in SIC and SOC vertical distribution than changes in storage. Moreover, larch growth generally decreased SIC and increased SOC. Linear correlation and multiple-regression analysis showed that the SIC influences soil acidity, whereas SOC affects soil nitrogen. This clearly indicates that larch growth could result in divergent changes in SIC and SOC levels, particularly in their vertical distribution; further, changes in SIC and SOC may variably affect soil physicochemical properties.

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**Keywords** Soil inorganic carbon (SIC) · Soil organic carbon (SOC) · Soil physicochemical properties · *Larix gmelinii* plantation

## Introduction

Soil organic carbon (SOC) is approximately 1,500 Pg (Post et al. 1982), and soil inorganic carbon (SIC) is about 930–1,738 Pg of carbonate C in the top 1 m of soil depth (Schlesinger 2002; Eswaran et al. 1995; Ming 2002). Small changes in SOC and SIC may radically alter the carbon balance of forest ecosystems. SOC dynamics during environmental changes is much better documented (Post et al. 1982; Lal 2004; Luo et al. 2007) than those in SIC dynamics, especially during forest regrowth (Pan 1999; Lal and Kimble 2000). SOC and SIC can interact with each other, e.g., SOC accumulation in bare soil with carbonates may induce the dissolution of SIC (Pan 1999; Duan et al. 1999), while respiratory $CO_2$ from soil organic matter (SOM) decomposition and root respiration can be used in secondary SIC formation (Lal 2002; Entry et al. 2004). If both SIC and SOC have the same tendency for change, studies of the soil carbon balance should include both components or else an underestimation of the soil carbon sequestration/depletion will occur. In contrast, overestimation could occur when the SIC and SOC changes dramatically during forest regrowth (Zu et al. 2011). Studies have shown that the larch plantation in NE China could largely improve soil organic carbon storage in the surface soil layer (Wang et al. 2011), but the SIC changes have not been examined. Thus, a concurrent study on the changes in the SIC and SOC during forest plantation development is an important issue for an exact carbon balance study; here, a case study of the larch plantation forest in this region is presented.

Besides the changes in the total amount of SOC and SIC, the changes in the vertical distribution during plantation development are also important for the stability of carbon sequestration in soils (Gleixner et al. 2009). Given that the total amount of SOC or SIC does not change, more carbon at the soil surface may pose the risk of efflux back to the atmosphere. In contrast, higher SOC or SIC content in deep soils may mean that their lifespan may be longer than that on the surface soil (Lorenz et al. 2011). Together with the analysis of the total amount of SOC and SIC, statistical analysis of the vertical changes of these carbon components should be helpful in understanding soil carbon dynamics during forest development.

Soil nutrient availability and soil physicochemical properties are important for the sustainable management of plantations (Lu et al. 1999; Chen and Xiao 2006) and understanding the relationship with SOC and SIC may support the management of soil fertility. For example, SOC is well known for its regulation of the availability of soil nitrogen (HLJTR 1992; Bronick and Lal 2005), while the function of SIC may be to regulate the supply of $Ca^{2+}$ for soil colloids as well as for acidity regulations (Bronick and Lal 2005; Serrano-Ortiz et al. 2010). However, few documents have focused on the concurrent influences of SOC and SIC on soil fertilities, even though in the natural state, these variables co-exist. The lack of concurrent measurements of these parameters has made it difficult to evaluate the effects of SIC and SOC on soil physicochemical properties in forest plantation development (Bronick and Lal 2005). Therefore, in this study, concurrent measurements of SIC, SOC, and variable soil physicochemical parameters were performed and statistical analysis (e.g., linear correlation analysis and multiple-regression analysis) was used to determine the impact of changes in the soil carbon on soil fertility during forest plantation development.

In studies of carbon dynamics, proper methods of site selection, soil sampling, and statistical data analysis can help to generate reliable results. The chronosequence method (spatial–temporal substitution method) was used for sampling and this method is a commonly used method to conduct long-term studies of carbon dynamics during forest development (Walker et al. 2010; Wang et al. 2011). The huge area of larch plantation with variable ages (over 50 % of total afforestation area) in the large, flat terrain of NE China (Wang 1992; Wang et al. 2005a; Sun et al. 2007) was an ideal location for this study. The extensive and typical dark-brown forest soil in this region may facilitate soil sampling (NEFU 1984); the shallow root feature of larches also favors the identification of vertical distribution differences in SOC and SIC at relative shallow sampling depth (Wang et al. 2005b). Furthermore, the heterogeneity of soil results in a requirement for a large number of samples owing to large intra-treatment variance (Wang et al. 2011). In this study, statistical power analysis was used to determine the following: the power of the original data in finding significant differences, the number of replicates needed for a statistically significant observation, and the least-significant value (LSV) (Kravchenko and Robertson 2011). In the process of regression analysis between the plantation age and carbon storage, a further power analysis can strengthen the robustness of the results.

The aims of this paper are: (1) to determine the changes in SIC and SOC storage at different soil layers as well as their changes in vertical distribution during the development of the larch plantation, and (2) to examine the effect of changes in SIC and SOC levels on soil sustainability. Results of correlations between the SIC, SOC, and larch age, tree size, and biomass status, and their relationships with other soil physicochemical properties were used to address these aims.

## Materials and methods

### Study sites and soil sampling

All study sites were located in the central region of the *Larix gmelinii* plantations in NE China (45°20′–47°14′, 127°30′–127°55′). This region has a continental monsoon climate, with an average annual temperature ranging from −0.3 to 2.6 °C and precipitation from 676 to 724 mm. The saplings, shrubs, and herbs in these larch plantations are *Betula platyphylla*, *Fraxinus mandshurica*, *Quercus mongolica*, *Acanthopanax senticosus*, *Euonymus pauciflorus*, *Agrimonia obtusifolia*, *Chelidonium majus*, *Cacalia hastata,* and others. In general, the soil in this region is the typical dark-brown forest soil (Wu et al. 2009; Wang et al. 2011).

For the chronosequence plot series, the stand selection criteria restrict the differences between the sites so that the length of larch age is the main variable influencing uneven changes in forest soil among the stands selected. As well as the stand age, topographic position, slope, and elevation may influence soil carbon and soil fertility (Garten et al. 1994; Enoki et al. 1996). The plots have a similar elevation of about 290 m (SE 6.8) and slope of 5.4° (SE 0.76) to minimize the differences from non-chronosequence sources. In total, 49 plots with detectable SIC and SOC in 0–80 cm soil profiles were used. The plot size was 20 m × 20 m. In each plot, four profiles of 2-m long, 1-m wide and 0.8-m deep were dug out. Soil samples were collected from layers at depth 0–20, 20–40, 40–60, and 60–80 cm using 100-$cm^3$ rings of soil cutting, and four soil samples from the same layer were mixed into a composite sample.

### Determination of SIC, SOC, and other physicochemical properties

Soil cups of 100 $cm^3$ were used to collect soil from each layer of the soil profile, and the samples were placed in cloth bags and air-dried in a ventilated room until they reached a constant weight to determine the air-dried soil bulk density.

After roots in the soil sample were carefully picked out, the samples were ground with a wooden rolling pin and passed through a 2-mm soil sieve. The gravels were sieved out of the soil sample and the gravel weight and volume were measured. The <2 mm components of the soil sample were pulverized for approximately 3 min and passed through a 0.25 mm soil sieve. The soil samples <0.25 mm were stored in laboratory prior to measurement of SIC, SOC, soil N, and soil pH.

SIC was determined by a gasometric method, which measures the total $CO_2$ volume evolved during treatment with HCl (Goh et al. 1993; Singh et al. 2007). SOC was measured by the heated dichromate/titration method, and alkali-hydrolyzed N was determined by the alkali diffusion method (Bao 2000). The soil samples and the standard soil sample (ASA1, Institute of Geophysical and Geochemical Exploration, Langfang, China) were measured together to ensure that the digestion was complete.

Total soil N concentration was determined by the Semimicro–Kjeldahl method (Bao 2000). The pH and electrical conductivity (EC) of the soil solution (1 part soil to 5 parts water) were measured by an acidity meter (Sartorius PB-21, Shanghai, China) and a conductivity meter (SL1-DDSJ-308A, Shanghai, China), respectively.

### Larch age, tree size, and biomass density calculation

The age of larch trees was determined using an increment borer (Zhonglinweiye, Beijing). At least five wood cores in each plot were drilled, and tree rings were counted to obtain the mean age of the plantation. An allometric relation was used to calculate biomass for average tree (tree size) and biomass density (tree size × tree density) in each plot. The allometric relation determined by harvesting 17 trees is as following:

$$y = y_1 + y_2 = 0.0385 \times x^{0.9513} + 0.0164 \times x^{0.904}, \quad (1)$$

where $y_1$ is the aboveground biomass mass (sum of stem, branch, and leaf; unit kg) ($r^2 = 0.9902$, $p < 0.0001$) of larch, $y_2$ is belowground biomass mass (unit: kg) of larch ($r^2 = 0.9364$, $p < 0.0001$), $x$ is the DBH$^2$H ($x$; $cm^2$ m) of larch (unpublished data).

### Data analysis

For each soil layer, the storage of SIC, SOC, soil N, and alkali-hydrolyzed nitrogen was calculated as:

$$S = a \times \rho_b \times 0.2 \times (1 - V_{gravel}), \quad (2)$$

where $a$ is the concentration of each parameter (g $kg^{-1}$) in soil, $\rho_b$ is the soil bulk density (g $cm^{-3}$), the figure 0.2 represents the depth of each soil layer (0.2 m), and $V_{gravel}$ is the volume percentage of gravel (%).

Changes in SIC and SOC storage during forest development were quantified by the linear-regression analysis between their storages and larch age, average tree size, biomass density. The ratio of SIC, SOC in deep soil (40–80 cm) to surface (0–40 cm) soils was analyzed with larch age, tree size, and biomass density for examining the impact of growth on carbon vertical distribution. The possible functional difference of SOC and SIC in regulating soil properties was also quantified by linear-regression analysis between SOC, SIC, and variable soil properties (nitrogen, pH, bulk density, etc.) and a multiple-stepwise regression. Multiple-stepwise regression was used to fit the relations between SOC, SIC, and variable parameters in different soil layers. The significance of these correlations was statistically checked using Statistical Package for the Social Sciences (SPSS v. 17.0; SPSS Inc., USA). Multiple correlations were performed using this software. Stepwise entering of different parameters is performed when $p < 0.10$.

Large error during treatment can reduce the statistical power for detecting significant differences (Kravchenko and Robertson 2011). Thus, a power analysis was also performed using JFM 5.0 software (SAS, USA) to define the data statistical power for detecting the significance of the linear correlations. Three parameters were calculated via the power analysis: the LSV is the value of linear slope that would produce a $p$ value of 0.05, the least-significant number (LSN) is the number of observations that would produce a specified $p$ value 0.05 if the data have the same structure and estimates as the current sample; and power is the probability of getting a significant linear slope at or below a given $p$ value of 0.05.

## Results

### SIC, SOC, and other physicochemical properties: entire vertical comparison

As shown in Table 1, SOC, soil N, alkali-hydrolyzed N, and EC decreased with increasing soil depth; soil bulk density and SIC increased with soil depth. Numerically, SIC storage averaged from 17.10 to 24.92 g $m^{-2}$ in the vertical profile, and total storage for 0–80 cm soil was 83.38 g $m^{-2}$. Statistical analysis showed that SIC storage at 0–20 cm soil is significantly lower than that in deep layers of 40–60 or 60–80 cm ($p < 0.05$). Much higher SOC storage than SIC

**Table 1** Mean, maximum, and minimum values of soil inorganic carbon (SIC), soil organic carbon (SOC), and other soil physicochemical properties in soil layers across the 49 study sites

| | Soil layers | | | | |
|---|---|---|---|---|---|
| | 0–20 cm | 20–40 cm | 40–60 cm | 60–80 cm | 0–80 cm |
| SIC (g m$^{-2}$) | | | | | |
| Mean | 17.10a (1.30) | 19.00ab (1.51) | 24.92c (1.97) | 22.35bc (2.12) | 83.38 (3.60) |
| Maximum | 41.89 | 46.53 | 65.55 | 75.65 | 302.59 |
| Minimum | 4.59 | 5.79 | 6.00 | 5.59 | 18.36 |
| SOC (kg m$^{-2}$) | | | | | |
| Mean | 6.45a (0.36) | 3.70b (0.24) | 3.50b (0.25) | 1.69c (0.12) | 15.34 (0.70) |
| Maximum | 12.40 | 6.81 | 7.99 | 4.11 | 49.59 |
| Minimum | 2.96 | 1.37 | 0.72 | 0.63 | 2.52 |
| TN (g m$^{-2}$) | | | | | |
| Mean | 430.92a (31.61) | 274.49b (22.02) | 167.63c (15.65) | 133.76c (15.27) | 1,006.8 (55.1) |
| Maximum | 1014.10 | 620.40 | 480.44 | 525.07 | 4056.40 |
| Minimum | 48.56 | 65.71 | 29.14 | 17.29 | 69.16 |
| Alkali-hydrolyzed N (g m$^{-2}$) | | | | | |
| Mean | 29.66a (2.99) | 14.61b (1.62) | 10.45bc (1.30) | 7.00c (0.89) | 61.72 (4.47) |
| Maximum | 94.97 | 50.75 | 48.06 | 35.20 | 379.89 |
| Minimum | 5.45 | 1.94 | 1.09 | 0.38 | 1.53 |
| pH | | | | | |
| Mean | 5.54a (0.05) | 5.54a (0.06) | 5.53a (0.06) | 5.54a (0.07) | 5.54 (0.03) |
| Maximum | 6.23 | 6.28 | 6.38 | 6.42 | 6.42 |
| Minimum | 4.84 | 4.85 | 4.86 | 4.86 | 4.84 |
| EC (μs cm$^{-1}$) | | | | | |
| Mean | 50.59a (2.97) | 35.94b (2.00) | 32.02b (1.86) | 29.69b (1.83) | 37.06 (1.24) |
| Maximum | 130.50 | 86.00 | 79.00 | 63.60 | 130.50 |
| Minimum | 16.70 | 12.10 | 8.70 | 5.45 | 5.45 |
| Soil bulk density (g cm$^{-3}$) | | | | | |
| Mean | 1.08a (0.02) | 1.28b (0.02) | 1.41c (0.02) | 1.46c (0.02) | 1.31 (0.02) |
| Maximum | 1.59 | 1.70 | 1.65 | 1.67 | 1.70 |
| Minimum | 0.73 | 0.94 | 0.96 | 0.97 | 0.73 |
| C:N ratio | | | | | |
| Mean | 18.80a (1.71) | 15.66a (0.93) | 26.36b (2.39) | 18.50a (1.89) | 19.83 (0.94) |
| Maximum | 61.02 | 37.56 | 87.01 | 63.22 | 87.01 |
| Minimum | 8.15 | 4.00 | 9.08 | 3.07 | 3.07 |

Data in parentheses are the standard error of the mean

In the same profile from 0–20 to 60–80 cm, different letters indicate that the differences between these two layers are statistically significant ($p < 0.05$). The same letter indicates that the difference between these two layers is not statistically significant ($p > 0.05$)

storage was found; the total 0–80 cm SOC storage was 15.34 (SE 0.70) kg m$^{-2}$. In contrast to SIC, SOC storage decreased with soil depths and SOC storage in the surface soil was significantly higher than that in deeper layers ($p < 0.05$) (Table 1). The maximum and minimum of the data showed a similar tendency to that of the averages (Table 1).

Soil N storage at 0–80 cm profile was 1,006.8 (SE 55.1) g m$^{-2}$, and alkaline-hydrolyzed nitrogen storage was approximately 61.72 (SE 4.47) g m$^{-2}$. The pH value was approximately 5.54 (SE 0.03) and the EC value was about 37.06 (SE 1.24) μs cm$^{-1}$. Soil bulk density was about 1.31 g cm$^{-3}$ (SE 0.02) (Table 1). The vertical comparison showed no statistical differences in pH value, while significantly higher N storage, alkali-hydrolyzed N storage, and EC in the surface soil were observed ($p < 0.05$). With increase in soil depth, soil bulk density significantly increased from 1.08 to 1.46 g cm$^{-3}$. The C:N ratio in the 40–60 cm soil layer was significantly higher than that in other layers: the 0–20, 20–40, and 60–80 cm soil layers have similar C:N ratios ($p > 0.05$) (Table 1). For variable parameters, similar tendencies were observed in the maximum and minimum of the data (Table 1).

SIC and SOC changes with larch growth (age, tree size, and biomass density)

In general, 28 of the 30 tested correlations were not statistically significant, but some tendencies can be observed (Table 2). In the age–SIC relationship, there was a decreasing tendency at the surface soils (40 cm), but an increasing tendency at the 40–80 cm soils for SIC storage; however, no statistical significance was observed ($r^2 < 0.04$, $p > 0.10$), except a significant decrease with larch age in the 20–40 cm soil (slope = −0.2559 g $m^{-2}$ $year^{-1}$; $r^2 = 0.0796$, $p = 0.049$) (Table 2). Power analysis showed that more replicates (LSN value: 124 for 0–20 cm, 213 for 40–60 cm) may result in significant changes in SIC storage at each layer and the expected significant slopes (LSV 0.05) would be −0.2306 for 0–20 cm and 0.3495 for 40–60 cm. The LSN for 60–80 and 0–80 cm is very large (>1,000).

Contrary to the age–SIC relations, SOC showed an increasing tendency in the surface 20 cm soil, but

**Table 2** Linear-regression slope value, significance level, least significant value of linear slope, least significant number, and statistical power of variable linear analysis

| | Slope | SE | *p* value | LSV 0.05 | LSN 0.05 | Statistical power | $R^2$ | Intercept |
|---|---|---|---|---|---|---|---|---|
| SIC, g $m^{-2}$ (*y*) and larch age, year (*x*) | | | | | | | | |
| 0–20 cm | −0.1426 | 0.1146 | 0.2197 | 0.2306 | 124 | 0.10 | 0.032 | 21.425 |
| 20–40 cm | −0.2559 | 0.1270 | 0.0496 | 0.2554 | 49 | 0.38 | 0.079 | 27.368 |
| 40–60 cm | 0.1659 | 0.1755 | 0.3495 | 0.3532 | 213 | 0.05 | 0.019 | 19.895 |
| 60–80 cm | 0.0474 | 0.2104 | 0.8228 | 0.4233 | 3,713 | 0.05 | 0.0011 | 22.12 |
| 0–80 cm | −0.1852 | 0.4854 | 0.7045 | 0.9766 | 1,295 | 0.05 | −0.1852 | 90.807 |
| SOC, kg $m^{-2}$ (*y*) and larch age, year (*x*) | | | | | | | | |
| 0–20 cm | 0.014 | 0.032 | 0.658 | 0.0640 | 952 | 0.05 | 0.0042 | 6.0236 |
| 20–40 cm | −0.008 | 0.021 | 0.715 | 0.0427 | 1,393 | 0.05 | 0.0029 | 3.9359 |
| 40–60 cm | −0.051 | 0.021 | 0.018 | 0.0420 | 34 | 0.57 | 0.1141 | 5.0565 |
| 60–80 cm | −0.019 | 0.010 | 0.072 | 0.0204 | 58 | 0.31 | 0.0673 | 2.2539 |
| 0–80 cm | −0.064 | 0.068 | 0.354 | 0.1368 | 217 | 0.05 | 0.0183 | 17.27 |
| SIC, g $m^{-2}$ (*y*) and tree size, kg (*x*) | | | | | | | | |
| 0–20 cm | −0.0112 | 0.0078 | 0.1572 | 0.0157 | 94 | 0.16 | 0.0421 | 19.969 |
| 20–40 cm | −0.0148 | 0.0088 | 0.1006 | 0.0177 | 70 | 0.25 | 0.0563 | 23.377 |
| 40–60 cm | −0.0037 | 0.0121 | 0.7610 | 0.0244 | 2,013 | 0.05 | 0.002 | 25.869 |
| 60–80 cm | −0.0064 | 0.0144 | 0.6578 | 0.0290 | 950 | 0.05 | 0.0042 | 25.193 |
| 0–80 cm | −0.0361 | 0.0329 | 0.2779 | 0.0662 | 159 | 0.07 | 0.0025 | 94.407 |
| SOC, kg $m^{-2}$ (*y*) and tree size, kg (*x*) | | | | | | | | |
| 0–20 cm | 0.00015 | 0.00219 | 0.947 | 0.0044 | 41,550 | 0.05 | 1e−04 | 6.4155 |
| 20–40 cm | −0.00033 | 0.00146 | 0.819 | 0.0029 | 3,566 | 0.05 | 0.0011 | 3.7847 |
| 40–60 cm | −0.00232 | 0.00148 | 0.125 | 0.0030 | 79 | 0.21 | 0.0494 | 4.0904 |
| 60–80 cm | −0.00123 | 0.00070 | 0.084 | 0.0014 | 63 | 0.28 | 0.0621 | 2.0025 |
| 0–80 cm | −0.00373 | 0.00467 | 0.428 | 0.0094 | 297 | 0.05 | 0.0134 | 16.293 |
| SIC, g $m^{-2}$ (*y*) and biomass density, ton $ha^{-1}$(*x*) | | | | | | | | |
| 0–20 cm | −0.0053 | 0.0146 | 0.7186 | 0.0295 | 1,435 | 0.05 | 0.0028 | 18.157 |
| 20–40 cm | −0.0083 | 0.0166 | 0.6202 | 0.0334 | 759 | 0.05 | 0.0053 | 21.257 |
| 40–60 cm | 0.0313 | 0.0218 | 0.1584 | 0.0439 | 94 | 0.16 | 0.0419 | 18.713 |
| 60–80 cm | 0.0065 | 0.0265 | 0.8082 | 0.0533 | 3,161 | 0.05 | 0.0013 | 22.273 |
| 0–80 cm | 0.0242 | 0.0611 | 0.6943 | 0.1229 | 1,206 | 0.05 | 0.0033 | 80.401 |
| SOC, kg $m^{-2}$ (*y*) and biomass density, ton $ha^{-1}$ (*x*) | | | | | | | | |
| 0–20 cm | 0.0073 | 0.0039 | 0.0647 | 0.0078 | 55 | 0.33 | 0.0707 | 5.001 |
| 20–40 cm | 0.0044 | 0.0026 | 0.0959 | 0.0052 | 68 | 0.26 | 0.0579 | 2.8242 |
| 40–60 cm | −0.0018 | 0.0028 | 0.5229 | 0.0056 | 457 | 0.05 | 0.0087 | 3.8541 |
| 60–80 cm | −0.0005 | 0.0013 | 0.7207 | 0.0026 | 1,458 | 0.05 | 0.0027 | 1.7836 |
| 0–80 cm | 0.0095 | 0.0085 | 0.2725 | 0.0172 | 155 | 0.07 | 0.0256 | 13.463 |

decreasing tendencies in the deeper soils; no significant linear correlations were found except in the 40–60 cm soil ($r^2 = 0.1141$, $p = 0.018$). Pooling the entire 0–80 cm soil layers together, no significant changes were found in either the SIC or SOC storage ($r^2 < 0.02$, $p > 0.10$) (Table 2). Replicates of 58–217 in 60–80 and 0−80 cm soils may result in statistically significant regressions and the LSV would be −0.019 and −0.064, respectively. LSN for 0–20 and 20–40 cm is very large (952–1,393) (Table 2). The LSVs for the 0–20, 20–40, 40–60, 60–80, and 0–80 cm soils were 1.6–8.9 times higher than the observed slope values, except in the 20–40 cm soil (0.2554 vs. 0.2559) (Table 2). Similar to SIC, the SOC data could only recognize much higher slope values (2- to 6-fold) than the observed slopes except in the 40–80 cm soil.

As tree size increased, SIC storage decreased, but not significantly ($p > 0.05$) in the 0–20, 20–40, 40–60, 60–80 cm soils, and total 0–80 cm soil profile ($r^2 < 0.07$, $p > 0.05$). Similarly, SOC storage also showed a non-significant correlation with tree sizes ($r^2 < 0.06$, $p > 0.05$) (Table 2). Using the production of tree density and average tree size in each plot as an indicator for biomass density (ton $ha^{-1}$), the correlations between biomass density and SIC and SOC storage were analyzed; no significant correlations were found in SIC ($r^2 < 0.05$, $p > 0.10$), but better correlations were found in SOC. For example, nearly significant increasing tendencies were observed in the relationship between SOC and biomass density at the 0–20 cm layer ($r^2 = 0.0707$, $p = 0.065$) and 20–40 cm soil layer ($r^2 = 0.0579$, $p = 0.095$) (Table 2); more replicates (LSN 55–68) could make these correlations statistically significant. However, for most of the correlations, it was impossible to find significant correlations simply by increasing the replicate numbers; for example, the LSN for the top 40 cm of the SOC-tree size relations was several thousands and the LSN for deep soil (>40 cm) of the SIC–tree size relations was also hundreds to thousands. Such large sample numbers make this impossible in practice without increasing data deviation (Table 2).

## SIC and SOC vertical distribution changes with larch growth (age, tree size, and biomass density)

Using the ratio between 0–40 and 40–80 cm as an indicator of the vertical distribution of SIC and SOC, dramatic contrary patterns in SIC dynamics compared to those of SOC were observed (Fig. 1). The SIC ratio significantly decreased with larch age ($r^2 = 0.2371$, $p = 0.0004$), tree size ($r^2 = 0.199$, $p = 0.013$), and biomass density ($r^2 = 0.2117$, $p = 0.0009$). However, the SOC ratio was positively correlated with the development of larch plantation ($r^2 = 0.1497$ and $p = 0.006$ for larch ages; $r^2 = 0.0975$ and $p = 0.0289$ for tree size; $r^2 = 0.161$ and $p = 0.0043$ for biomass density) (Fig. 1). Using the significant slopes as SIC or SOC logarithmic change rates, the SIC ratio decreased at rates of 0.592, 0.232, and 0.412, while the SOC ratio increased 1.0804, 0.3732, and 0.8251 with the same increases in larch age, tree size, and biomass density (Fig. 1).

Power analysis showed that the data had a much higher power to distinguish the changes in these ratios than it did in the absolute SIC and SOC storage values (Table 2; Fig. 1). In the case of the SOC ratio, the statistical power was 0.55–0.80, while the power for the SIC ratio was 0.91–0.97. The LSN for the SIC ratio was 15–19 and for the SOC ratio was 23–40 (Fig. 1), which are much smaller than those in absolute values of SOC and SIC (Table 2). The LSV for all the relationships between the SIC ratio, SOC ratio, and different variables of larch growth were lower than the observed coefficient values (Fig. 1), while those quantities for absolute values showed the opposite trend (Table 2).

## Possible effect of the SIC, SOC on other soil physicochemical properties

Changes in SIC and SOC storage may affect the soil physicochemical properties differently, as manifested by the opposing correlations between SOC and SIC and variable soil properties (Fig. 2). The SIC storage was significantly correlated with soil EC (slope = − 0.4148; $r^2 = 0.105$, $p < 0.001$) and soil pH (slope = 0.0127; $r^2 = 0.1643$, $p < 0.0001$), but no correlations with soil N, alkali-hydrolyzed N, and bulk density were observed ($r^2 < 0.02$, $p > 0.05$). Conversely, the SOC storage was significantly correlated with soil N (slope = 64.185; $r^2 = 0.6686$, $p < 0.0001$), alkali-hydrolyzed N (slope = 3.0796; $r^2 = 0.2347$, $p < 0.0001$), and bulk density (slope = −0.0653; $r^2 = 0.5778$, $p < 0.0001$). The soil EC could be affected by both SIC and SOC, but their influences were in contrary directions; SIC and EC were negatively correlated (slope = −0.4148; $r^2 = 0.105$, $p < 0.001$), while SOC and EC were positively correlated (slope = 2.9466; $r^2 = 0.1817$, $p < 0.001$) (Fig. 2). No significant correlations between SIC, SOC, and C:N ratio were found, while significant correlations between soil nitrogen and C:N ratio ($\ln(C/N\ ratio) = -0.3937\ \ln(SN) + 4.8814$, $R^2 = 0.3691$) was observed ($p < 0.05$) (data not shown).

Similar to the simple regression analysis, multiple-correlation analysis between SOC, SIC, and variable soil parameters (soil N, alkali-hydrolyzed N, available Si, pH, EC, and bulk density) as well as larch growth (age, tree size, and biomass density) showed the similar findings (Table 3). Parameters included in the multiple regressions of SIC included pH, age, soil N, and bulk density; only pH

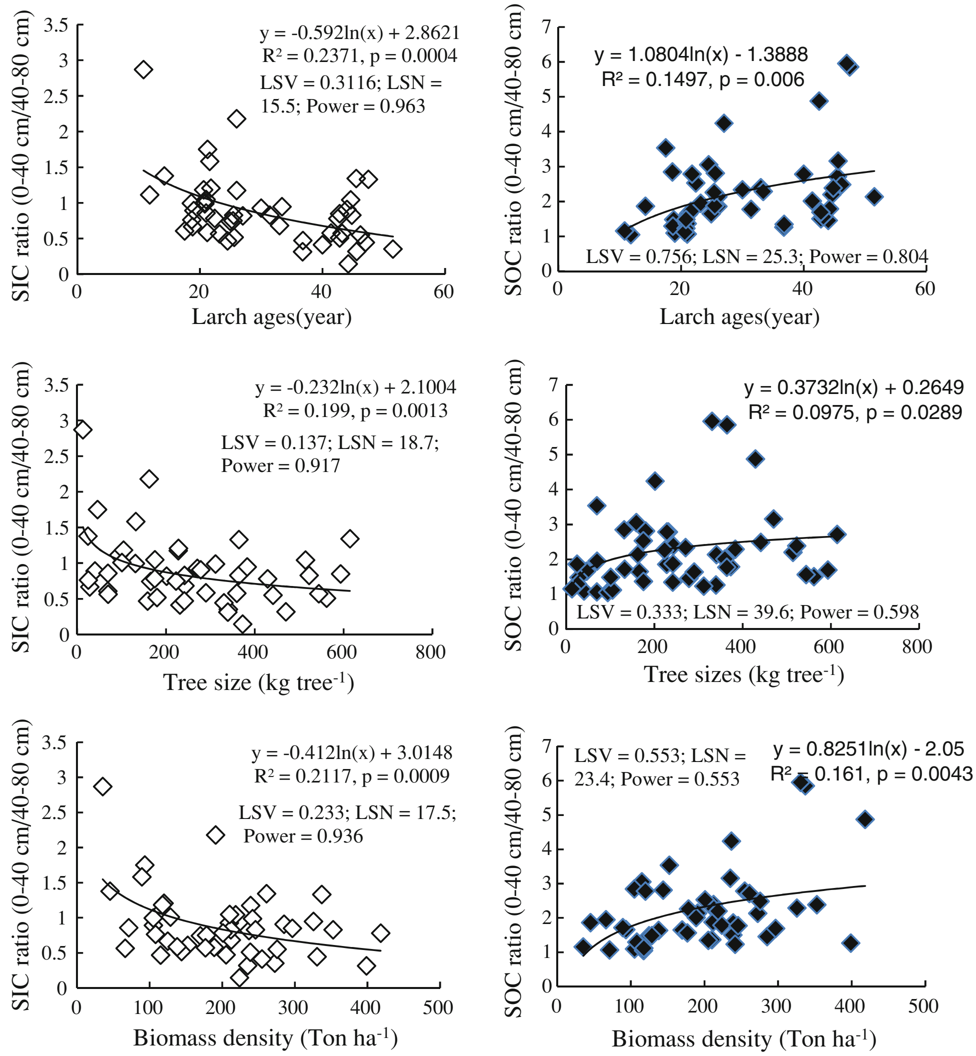


**Fig. 1** Vertical changes (0–40 and 0–80 cm) of SIC (*left column*) and SOC (*right column*) with the growth of larch forests (age, tree size, and biomass density)

was observed in different layers, which indicates the importance of SIC affecting soil pH. In contrast, SOC-related multiple-regression analysis showed that soil N was the most important parameter in different soil layers and the total 0–80 cm soil profile, and all the other entering parameters of biomass, age, alkali-hydrolyzed N, and bulk density differed in different layers, which indicates the importance of SOC on soil nitrogen. The $R^2$ values for SIC were lower than 0.31, while those for SOC were higher than 0.51 (Table 3).

## Discussion

Total SIC storage in China is approximately 60 Pg C, representing 1/20 of the global SIC pool (Wu et al. 2009). Similar magnitudes of SIC and SOC in China have been reported (Li et al. 2007), suggesting equal significance of SIC and SOC for the carbon budget. Strong carbonate leaches in humid climatic conditions cause some regions, such as southern and northeastern China, to have very low SIC content (Wu et al. 2009). This study confirmed this observation; SIC storage within 80 cm soils is 83.38 g $m^{-2}$, which is about 0.5 % of the SOC storage (15.34 kg $m^{-2}$) (Table 1) and is also much lower than that in arid and semiarid regions in China. In the arid soil zone of Northwestern China, the SIC storage ranges from 0.4 (±0.1) kg $m^{-2}$ in allitic soils to 5.5 (± 0.7) kg $m^{-2}$ in siallitic soils, while the SOC storage is generally low (Wu et al. 2009). Comparisons reveal that very low SIC storage (at most 20 % of that in allitic soil), but very high SOC storage is an important feature for carbon storage in the larch plantations in Northeastern China. Many studies on the soil carbon balance have focused on other regions of

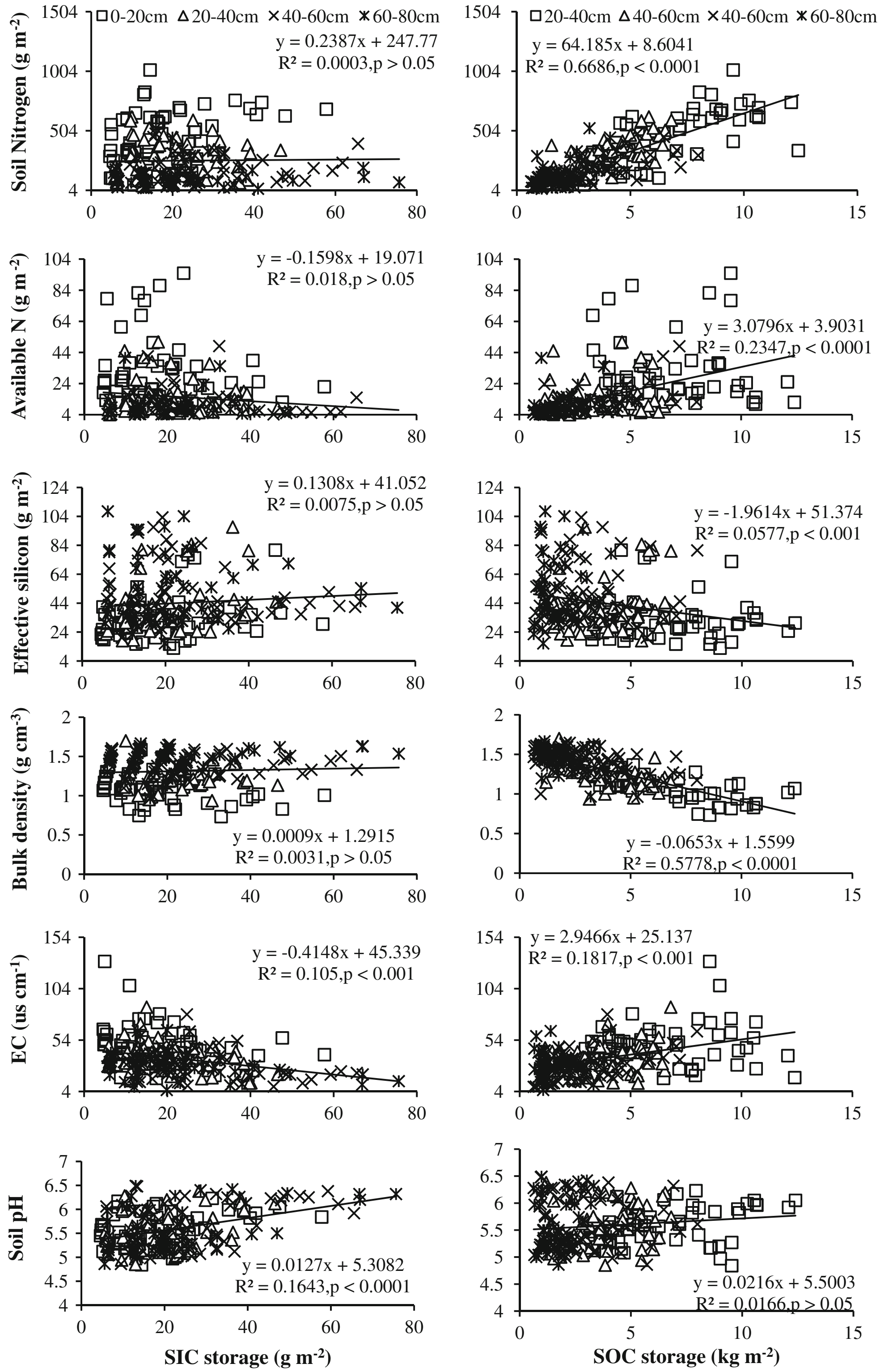


**Fig. 2** Differences in the correlations between SIC (*left column*), SOC (*right column*) and variable soil physicochemical properties

high SIC and low SOC (Wen 1989; Li et al. 1999; Pan 1999). However, this study attempted to examine the SIC and SOC dynamics in larch plantations in NE China, where high SOC and low SIC is present.

One conclusion of this study is the contrary vertical changes in SIC and SOC storage: SIC storage tends to decrease in surface soils, while SOC storage tends to accumulate in surface soils. This was manifested in the

**Table 3** Results of multiple-regression analysis between SIC, SOC, and variable parameters of larch forest soil

| Items | Equations | $R^2$ |
|---|---|---|
| SIC ($y$) multiple-regression stepwise entering at $p < 0.10$ significance | | |
| 0–20 cm | SIC = −18.7 − 0.162age + 7.35pH | 0.11 |
| 20–40 cm | SIC = −11.3 − 0.31age + 7.15pH | 0.18 |
| 40–60 cm | SIC = −72.35 + 17.6pH | 0.31 |
| 60–80 cm | SIC = −71.98 + 17.9pH − 0.037TN | 0.28 |
| 0–80 cm | SIC = −63.3 + 12.90pH + 9.68bulk density | 0.18 |
| SOC ($y$) multiple-regression stepwise entering at $p < 0.10$ significance | | |
| 0–20 cm | SOC = 1.82 + 0.0077TN + 0.0066biomass | 0.51 |
| 20–40 cm | SOC = 0.587 + 0.0084TN + 0.0041biomass | 0.67 |
| 40–60 cm | SOC = 1.18 + 0.0075TN + 0.065available N + 0.0367 EC − 0.0259age | 0.69 |
| 60–80 cm | SOC = 1.39 + 0.0038TN + 0.038available N − 0.015age | 0.54 |
| 0–80 cm | SOC = 8.02 + 0.0061TN − 4.38bulk density | 0.68 |

significant decreases of the SIC ratio between the top 40 cm soil and the deep 40–80 cm soil ($p < 0.05$), whereas the SOC ratio was markedly increased with larch age and biomass density ($p < 0.01$) (Fig. 1). Comparing the absolute values of SOC and SIC storage, the data statistical power for these vertical distribution changes increased several folds, indicating that the data are more reliable for identifying the relative SIC and SOC changes in the vertical profile than the absolute values of SIC and SOC (Table 2; Fig. 1). In fact, the decreasing tendencies in SIC storage and increasing tendencies in SOC in the surface 40 cm soils were observed and contrary tendencies were observed in deep soil (40–80 cm) (Table 2). These contrary changes in absolute values have favored the observation in the vertical change, as shown in Fig. 1. Many studies have examined the carbon balance during the growth of forests, and large variations are observed in different reports. Some found a rather high SOC accumulation rate (11–238 g C $m^{-2}$ $year^{-1}$) (Covington 1981; Hansen 1993; Garten 2002; Zhou et al. 2006; Luyssaert et al. 2008; Springsteen et al. 2010), and others found a nearly neutral SOC accumulation (0–7.6 g C $m^{-2}$ $year^{-1}$) (Richter et al. 1999; Wirth et al. 2002; Schedlbauer and Kavanagh 2008), and still others found significant SOC depletion (about −14.2 g C $m^{-2}$ $year^{-1}$) (Klopatek 2002; Law et al. 2003). In the case of SIC, either secondary SIC accumulation (Lal 2002; Entry et al. 2004) or relief of SIC by dissolution (Pan 1999; Duan et al. 1999) were also reported. These conflicting conclusions show the difficulty of estimating the soil carbon balance in absolute values. The findings in this study indicate that for absolute storage values, 28 out of 30 relations were not statistically significant (Table 2), but the relative vertical distribution changes owing to the development of forest growth were more easily discriminated via relatively few replicates with a high statistical power (Fig. 1).

Therefore, the results clearly manifested that there are contrary changes in the vertical distribution of SIC and SOC, which is significant as it raises the possibility of determining the soil carbon budget through the ratio changes. In general, the influence of trees on the soil is much stronger in surface soils than in the deep soils, and many studies only focus on surface soil (e.g., Sartori et al. 2007). Because the larch is a tree species with a very shallow root system, most of the roots were within 40 cm soils (Liu et al. 1992; Han and Liang 1997; Wang et al. 2005b; Kajimoto et al. 2007); therefore, in theory, its growth may more strongly affect the SIC and SOC at the surface soil (<40 cm) than at the deep soil (>40 cm) (Lorenz et al. 2011). Because the SIC and SOC storage in deep soil (40–80 cm) is closer to the soil status before the tree growth, the ratio between the surface soil and deep soil may be a good indicator of the dynamics of SOC and SIC storage due to tree growth. The contrary changes in the SIC ratio and SOC ratio may indicate that the growth of the larch plantation forest could result in SIC depletion and SOC accumulation in surface soil in comparison with deep soils. An approximate estimation was calculated as follows (Fig. 3). The assumed stable storage data in 40–80 cm soil were SIC at 47.2 g $m^{-2}$ and SOC at 5.19 kg $m^{-2}$ (Table 1). Surface 0–40 cm changes of SIC and SOC storage can be calculated by a multiplication of the logarithmic change rate and the SIC and SOC storage in the 40–80 cm layer (Fig. 3 right): SOC increases with log(age), log(tree size), and log(biomass density) were 5.61, 1.94, and 4.28 kg $m^{-2}$, respectively; SIC decreases were 27.9, 11.0, and 19.4 g $m^{-2}$, respectively. Accordingly, approximately 0.5–0.6 % overestimation in the soil carbon accumulation rate can be observed without considering SIC depletion (Fig. 3 right). This means that the SIC and SOC dynamics in vertical profiles may balance each other, which may relieve the changes in the total

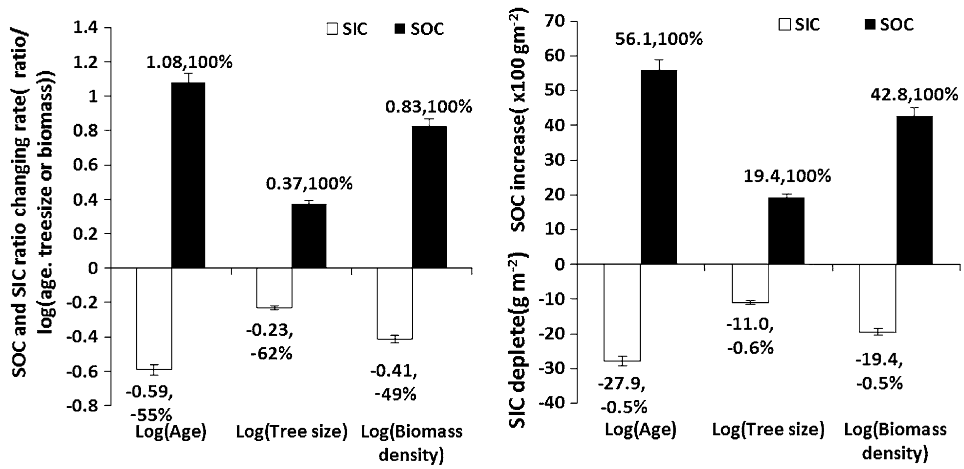


**Fig. 3** Logarithmic rate of change of the SIC and SOC ratio during larch growth (*left*), and the subsequent estimation of SIC and SOC storage changes in surface 0–40 cm soil with reference to relative stable storage in 40–80 cm soil (*right*). *Vertical bars above each column* represent 5 % error. *Data above and below the column* represent the value and its relative percentage to the SOC changing rate (100 %)

carbon in soil when both carbon components are considered rather than only one. As manifested in Fig. 3 (left), the decreasing rate of the SIC ratio in this study was −0.59 ratio/log(year), −0.23 ratio/log(kg tree$^{-1}$), and −0.41 ratio/log(ton ha$^{-1}$), which are generally about 49–62 % of the logarithmic increase in the rate of the SOC ratio. The reason for such a small contribution of the SIC to the total carbon dynamics (−0.6 %) is due to the much smaller percentage of SIC storage (SIC/SOC = 0.5 %) (Table 1). The contribution of SIC in carbon dynamics should be much higher in other sites with high SIC content. The conclusions of this study are reasonable in the typical high SOC and low SIC soils in NE China, because all aboveground litters dropping on the surface soil may result in SOC accumulation, while the abundance of organic acid in the SOC could dissolve the carbonates and make Ca nutrient available for tree growth. Some studies with concurrent SIC and SOC measurement show a similar tradeoff effect between SOC and SIC (Sartori et al. 2007; Zu et al. 2011).

The differences in the SIC and SOC in regulating soil properties have been examined using their correlations with variable parameters of soil as well as their multiple correlations (Table 3; Fig. 2). Soil fertility and soil physical properties are mainly determined by SOC but not SIC, which is manifested by the close correlations between soil N, soil alkali-hydrolyzed N, and soil bulk density with SOC ($r^2 > 0.23$, $p < 0.0001$), but not with SIC ($r^2 < 0.018$, $p > 0.05$) (Fig. 2). In contrast, soil acidity is mainly regulated by SIC ($r^2 = 0.1643$, $p < 0.0001$). Multiple regressions showed more detailed information on different vertical layers (Table 3). In the case of SIC, pH entered the multiple regressions through the profile, but SIC in deep soils (coefficient: 17.6–17.9) had more impact on the pH than those in surface soils (coefficient: 7.15–7.35) (Table 3). In the case of SOC, soil N entered the regressions though the soil profile; and SOC in the surface soils had more effect on soil N than those in deep soils (Table 3). The contrary function of SIC and SOC on soil bulk density were also found: SIC positively affected soil bulk density (coefficient: 9.68) and SOC negatively affected soil bulk density (coefficient: −4.38) (Table 3). Similar results can also be found in Fig. 2. Bulk density is an indicator for soil physics. This difference clearly suggested that SOC and SIC are functionally different in regulating soil physical properties. Therefore, both linear correlation and multiple-correlation analysis showed that SIC and SOC may be functioning differently for soil fertility and physical property. Larch plantation growth could induce more SOC, but less SIC in surface soil comparing with deep soil (Fig. 1); this finding indicates that the surface soil will become more acidic, but higher in nitrogen. These results are consistent with published data; Lu et al. (1999) and Chen and Xiao (2006) found that soil acidification during larch plantation development, and Wang et al. (2011) have reported that nitrogen enrichment in some larch plantation in NE China.

## Conclusion

Larch plantation development leads to significant changes in the vertical distribution of SIC and SOC, which has been revealed by a chronosequence plot study with 49 replicating plots. Significant decreases in the SIC ratio between 0–40 and 40–80 cm soils were found ($p < 0.05$) when larch age, tree size, and biomass density increased, which were contrary to the significant increase in SOC ratio ($p < 0.05$). This finding indicates that larch growth may affect the changes in SIC and SOC differently; however, these opposing changes were difficult to discriminate with the absolute values of SOC and SIC from the current data set. This divergence in the changes in SOC and SIC suggests that carbon balance studies should include both of these carbon components for accurate results. As suggested by the regression analyses, the SIC changes could have more effects on soil pH, while the SOC changes have more effects on soil N availability. In this study, without the inclusion of SIC in the total soil carbon budget, a −0.6 % overestimation of soil carbon accumulation during development of larch plantation is possible. However, the contribution of SIC should be much greater in soil with a higher SIC storage percentage.

**Acknowledgments** This study was supported financially by China's Ministry of Science and Technology (2011CB403205), China's National Foundation of Natural Sciences (31170575, 40873063), China's postdoctoral foundation (201003406&20080430126) and basic research fund for national universities from Ministry of Education of China (DL12DA03).

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