Catena 249 (2025) 108697

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Long-term afforestation of black pine over two centuries asymptotically enhanced SOC and TN stocks in a typical coastal sand dune of Japan

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ARTICLE INFO

Keywords:
Black pine
Carbon sequestration
Land use change
Shonai sand dunes
Soil depth
Temperate coastal regions

ABSTRACT

Afforestation is widely recognized as a valuable approach to enhance terrestrial carbon (C) sequestration and nitrogen (N) cycling. However, it remains unclear how soil organic C (SOC) and total N (TN) stocks respond to long-term black pine afforestation in Shonai sand dunes, Japan. Here, soil samples from coastal forest sand dunes were collected in five depths (0–50 cm at 10 cm intervals) across 20 sites spanning average 5 years to 210 years to analyze SOC and TN stocks, along with related parameters. Soil bulk density and pH significantly increased, whereas electrical conductivity significantly decreased along the 0–50 cm soil depths. Plantation age exhibited negative correlations with bulk density and pH values in 0–50 cm soil depths. SOC and TN contents declined across the 0–50 cm soil depths in each plantation age site. Moreover, SOC and TN contents increased from 5 to 210 years in each soil depth from 0–50 cm, except for the upper layer (0–10 cm), where SOC and TN contents followed the order 5-year < 25-year < 55-year < 210-year < 105-year. Asymptotic increases in SOC and TN stocks were observed in the upper layer with plantation age, whereas significantly linear increases were noted in the 10–50 cm soil depths. SOC and TN stocks in the 0–50 cm depths markedly increased from 5 to 105 years, with a gradual slowdown after 105 years. The C/N ratio consistently increased from 7.8 to 16.0 with SOC content below 6 g kg^{-1}, stabilizing regardless of SOC content beyond this threshold. Redundancy analysis highlighted bulk density as the most dominant factor, explaining 68.2 % of the variation in SOC and TN stocks. Conclusively, black pine afforestation in Shonai sand dunes caused asymptotic SOC and TN accumulation within 105 years, with a subsequent slowdown up to 210 years in the whole 0–50 cm soil depths.

1. Introduction

With the increasing global population and rapid socioeconomic development occurring, climate change is emerging as a critical environmental issue due to substantial greenhouse gas emissions (i.e. carbon dioxide (CO_2), methane, and nitrous oxide). This presents major challenges to human survival and sustainable development (Korkanc, 2014; Rehman et al., 2022). The fluctuations in the amount of carbon (C) sequestered by vegetation and soils closely correlate with changes in the accumulation of CO_2 in the atmosphere (Ballantyne et al., 2012; Keenan et al., 2016; Yun et al., 2022). It is widely acknowledged that soil constitutes the largest terrestrial C reservoir, and C dynamics in soil are highly susceptible to changes in land use and vegetation induced by anthropogenic activities (Lal, 2008; Smith et al., 2008; Köchy et al., 2015; Hosogoe et al., 2024). Minor changes in soil C pools resulting from land use changes may have profound effects on atmospheric CO_2 concentration, potentially triggering substantial feedbacks to future climatic change (Powlson et al., 2011; Wang et al., 2014; Li et al., 2022).

Over the past decades, increasing evidence have demonstrated that the newly sequestered soil organic C (SOC) after afforestation is originally and primarily derived from plant litter inputs (Kögel-Knabner 2002; Cao et al., 2020; Li et al., 2023). The sequestered soil C via

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https://doi.org/10.1016/j.catena.2024.108697
Received 20 March 2024; Received in revised form 18 August 2024; Accepted 29 December 2024
Available online 3 January 2025
0341-8162/

afforestation or reforestation is usually stored in an unstable form and could be easily lost due to alteration of soil properties and environmental conditions (Dynarski et al., 2020). Large uncertainties remain in SOC and TN stocks as well as their active composition in responses to long-term afforestation. For instance, previous studies have indicated that afforestation can significantly increase SOC content (Korkanc, 2014; Yao et al., 2023; Dewi et al., 2024). However, afforestation of crop field (up to 17 years) did not change soil C and N stocks (Chia et al., 2017). To date, relatively limited studies have been done on long-term influence of afforestation on organic C dynamics of sandy soils in temperate coastal regions despite many such studies on other terrestrial ecosystems and soil type (Korkanç, 2014; Chia et al., 2017; Chen et al., 2018; Hou et al., 2019; Guo et al., 2021; Li et al., 2023). Thus, a full understanding of SOC and TN stocks, and their variation with soil depth in afforested sandy lands is both timely and imperative for accurate assessment of long-term C sequestration under future afforestation programmes.

Coastal forests, artificial ecosystems extending around the four main islands of Japan, encompass 25 km^2 in the sand dunes of the Shonai region in Yamagata Prefecture, Japan (Nakajima and Okada, 2011). Japanese black pine (*Pinus thunbergii*) coastal forests play a crucial role in disaster prevention (i.e. windstorms, tsunamis, tide damage, and sand deposition) and contribute to the maintenance of regional landscapes and biodiversity in Japan (Lopez et al., 2014; Murata et al., 2022). The history of black pine plantations in the Shonai Plain dates back approximately 400 years, initially established as windbreak forests. With the growing local population, some Shonai sand dunes are used for agricultural production, a practice spanning 400 years, including melon, greenhouse flower, vegetables, and rice cultivation, with the latter cultivated using polyethylene film lining (Wakamatsu and Wakamatsu, 2011; Dewi et al., 2024). Currently, nearly 25 km^2 of Shonai sand dunes are dedicated to pure black pine plantations of various ages, whereas other areas are designated for mixed cultivation of black pine and crops (i.e. melons and greenhouse flowers). Sandy soils in this region are characterized by low fertility due to minimal C and clay mineral contents, unfavorable physical properties (i.e. low aggregate stability, low resistance to compaction, and small porosity), and poor cation exchange capacity and base saturation (Huang and Hartemink, 2020). However, little information exists on whether C and N stocks distinctly increase with different black pine plantation ages in the Shonai sand dunes. Additionally, it remains poorly understood whether soil physicochemical properties vary markedly with soil depth from 0 to 50 cm in the development of coastal forests in the Shonai sand dunes of northeastern Japan.

Generally, soil organic matter (SOM) can be categorized into labile and stable fractions based on microbial decomposability and utilization (von Lützow and Kögel-Knabner, 2009; Strosser, 2010). Previous studies have indicated that soil soluble organic C and N, extracted using cold and hot water, can be considered labile SOM (JSSSPN, 1986; Strosser, 2010). It has been documented that cold water (20 °C) extractable C and N (CWEOC and CWEON) are effective indicators to reflect the quantity of available SOM and hot water (80 °C) extractable organic C and N (HWEOC and HWEON) can be used to display the maximum of labile C and N pools (Ghani et al., 2003; Nguyen-Sy et al., 2020; Wu et al., 2020). To date, the dynamic trends of CWEOC and HWEOC along soil depths from 0 to 50 cm and their responses to long-term plantation of black pine remain unclear in coastal sandy soils.

To address the aforementioned knowledge gaps, the present work was designed to characterize key soil properties in different plantation ages of black pine ranging from 1 to 250 years. The primary objectives of this study were to investigate the dynamics of soil C and N storage and availability with different plantation ages of black pine coastal forests in sand dunes. Notably, we carried out this research on the basis of the assumption that all of plantation age sites had the identical initial soil properties because it is impossible to collect the initial sandy soil with more than 90 % sand prior to the afforestation lasting for approximate 400 years. We hypothesized that both SOC and TN stocks increase and soil physical properties improve with the plantation ages of black pine but vary with depth in the soil profile mainly due to the increased plant-derived organic matter input into soil and nutrient redistribution (leaching) along soil layers.

2. Materials and methods

2.1. Site description and forest plantation

The study area was located in a coastal sand dune of Shonai region, Yamagata Prefecture, northeastern Japan (38°47′07″ N,139°45′13″ E–38°55′09″ N, 139°48′34″E) (Fig. S1). This area experiences a typical humid temperate climate, with a mean annual temperature and precipitation of 13.0 °C and 1986.8 mm, respectively, recorded from 1991 to 2020, based on the Japan Meteorological Agency database for the Sakata Meteorological Observatory (https://www.data.jma.go.jp/obd/stats/etrn/view/nml_amd_ym.php). The soil is classified as Arenosol according to FAO Soil Taxonomy and the soil texture consists of 93.3 % sand, 1.0 % silt, and 5.7 % clay (Miyasaka et al., 2014). The particle size of soil is generally fine (< 2 mm) without the existence of visible coarse fragment (> 2 mm). Japanese black pine trees, ranging from 1 to 250 years old, had been planted in the Shonai sand dunes across different areas since Edo period (1603–1868), based on information from the Forest Creation and Promotion Office, Forest Maintenance Division in the Shonai Branch, Yamagata Prefecture, Japan. There were natural black pine forests before Waring States period in Japan (1467–1568), but they were destroyed by warfare and deforestation. For preventing the natural disasters, such as flying sand, wind storm and tide damage, local people started afforestation with black pine in the Shonai sand dunes (Nakajima and Okada, 2011). Notably, the type of plantation management was the same throughout different periods. The densities of the black pine trees were approximate 350 trees ha^{-1} for the tree ages larger than 110 years, around 2000 trees ha^{-1} for the tree ages less than 55 years. The diameters at breast height of black pine were around 40 cm for the tree ages larger than 110 years, around 20 cm for the tree ages less than 55 years (Taki et al., 2013). The surface organic layer in the black pine stand ranges from 0 to 5 cm depth and herb and grass were scattered on the ground layer.

2.2. Soil collection and analysis

Black pine forests in this study were categorized into five groups based on their plantation ages; the 5-year, 25-year, 55-year, 105-year, and 210-year sites, representing average ages of 1–15, 20–30, 50–60, 80–110, and 180–250 year, respectively. Soil samples were collected from five soil layers (0–10, 10–20, 20–30, 30–40, and 40–50 cm) using a DIK-106B soil sampler (Daiki, Saitama, Japan) for each age group. Detailed information of soil sampling sites is provided in Fig. S1. Five randomly sampled cores from each site were mixed to create one composite soil sample. Soil samples for measuring bulk density were taken in each soil layer from 0–50 cm in all plantation age sites using volumetric cutting ring (100 cm^3). After removing visible plant residues, soil samples were sieved through a 2 mm sieve and air-dried at room temperature (20 °C). Then, soil samples were used for analyzing SOC, TN, soluble organic C and N, soil pH, and electrical conductivity (EC) as described below.

The SOC and TN contents were quantified via combustion using an elemental analyzer (Sumika Chemical Analysis Service, Tokyo, Japan). The soil C:N ratio (C/N) was calculated based on SOC and TN values (Tang et al., 2024). Soil pH and EC were measured on a soil suspension (1:2.5 ratio of soil: water) after 30 min of shaking, using a pH meter (D-51, Horiba, Kyoto, Japan) and an EC meter (Cond-meter DS-51, Horiba, Kyoto, Japan), respectively (JSSSPN, 1986). Soil moisture was measured following oven-drying for 48 h at 105 °C. Soil bulk density was calculated as the mass of soil divided by the volume of a cutting ring. Soil soluble organic C and N extracted using cold water at room temperature (CWEOC and CWEON, respectively) and hot water (80 °C) (HWEOC and HWEON, respectively) were obtained using the modified methods described by Ghani et al. (2003). Briefly, a 3 g air-dried soil sample was added to a 50-mL centrifuge tube with 30 mL of deionized water and shaken for 30 min at room temperature. After centrifugation at 3000 rpm for 30 min and filtration through a prewashed 0.45 μm membrane filter (Millex-HV, Ireland), dissolved organic C (DOC) and dissolved total N (DTN) were analyzed using thermal oxidation method (TOC VCPH with TNM-1, Shimadzu, Japan) and via colorimetric methods, respectively (JSSSPN, 1986). DON was calculated as the difference between DTN and inorganic N. For hot water extraction, 3 g soil sample with 30 mL of deionized water was manually shaken for 2 min, and the tube was placed in a water bath at 80 °C for 16 h. After cooling, the suspension underwent the same centrifugation and filtering procedures as described for the cold water extractions. Additionally, the amounts of HWEOC and HWEON were determined following the procedures described for cold water extractions. More detailed procedures were described by Wu et al. (2020).

2.3. Calculation and Statistical analysis

The stocks of SOC and TN (t ha^{-1}) across soil depths were calculated using the following Eqs. (1) and (2) (Kautsar et al., 2020; Thura et al., 2023).

$$\text{SOC stock} = \text{SOC} \times BD \times D \times 0.1 \tag{1}$$

$$\text{Soil TN stock} = \text{TN} \times BD \times D \times 0.1 \tag{2}$$

where SOC and TN are the SOC and TN concentrations (g kg^{-1}), respectively; BD is the bulk density (g cm^{-3}), and D is the soil depth (cm).

Prior to analysis of variance (ANOVA), all data were checked for normality using the Shapiro-Wilk's test and homogeneity of variance using Levene test, respectively. When necessary, data were transformed using log or reciprocal functions to improve homogeneity of variance and /or normality of the data. Two-way ANOVA was operated to assess the effects of plantation age and soil depth on soil basic physicochemical properties, SOC and TN contents, C/N ratio, and water extractable organic C and N. The trends of SOC and TN stock along with plantation age and soil depth were fitted with exponential and power functions using the following Eqs. (3) and (4). Notably, the trend of C/N ratio with SOC content was quantified by a double exponential growth model as described in Eq. (5).

$$\text{SOC (TN) stock} = a + b*(1 - e^{c*x}) \tag{3}$$

where a,b, c, and x is the intercept, coefficient, increasing rate constant, and plantation age, respectively.

$$\text{SOC (TN) stock} = a * \text{x}^{\text{b}} \tag{4}$$

where a, b, and x is maximum potential as a constant, power coefficient as decreasing rate constant, and soil depth, respectively.

$$C/N = \text{a}*(1 - \text{e}^{b*\text{x}}) + c*(1 - \text{e}^{-d*\text{x}}) \tag{5}$$

where a and c are coefficients, b and d are increasing rate constants, and x is SOC content, respectively.

Pearson correlations were conducted to quantify the relationship among all measured soil properties, plantation age, and soil depth. Redundancy analysis (RDA) from Canoco 5.0 software (Gamma Design Software, Canoco 5.0 LLC Plainwell, MI) was performed to determine the proportions of variability in SOC and TN contents, stocks, and C/N ratio as responsive variables explained by soil depth, plantation age, and soil basic properties (pH and EC) as independent variables. All regression curves fitting parameters were determined and goodness-of-fit tests were performed using SigmaPlot Version 12.5 (Systat Software). Statistical significance was indicated at $P < 0.05$. All statistical analyses were performed using IBM SPSS Statistics 27.0 (IBM Corp., New York, NY, USA) unless otherwise stated.

3. Results

3.1. Changes in soil bulk density, pH, and EC

Statistical analysis suggested that there were highly significant effects ($P < 0.001$) of plantation age and soil depth on soil bulk density, pH and EC values (Fig. 1a–c). Additionally, significantly interactive effects ($P < 0.01$) of plantation age and soil depth were observed for soil bulk density and EC value (Fig. 1b, c). Soil pH, EC, and bulk density varied from 4.97 to 6.16, 10.57 to 133.50 μS cm^{-1} and, 1.15 to 1.48 g cm^{-3}, respectively, across the 0–50 cm soil depth under five plantation age sites (Fig. 1a–c). Soil EC decreased with soil depth from 0 to 30 cm and stabilized from 30 to 50 cm across plantation age sites from 5 years to 105 years. However, in the 210-year site, soil EC continued to decrease down to 40 cm soil depth. Conversely, soil pH in 55-year site rapidly increased down to 40 cm and remained relatively stable in 40–50 cm soil depths. Both 25- and 105-year sites showed increased pH up to 20 cm soil depth and then keep stable in 20–50 cm soil depths. Soil pH in 5-year site increased down to 30 cm but decreased in 30–40 cm soil depths and remain stable in 40–50 cm soil depths. Soil pH in 210-year site increased in 0–20 cm and 30–40 cm soil depths but does not alter in 20–30 cm and 40–50 cm soil depths (Fig. 1b). Overall, soil pH exhibited a decreasing trend with plantation age, whereas soil EC increased with plantation age in the 0–30 cm soil depths. Minor changes in bulk density were observed in the 5-year site across the five soil depths. However, bulk density in three age sites from 25 to 105 years increased in soil depth from 0 to 30 cm and stabilized in the 30–50 cm soil depths. The 210-year site showed a continuous decline in bulk density down to 50 cm depth (Fig. 1a). In the 0–10 cm depths, soil bulk density followed the order 105-year < 55-year < 210-year < 25-year < 5-year. Moreover, three sites with plantation ages > 55-years (55-year, 105-year, and 210-year sites) showed significantly lower bulk density compared with two sites with plantation ages < 25 years (5-year, and 25-year sites) in the 0–20 cm soil depth (Fig. 1a).

3.2. Dynamics of SOC and TN contents, and C/N ratio

Statistical results indicated that the highly significant effects of soil depth and plantation age on SOC, TN, and C/N ($P < 0.01$). Moreover, there were highly significant interactive effects of soil depth and plantation age on both SOC and TN contents (Fig. 2a, b). The dynamics of SOC, TN, and C/N (SOC/TN) in the 0–50 cm soil depths under five black pine plantation ages were shown in Fig. 2. SOC and TN contents, and C/N varied from 0.44 to 20.51 g kg^{-1}, 0.05 to 1.25 g kg^{-1}, and 7.75 to 17.90 in the 0–50 cm soil depths, respectively. SOC and TN contents under all plantation age sites except 5-year plantation site sharply decreased with soil depth from 0 to 30 cm and slowly decreased in the 30–50 cm range. Both SOC and TN contents significantly increased with plantation age from 5 to 210 years in 10–40 cm soil depths even though the differences in SOC and TN content between the two longer-aged plantation sites (i.e. 105 and 210 years) were not significantly different in 0–10 cm soil depth (Fig. 2a, b). C/N ratios decreased with soil depth from 0 to 50 cm under 5–105 year sites, whereas, in 210-year site, the C/N ratio was stable in the 0–30 cm depths but decreased with soil depth from 30 to 50 cm. Overall, the C/N ratio in the 10–40 cm soil depths increased with plantation age from 5 to 210 years. However, in the 0–10 cm soil depths, the C/N ratio followed the order 5-year < 25-year < 210-year < 105-year < 55-year.

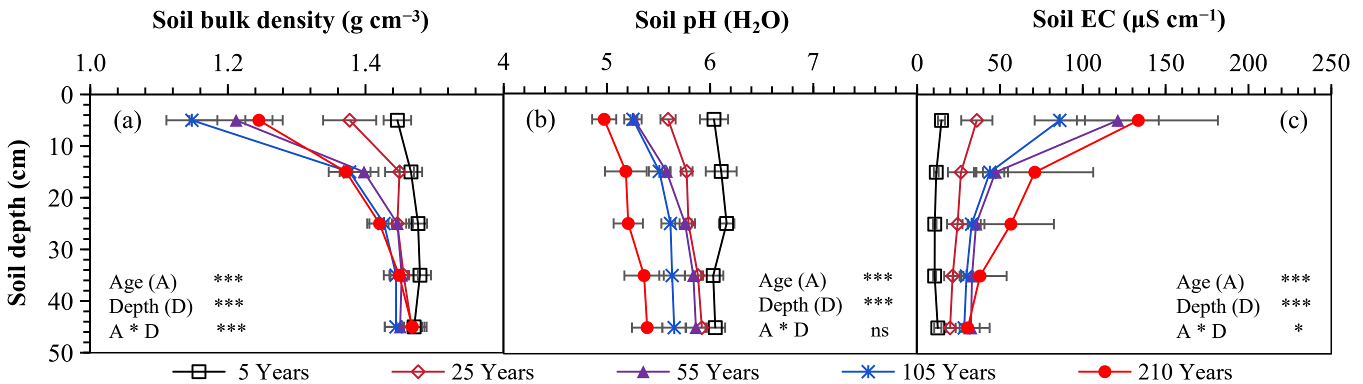

Fig. 1. Changes in soil bulk density (a), soil pH (b), and EC (c) in the 0–50 cm depths under five average plantation ages of black pine forest from 5 to 210 years in the Shonai sand dunes. Data were shown as means ± standard errors. *, $P < 0.05$; ***, $P < 0.001$; ns, no significance.

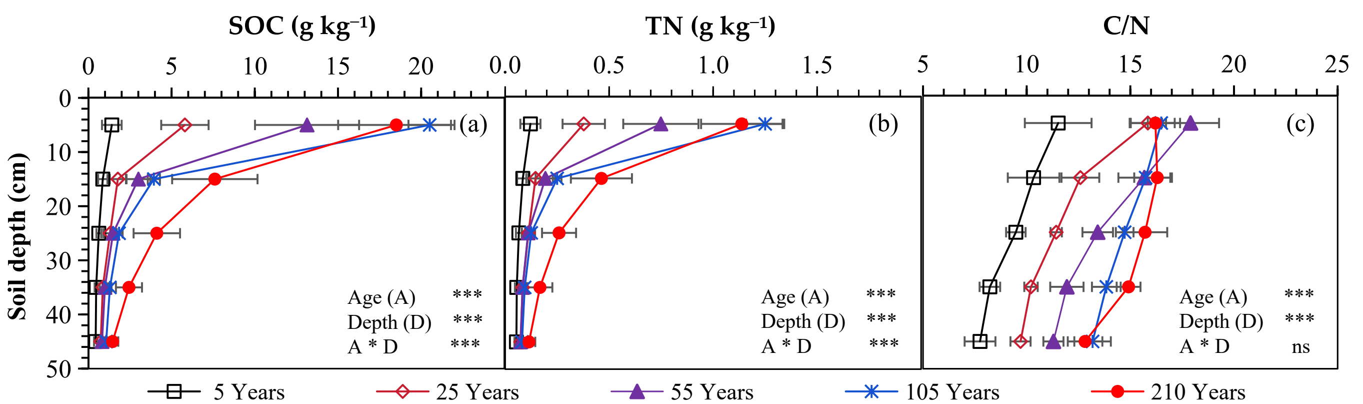

Fig. 2. Changes in SOC (a), TN (b), and C/N ratio (c) in the 0–50 cm depths under five average plantation ages of black pine forest from 5 to 210 years in the Shonai sand dunes. Data were shown as means ± standard errors. ***, $P < 0.001$; ns, no significance.

3.3. Changes in SOC and TN stocks

Statistical analysis indicated highly significant impacts of plantation age and soil depth on SOC and TN stocks ($P < 0.01$) and their interactive effects on these stocks were also highly significant ($P < 0.01$). SOC and TN stocks under each plantation age treatment exhibited similarly nonlinear decreasing trends with soil depth from 0 to 50 cm (Fig. 3a–e, 4a-e). SOC and TN stocks ranged from 0.64 to 23.45 t C ha^{-1} and from 0.08 to 1.44 t N ha^{-1}, respectively, across the 0–50 cm soil depths and five plantation age sites. Overall, the SOC and TN stock trends under each plantation age treatment were well-fitted with an power function (Figs. 3 and 4). SOC and TN stocks under each plantation age site sharply decreased in the 0–30 cm soil depths but gradually stabilized in the 30–50 cm range (Fig. 3a-f, 4a-f). The maximum potentials, coefficient (a), as a critical constant in power function equation (Eq. (4) in Figs. 3 and 4) for both SOC and TN stocks in the 0–50 cm soil depths followed the order 5-year < 25-year < 55-year < 105-year < 210-year. Unexpectedly, the power coefficient (b), considered as C and N stock accumulation rates, followed the order 5-year < 25-year < 210-year < 55-year < 105-year. Interestingly, an asymptotic increase in SOC and TN stocks with plantation age was found in the 0–10 cm soil depths. For the remaining four soil depths at 10–50 cm, significantly linear correlations were observed between SOC and TN stocks and plantation age (Figs. S2a–e, Figs. S3a–e).

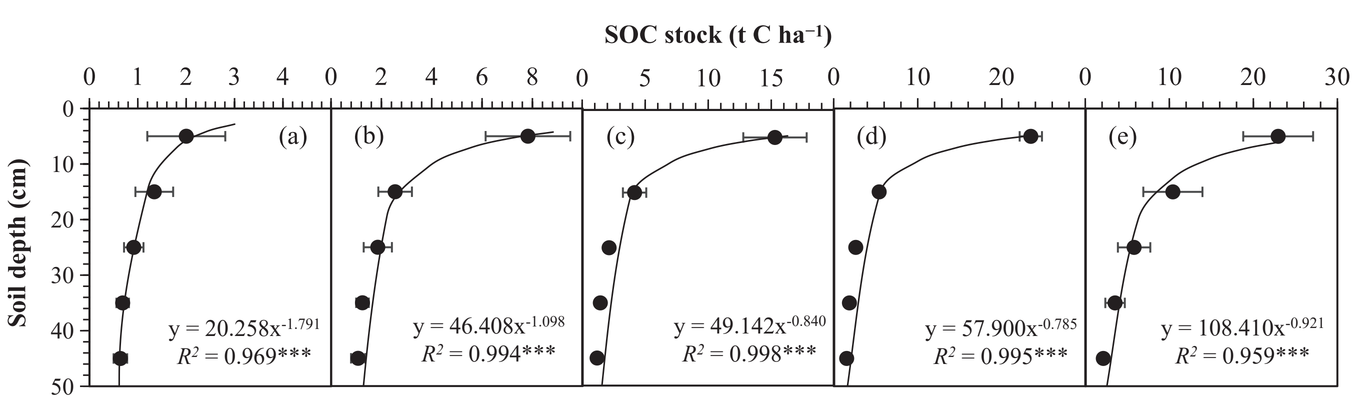

Fig. 3. Changes in SOC stock in the 0–50 cm depths under five average plantation ages of black pine forest from 5 to 210 years (a–e) in the Shonai sand dunes. ***, $P < 0.001$.

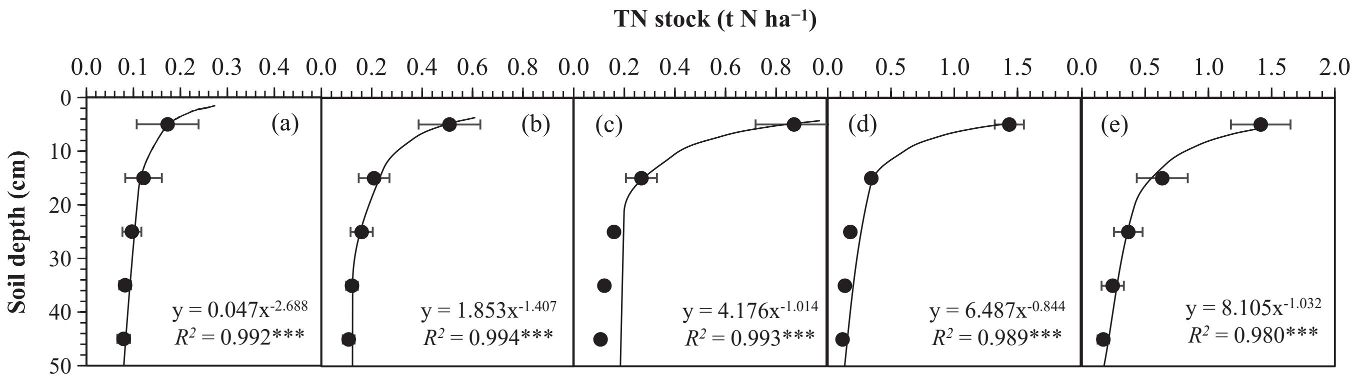

Fig. 4. Changes in soil TN stock in the 0–50 cm depths under five average plantation ages of black pine forest from 5 to 210 years (a–e) in the Shonai sand dunes. ***, $P < 0.001$.

3.4. Changes in soluble organic C and N extracted by cold water and hot water

Statistical analysis indicated highly significant impacts of plantation age and soil depth on all soluble organic C and N concentrations (Fig. 5a-d, $P < 0.001$), exhibiting similar trends as SOC and TN contents (Fig. 2). Moreover, their interactive effects on CWEOC, HWEOC, and HWEON concentrations, were also significant (Fig. 5a, b, d, $P < 0.05$). Soluble C and N extracted via cool and hot water were considered labile organic substrates for microbial utilization. Average concentrations of CWEOC and CWEON ranged from 18.88 to 140.99 mg kg^{-1} and 1.01 to 8.07 mg kg^{-1}, respectively, which were markedly lower than the corresponding HWEOC (45.71–1507.34 mg kg^{-1}) and HWEON (2.45–67.83 mg kg^{-1}) concentrations (Fig. 5a–d). CWEOC, CWEON, HWEOC, and HWEON concentrations rapidly decreased with soil depth from 0 to 30 cm, gradually decreased from 30 to 40 cm soil depth but remained stable at 40–50 cm. HWEOC and HWEON concentrations exhibited similar trends with plantation age in each soil depth. However, CWEOC, CWEON, HWEOC, and HWEON concentration trends according to plantation age varied markedly with soil depth from 0 to 30 cm. The HWEOC, HWEON, and CHEON concentrations in the 0–10 cm depth, both followed the order 5-year < 25-year < 55-year < 210-year < 105-year. However, the CWEOC concentration in the 0–10 cm depth followed the order of 5-year < 25-year < 210-year < 55-year < 105-year. In the 10–20 cm soil

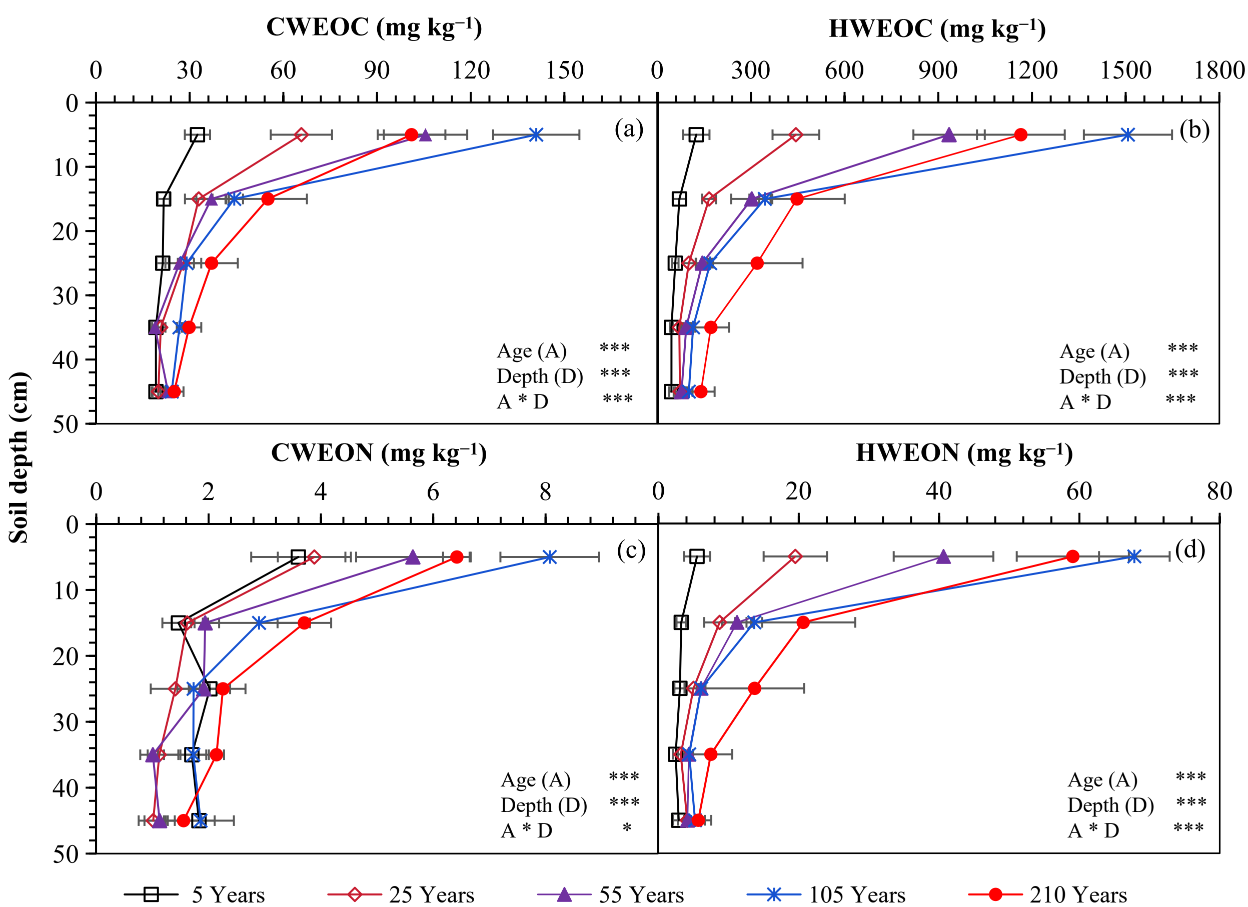

Fig. 5. Changes in soluble organic C and N extracted using cold water (a, c) and hot water (b, d) in soil samples from the 0–50 cm depths under five average plantation ages of black pine forest from 5 to 210 years in the Shonai sand dunes. Data were shown as means ± standard errors. *, $P < 0.05$; ***, $P < 0.001$.

depth, all soluble C and N concentrations increased with plantation age from 5 to 210 years.

3.5. The relationship between soil basic properties, SOC and TN contents, and their stocks

In this study, redundancy analysis was used to further investigate the main impact factors of SOC and TN contents and stocks along the soil depth and black pine forest plantation age in the Shonai sandy dunes. The first axis was highly associated with SOC and TN stocks, explaining 79.24 % of the variation; however, the second axis was correlated with C/N, accounting for only 4.94 % of variation (Fig. 6). Soil bulk density was the most dominate impact factor, explaining 68.2 % of variation for SOC and TN stocks, followed by pH, plantation year, soil depth, and EC, which together accounted for 84.2 % of the aforementioned variation (Table 1, Fig. 6). Additionally, soil pH was significantly positively correlated with bulk density but significantly negatively correlated with SOC and TN contents, stocks, as well as the C/N ratios (Table 1, Fig. 7). Expectedly, there are significantly positive correlations between SOC and TN contents, stocks, and soluble organic C and N (CWEOC, CWEON, HWEOC, and HWEON) concentrations (Fig. 7).

4. Discussion

4.1. Effects of black pine plantation age on soil properties of the Shonai sand dunes

The present study showed that plantation age and soil depth significantly and interactively affected soil bulk density, pH and EC (Fig. 1a-c). The distinct changes in these soil basic properties occurred in the 0–30 cm depths, being more pronounced than those in deeper depths, indicating that black pine plantations mainly affect surface soil (0–30 cm) properties, with higher SOC and TN contents likely due to litter and root exudate inputs (Fig. 2a, b). Decreasing pH was negatively correlated with increasing plantation age (Fig. 7). This finding is consistent with the results of Yesilonis et al. (2016), who found that lower pH in old forest soils compared with young forest soils, likely owing to long-term leaching of base cations and increased release of acidic root exudes with plantation age. Similar trends were found in a study on Scots pine plantation in sandy soil in southern Slovakia, which also indicated that soil pH decreased with increasing plantation age (Šurda et al., 2021). Bulk density reduction in the 0–10 cm soil depths with increasing black pine plantation ages (5–105 years) may be attributed to increasing SOM input from litter and root exudates over time. The significantly

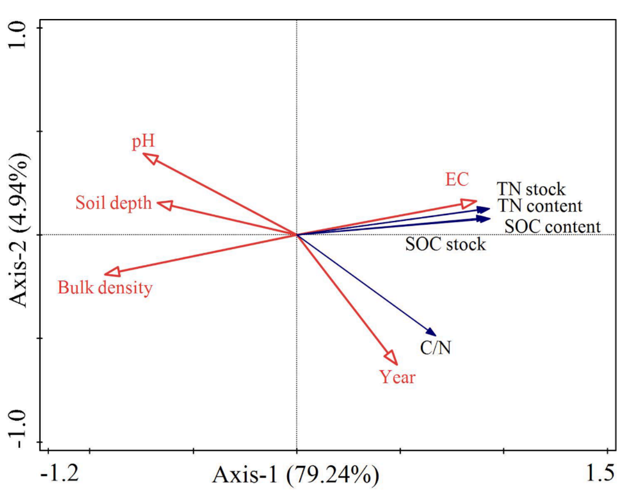

Fig. 6. Reduundancy analysis of soil bulk density, pH, SOC and TN contents and stocks, and C/N ratio in the 0–50 cm soil depths and five average plantation age gradients of black pine forest from 5 to 210 years.

Table 1
Redundancy analysis results of bulk density, EC, pH, soil depth, and year as impact factors (independent variables) to explain the total variations of SOC and TN contents, stocks, and C/N ratio as responsive variables. Contribution (%) displays the fraction of each impact factor in the whole explanation.

Impact factors	Explains (%)	Contribution (%)	*F* value	*P* value
Bulk density	68.2	81.0	210	0.002
pH	10.1	12.0	44.9	0.002
Soil depth	2.2	2.6	10.6	0.002
Year	2.3	2.7	12.6	0.002
EC	1.4	1.7	8.6	0.002

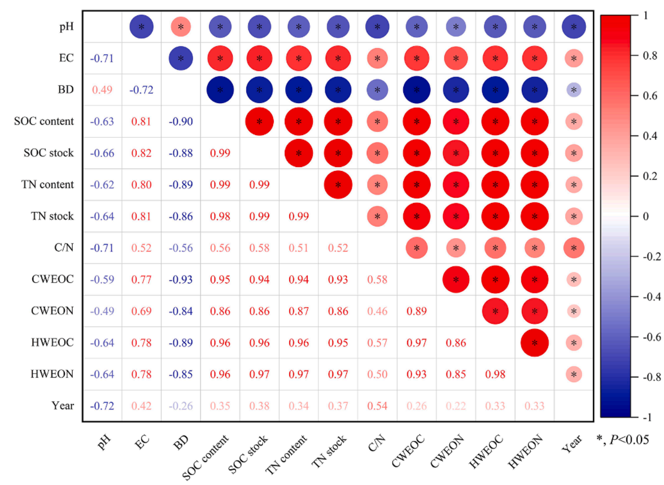

Fig. 7. The Pearson correlation analysis of soil basic properties (bulk density, pH, and EC), SOC and TN contents and stocks, C/N ratio, and available C and N (CWEOC, CWEON, HWEOC, HWEON) concentrations in the 0–50 cm soil depths and five average plantation age gradients of black pine forest from 5 to 210 years. *, $P < 0.05$.

increasing soil bulk density among the 0–50 cm soil depths is possibly ascribed to the rapid leaching of soluble nutrients (i.e. DOC, inorganic N, and base cations), and clay minerals, and less new SOM inputs along soil depths (Fig. 1a). It is obvious that the rapid leaching of soluble nutrients from top to deep layers via soil erosion can promote soil compaction, resulting in the enhanced soil bulk density. Our results are consistent with those of Yao et al. (2023), who reported that soil bulk density decreased with *Caragana korshinskii* plantation age from 13 to 55 years.

Soil EC, reflecting the soil's ability to conduct or attenuate electrical current, is often used to evaluate soil salinity (Zhang and Wienhold, 2002). Soil EC is suggested to be highly correlated with the status and movement of ions in soil water, as well as soil water content (Zhang and Wienhold, 2002; Acosta et al., 2011). In the present study, contrary to soil bulk density and pH, EC showed an increasing trend with plantation age across the 0–50 cm depth (Fig. 1c). This finding can be explained by following three reasons. Firstly, changes in soil hydrological status and ion movement due to afforestation likely contribute to higher soil EC values. In central-eastern Spain, the stand age of black pine was shown to impact on soil water repellency and hydraulic conductivity in the Mediterranean environment, with soil water infiltration being higher and repellency lower in older forests compared with younger pine stands (Zema et al., 2021). Secondly, soil base cations such as K^+ and Ca^{2+}, can be obtained from litter decomposition. Generally, increased black pine plantation age is accompanied by more litter accumulation which could be potentially decomposed by microorganisms, resulting in higher soil EC values from the substantial release of available nutrients. The decreasing EC with soil depth from 0 to 50 cm may be attributed to nutrient leaching and reduced SOM input. Thirdly, the black pine forests with long plantation ages can suffer from a series of long-term invasion of ocean water (wave), salinity dispersion, and deposition with extremely geological and meteorological disasters (i.e. tsunami, typhoon, and heavy rainfall (snow)), resulting in the enhanced soil EC values.

4.2. *Effects of black pine plantation age and soil depth on SOC and TN contents and stocks*

The afforestation in the Shonai sand dunes with black pine, spanning over two centuries, aimed to prevent sand deposition and improve local soil fertility (Shinohara et al., 2004). Similarly, the obtained findings in our study are expected to support efforts to increase C sequestration and promote N availability in the coastal forest ecosystems of Japan via optimized afforestation with black pine plantation. The present study revealed that SOC and TN stocks as well as their contents were substantially higher in the top soil layer (0–20 cm) compared with the sublayer (20–50 cm), aligning with the results of Selvaraj et al. (2017), who reported higher C accumulation in the topsoil. A previous *meta*-analysis emphasized the significant influence of stand age on SOC stock dynamics, particularly in the 0–20 cm soil depths (Hou et al., 2019).

Plantation age and soil depth had significantly interactive effects on SOC and TN contents, which could be resulted from high plant-derived SOM inputs and strong leaching of soluble organic nutrients from top- to deep soil layers (Fig. 2a, 2b). We applied a double exponential growth model to quantify the trends of C/N with SOC content and the results showed that the C/N increased up to 16 with SOC content up to 6 g kg^{-1} and stabilized with increasing SOC content (Fig. 8), possibly due to N limitation in these sandy soil samples. The increasing coefficients in two stages (2.610 and 0.377, respectively) suggest that soil C/N in early-stage plantations mainly depends on SOC content and shifts to N limitation in late-stage plantations. Statistical analysis underscored that highly significant impacts of plantation age and soil depth on SOC and TN contents and stocks ($P < 0.01$), corroborating previous research findings (Li et al., 2012; Chen et al., 2013; Chen et al., 2018; Guo et al., 2021; Thura et al., 2023) which consistently indicated that soil C and N stocks had similar temporal and spatial patterns with afforestation age and soil depths. It is well-known that SOC and TN are closely coupled with each other and their various transformation processes (i.e. mineralization, humification, and nitrification) are mainly mediated by microorganisms. Notably, plant-derived inputs (i.e. litter fall and root exudates release), and microclimate parameters (i.e. air temperature, humidity, wind speed, and solar radiation) also have profound impacts on SOC and TN stocks along soil profile (Mora et al., 2014; Jia et al., 2019). Therefore, more attention needs to be paid on the underlying stabilization mechanisms of soil C/N and quantification of the correlation of SOC content with C/N under long-term afforestation of black pine in sandy soils by fully considering the interaction of stand ages and density of black pine, and environmental variables (i.e. air temperature, illumination, soil temperature, and moisture movement).

Soil C stock is mainly mediated by the imbalance between SOM input as litter and root exudates, and its output as soil heterotrophic respiration (decomposition) and DOC leaching (Guo et al., 2021), both of which can increase with plantation age. Soil bulk density exhibited significant differences among the former three (5–55 years old) and latter two plantation age (105–210 years old) sites, possibly due to SOM accumulation in 0–20 cm soil depths and significantly negative correlation between bulk density and SOC content (Fig. 1a, Fig. 7). It has been confirmed that bulk density is negatively correlated with SOC content (Zhang et al., 2021). Higher SOM input from the stimulated plant photosynthesis and root rhizodeposition, equivalent to even surpassing its output primarily as respiration, resulted in the net accumulation or maintenance of SOC and TN stocks in the 0–10 cm soil depths after 105-year black pine plantation. These hypotheses need to be further confirmed in the future, particularly in the long-term plantation forests (> 210-year old).

Asymptotic increases in SOC and TN stock with plantation age were evident only in the 0–10 cm soil depths. Surprisingly, a significantly linear correlation between SOC and TN stocks, and black pine plantation age was observed in the 10–50 cm soil depths (Figs. S2, S3). These results suggest that long-term black pine plantation in the Shonai sand dunes not only promotes organic C and TN accumulation in the top soil layer but also facilitates organic matter accumulation from the top layer to the subsoil depth (> 10 cm). The transition of C and N along soil depths may be explained by the stimulated root rhizodeposition with increasing black pine plantation age and rapid soluble OC and N leaching across the 0–50 cm soil depths (Fig. 5a–d). Our results align with those of Guo et al. (2021), who conducted a systematic analysis demonstrating that forest age significantly influences SOC and TN stocks

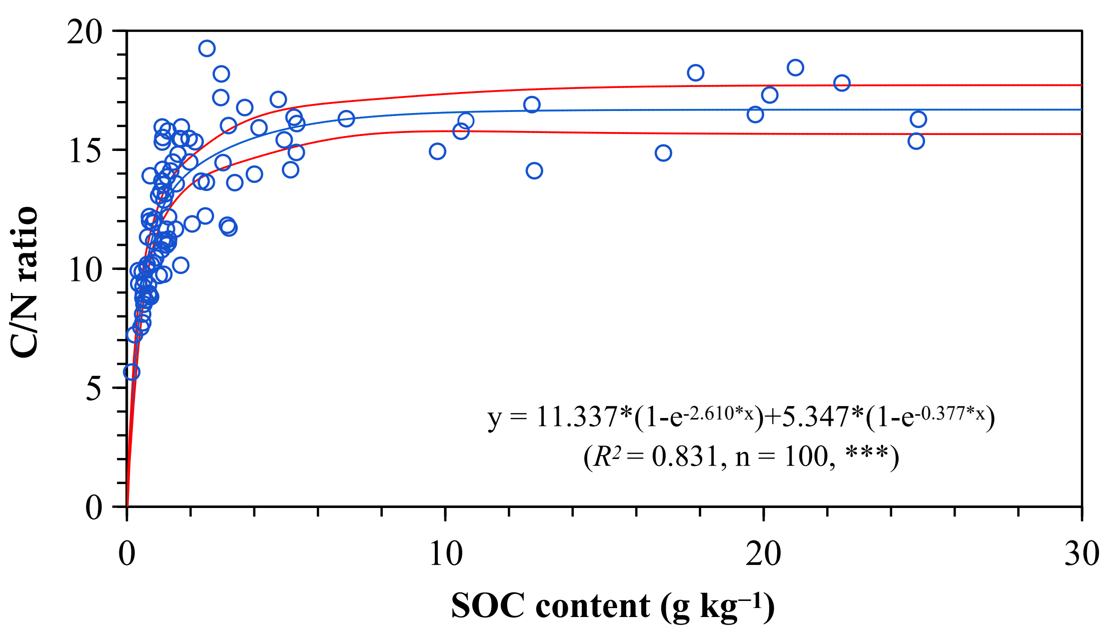

Fig. 8. Trend of C/N ratio with SOC content in the 0–50 cm soil depths and five average plantation age gradients of black pine forest from 5 to 210 years. ***, $P < 0.001$.

in the 0–100 cm soil depth range.

Specifically, afforestation for < 20 years leads to accumulation of SOC and TN stocks only at the soil surface (0–20 cm), whereas afforestation for >20 years results in accumulation of SOC and TN stocks to a soil depth of 100 cm. Considering the entire 0–50 cm soil depths, we found that SOC and TN stocks were 5.59–44.88 t C ha^{-1}, and 0.55–2.83 t N ha^{-1}, respectively, both increasing asymptotically following plantation after 105 years (Fig. 9a, 9b). Similarly asymptotic relationship between SOC stock and forest stand age in mangroves (7–60 years old) was also observed by Thura et al. (2023). Our results indicate that black pine transplantation can substantially facilitate SOC and TN stocks accumulation in the 0–50 cm soil depths over 210 years after afforestation. Moreover, our study provides key data on the effectiveness of black pine afforestation in C and N sequestration to improve the fertility of sandy soils in the Shonai sand dunes for regional sustainable development. Notably, we mainly focus on SOC and TN stocks in 0–50 cm soil depth under five plantation ages of black pine, the rates and amounts of C and N accumulation are unavailable to quantify in this study. Therefore, it is necessary to overall evaluate the specific responses of both annual C and N sequestration and loss (decomposition and leaching) in each soil depth to long-term afforestation of black pine in the Shonai sand dunes.

4.3. Effects of plantation age of black pine on soluble C and N in soil depth

The distinct changes in concentration of four soluble organic C and N compounds (CWEOC, CWEON, HWEOC, and HWEON) between the 0–10 cm and 10–20 cm soil depths could be attributed to the similar trends as those of SOC and TN contents with soil depth and plantation age (Fig. 2a–c, Fig. 5a–d, Fig. 7). It has been widely evidenced that labile C and N pools (i.e. DOC and DON) decrease with soil layers and have highly positive correlation with SOC and TN contents (Zhang et al., 2006; Zhang et al., 2019). The 210-year plantation age site exhibited the highest CWEOC, HWEOC and HWEON concentrations in the 20–40 cm soil depth (Fig. 5). These findings suggest that long-term plantation of black pine can facilitate labile SOM accumulation. Notably, soil erosion driven by heavy precipitation can also contribute to rapid soluble SOC leaching along soil depths by increasing soil water infiltration. Importantly, soil inorganic N and DOC at different soil depths were not determined in this study; thus, future research should focus on the leaching processes of labile nutrients and microorganism-mediated decomposition of labile C and N in soil depths under long-term black pine plantation. Additionally, the present study primarily focuses on the feedbacks of water extractable organic C and N to five plantation ages of black pine along soil depths. Given the majority of SOC, more attention needs to be paid to the effects of afforestation age of black pine on the changes in quality and quantity of stable organic C in soil profile.

5. Conclusions and future perspectives

In this study, black pine plantation age significantly influenced soil bulk density and EC values in 0–30 cm depths, as well as soil pH values, SOC and TN contents in the 0–50 cm depths of sandy soils in the Shonai sand dunes. Moreover, over the past two centuries, SOC and TN stocks in the 0–50 cm soil depth have exhibited an asymptotic increase with black pine forest plantation age in the Shonai sand dunes. The C/N ratio increased from 7.8 to 16.0 with the rise in SOC content up to 6 g kg^{-1}, stabilizing thereafter regardless of further increase in SOC content (>6 g kg^{-1}). The results suggested that long-term afforestation with black pine plantation can facilitate C sequestration and N retention, thus improving soil fertility in the Shonai sand dunes of Japan, especially in the top layer (0–10 cm). Given our emphasis on SOC and TN stocks, future investigations should explore the underlying mediating mechanisms, possibly including annual litter input, root biomass, and C accumulation in subsoil layer (below 20 cm), characterizing the long-term artificial afforestation of black pine and its impact on SOC stock and N availability in the 0–100 cm soil depth of the Shonai sand dunes, as a representative cold coastal region in northeastern Japan. Additionally, the overall effects of vegetable properties (i.e. stand canopy and density of black pine), climatic factors (i.e. air temperature, solar radiation, precipitation, and wind movement), and human activities (i.e. urban expansion and forest fires) on soil basic physicochemical properties (i.e. pH, EC, exchangeable base saturation, porosity, and contents and forms of available nutrient), SOC and TN stocks in 0–50 cm soil depths are needed to be highlighted in future research. Overall, this study offers new information and scientific guidance to enhance SOC stocks and improve soil fertility by optimizing afforestation management in sandy coastal regions of Japan with low SOM content and poor soil structure.

CRediT authorship contribution statement

Shuirong Tang: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Xingkai Xu:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Yanzheng Wu:** Methodology, Investigation, Formal analysis. **Lei Meng:** Methodology, Conceptualization. **Keitaro Tawaraya:** Methodology, Conceptualization. **Weiguo Cheng:** Writing – review & editing, Validation, Supervision, Resources, Investigation, Formal analysis.

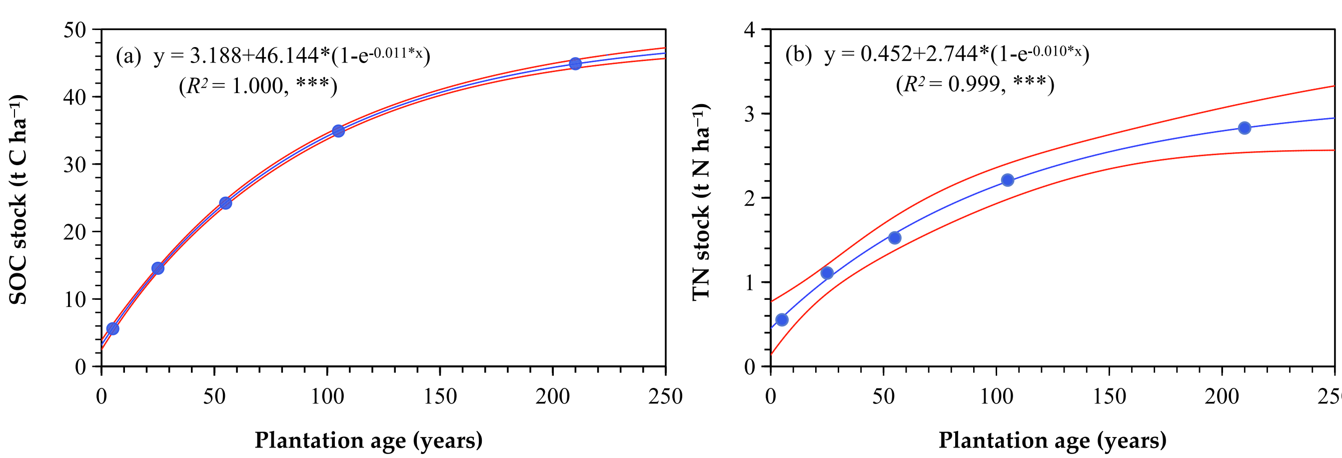

Fig. 9. Trends of SOC (a) and TN (b) stock in the 0–50 cm soil depths under five average plantation ages of black pine forest from 5 to 210 years in the Shonai sand dunes. Blue line represents the exponential growth model, whereas red lines indicate the upper and lower bounds of the 95 % confidence interval. ***, $P < 0.001$.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We are grateful to Mr. Kanichi Umetsu, Director of Forest Creation and Promotion Office, Forest Maintenance Division in Shonai Branch, Yamagata Prefecture for providing the information and guiding us to collect soil samples for this study. We are also thankful to Shouhei Sato, Yuka Okamoto, Kasumi Nakagawa, Tsubasa Horinouchi, Kazune Toita, Katsuya Kasahara, the students from the lab of Plant Nutrition and Soil Science, Faculty of Agriculture, Yamagata University for soil sampling and measurement, and Erpeng Feng in Henan Agricultural University for the assistance in redundancy analysis. The manuscript was financially supported by the Grant for Environmental Research Projects of Sumitomo Foundation, Japan (No. 173275), the Japan Society for the Promotion of Science (JSPS, No. P22398), State key Laboratory of Atmospheric Environment and Extreme Meteorology, Chinese Academy of Science, China (No. LAPC-KF-2023-02), and "111" Project (No. D20024).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2024.108697.

Data availability

The authors do not have permission to share data.

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