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Biomass Accumulation and Carbon Sequestration in an Age-Sequence of Mongolian Pine Plantations in Horqin Sandy Land, China

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Abstract: The Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) was first introduced to the southeastern Horqin sandy land in the mid-1950s. Since then, it has been widely planted and has become the most important conifer species in Northern China, providing significant ecological, economic and social benefits. However, its function in sequestering carbon at different developmental stages has been little studied. In this study, twenty plots inventory and destructive sampling of eight trees were conducted in 12-, 19-, 34-, 48- and 58-year-old Mongolian pine stands of China. Allometric biomass equations (ABEs) for tree components were established and used to determine the magnitude and distribution of tree biomass and carbon density. The carbon density of the understory, forest floor and soil was also determined. The ABEs with age as the second variable could simply and accurately determine the biomass of plantation tree branches, foliage and fruit, which were considerably influenced by age. With increasing stand age, the proportion of stem biomass to total tree biomass increased from 22.2% in the 12-year-old stand to 54.2% in the 58-year-old stand, and the proportion of understory biomass to total ecosystem biomass decreased, with values of 7.5%, 4.6%, 4.4%, 4.1% and 3.0% in the five stands. The biomass of the forest floor was 0.00, 1.12, 2.04, 6.69 and 3.65 Mg ha^{-1} in the five stands. The ecosystem carbon density was 40.2, 73.4, 92.9, 89.9 and 87.3 Mg ha^{-1} in the 12-, 19-, 34-, 48-, and 58-year-old stands, in which soil carbon density accounted for the largest proportion, with values of 67.4%, 76.8%, 73.2%, 63.4%, and 57.7% respectively. The Mongolian pine had the potential for carbon sequestration during its development, especially in the early stages, however, in the later growth stage, the ecosystem carbon density decreased slightly.

Keywords: Mongolian pine; age-sequence; Biomass accumulation; carbon sequestration; soil carbon density; plantation ecosystem

1. Introduction

Under the influence of anthropogenic activities and climate change, the concentration of greenhouse gases such as carbon dioxide (CO_2), methane, and nitrogen oxides in the atmosphere has increased and brought about a series of environmental problems. The global atmospheric CO_2 concentration reached 391 ppm in 2011, 40% higher than the preindustrial level [1]. Forests, as the largest carbon reservoir in terrestrial ecosystems, play an important role in mitigating elevated atmospheric CO_2 concentrations and preventing global warming [2,3]. Forests cover 30.6% of the world's land area, and the annual net carbon sequestration rate from 1990 to 2007 was 2.4 ± 0.4 Pg, which is equivalent to one third of the fossil fuel carbon emissions in 2009 [4,5]. As an important type of forest, planted forests have the dual mission of timber production and ecological restoration, accounting for 7% of global forest area and having an important impact on the global carbon cycle [4]. China has the largest forest plantation area in the world, and the area of planted forests in China has reached 69.33×10^6 ha, occupying 36% of the total forest area of China [6]. Since the late 1970s, China's government has launched a series of national forestry projects, such as the Three North Shelterbelt Project, the Grain for Green Project, the Yangzi River Basin Shelterbelt Project, and the Beijing-Tianjin Sandstorm Source Control Project. In this context, China's desertification and sandification areas have been continuously reduced for three consecutive monitoring cycles since 2004, and 38% of governable sandy land had been effectively treated by 2014 [7]. In addition, China's planted forests play an important role in carbon sequestration and climate regulation. The total carbon storage of planted forests in China was 0.77 Pg in 1999–2003, 3.08 times higher than in the early 1970s [8]. With the growth of more plantations from young to mature and the continuous implementation of afforestation and reforestation projects, planted forests in China will have a greater carbon sink function and play an increasingly important role in changing the carbon cycle and regulating climate in the future [8,9].

When estimating forest carbon storage at a regional or national scale, forest biomass is usually obtained by multiplying timber volume by a biomass expansion factor (BEF) for specific tree species [10]. There are considerable uncertainties in using the above method to evaluate the biomass of planted forests. Young trees that are not merchantable are omitted in forest resource inventories; in addition, the BEF is not constant and varies depending on forest type, growth condition and phase of stand development [10–12]. At the tree or plot scale, the allometric biomass equation (ABE) established by destructive sampling is often used to calculate the biomass of the whole tree or of tree components [13–16]. The accuracy of the ABE method is relatively high, but it is not suitable for large-scale biomass assessment due to difficulties in obtaining parameters such as diameter and/or height [11]. In recent years, technologies for obtaining airborne data, such as airborne laser scanning (ALS), which can obtain species composition, stand height and density, have developed rapidly, making it possible to obtain more forest stand parameters [17]. The fusion of ALS technology and older methods (BEF and ABE) makes it possible to accurately estimate the biomass of young forests on a large scale and further improve the accuracy of forest carbon assessment [11].

Field investigations on the tree or stand level provide basic data to establish ABEs or determine BEF, which are often necessary for large-scale carbon estimation. More importantly, studies on the biomass and carbon accumulation, distribution, and carbon sequestration rate at different developmental stages of planted forests are of great significance to carbon sink prediction and the management of planted forests [14,18,19]. Stand age, as a critical factor affecting the above processes, has been considered in the study of carbon reservoirs in plantations. In most cases, the growth of a planted forest is an incremental process of biomass and carbon stock accumulation, with a higher accumulation rate in early stages [20,21]. Age also plays an important role in the distribution of ecosystem biomass and carbon. For example, the proportion of stem biomass to aboveground or total tree biomass was reported to increase with increasing stand age. In addition, age-specific equations are strongly recommended for determining the biomass of tree branches and foliage because the biomass of tree crown parts could be heavily influenced by age [13,14,22]. For changes in the soil carbon stock with age, different studies have shown that soil carbon stocks are age-independent [20,23], increase with age increment [14,22] or show an initial decline followed by an increase [21,24]. One possible explanation for this inconsistency is that, in addition to stand age, many other factors influence soil carbon, such as climate, soil properties, forest type and previous land use.

Compared with the aboveground biomass of trees, tree root biomass is more difficult to obtain, thus, it is commonly estimated from a standard root to shoot biomass ratio. For example, the IPCC assumes that, for a coniferous species, root biomass is equal to 20% of the aboveground biomass [25]. However, in the lifespan of a forest stand, the proportion of root biomass is not constant and varies during stand development. The proportion of root biomass to total tree biomass was 24%, 19%, 14% and 18% in 2-, 15-, 30-, and 65-year-old white pines, respectively [13]. Root to shoot biomass ratios ranging from 0.20 to 0.36 were reported for 8-, 19-, 30-, 35-, and 51-year-old Korean pines [26]. Due to the change in the root-to-shoot ratio with age and a relatively large proportion of root biomass, tree roots are a nonnegligible part of the carbon reservoir in planted forests. Apart from overstory trees and the soil, the understory layer and the forest floor are also potential carbon pools. Because of the more intense competition for light and nutrients with increasing age, the carbon storage of the understory declined in many previous studies [14,27]. Compared with the understory, the carbon stored in the forest floor accounts for a larger proportion of ecosystem carbon, sometimes even greater than that of tree roots [14]. The forest floor carbon proportion values were 9.4% and 11.4% for 15-year-old white pine and 25-year-old Mongolian pine stands, respectively [23,28]. In addition to the carbon stock in the aboveground tree and soil, the carbon of the tree roots, understory and forest floor accounts for a large proportion of total carbon, especially in planted forests. Because of the lack of information about the above ecosystem components in forest inventories, these three components are often neglected in large-scale carbon assessment. However, it is necessary to accurately estimate the magnitude and distribution of the above ecosystem components in stands of various ages to improve the accuracy of the estimation of carbon stock in plantation ecosystems.

Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) is a geographical variety of Scots pine (*Pinus sylvestris* L.) and is naturally distributed in the Daxinganling mountain range and Honghuaerji forest of the Hulunbuir sandy plains of China and in parts of Russia and Mongolia [29,30]. Due to its cold and drought resistance, it has become one of the most important tree species for reforestation in Northern China, with more than 3.0×10^5 ha on sandy land in Northern China planted in Mongolian pine [31]. In recent decades, a huge number of Mongolian pines have been planted in the Three-North (northeast, north, northwest) regions of China and have played a major role in timber production, the establishment of windbreaks, sand fixation and conservation of soil and water [32]. However, since the early 1990s, the first introduced Mongolian pine plantations located in Southeastern Horqin sandy land began to decline due to dieback, the absence of natural regeneration, low growth rates and mortality [33]. In view of this decline, a large number of studies have been conducted from many perspectives, including water use strategy, decreasing groundwater, hydraulic architecture, and differences in plant nutrients and soil microbes among origin regions [32,34–36]. Studies on the accumulation and distribution of ecosystem biomass and carbon in Mongolian pine plantations during different growth stages are relatively lacking. The objectives of this study were (1) to establish the ABEs for Mongolian pine and its individual components with consideration of stand age; (2) to determine the magnitude and distribution of tree and ecosystem biomass in relation to stand age; and (3) to estimate the allocation of the carbon stock of the Mongolian pine ecosystem with increasing stand age.

2. Materials and Methods

2.1. Site Description

This study was conducted at the Experimental Base of Liaoning Institute of Sand-fixation and Afforestation (42°42′ N, 122°29′ E, 225 m above sea level), which is located in the Zhanggutai region, Liaoning Province, southeastern Horqin sandy region (Figure 1). This area experiences a typical temperate continental monsoon climate. The mean annual temperature is 7.7 °C (for 1954–2010), and the mean annual precipitation is 474 mm, of which 67% falls during June–August [34]. The annual evaporation is approximately three times the annual precipitation, and the annual frost-free period is 150–160 days. The geomorphology is characterized by staggered distributions between oval or round sand dunes and low-lying land caused by wind erosion. The main soil type is aeolian sandy soil, accounting for 89.4% of soil, and other soil types include meadow soil, peat soil, and paddy soil. Since 1953, planting experiments with *Pinus sylvestris* var. *mongolica* were conducted in the Zhanggutai region. The planting experiments succeeded in 1955, and China's first sand-fixation Mongolian pine plantation was established. There are a large number of Mongolian pine plantation stands with different ages and densities. Other woody plants in this region include *Pinus tabuliformis* Carr., *Populus* L. and *Ulmus* *pumila* L. The main understory herbaceous plants include *Digitaria sanguinalis* (L.) Scop., *Setaria viridis* (L.) Beauv., *Chloris virgate* Sw., *Cleistogenes squarrosa* (Trin.) Keng, *Eragrostis pilosa* (L.) Beauv., *Geranium wilfordii* Maxim., *Elymus dahuricus* Turcz., *Euphorbia pekinensis* Rupr., *Portulaca oleracea* L., and *Axyris amaranthoides* L.

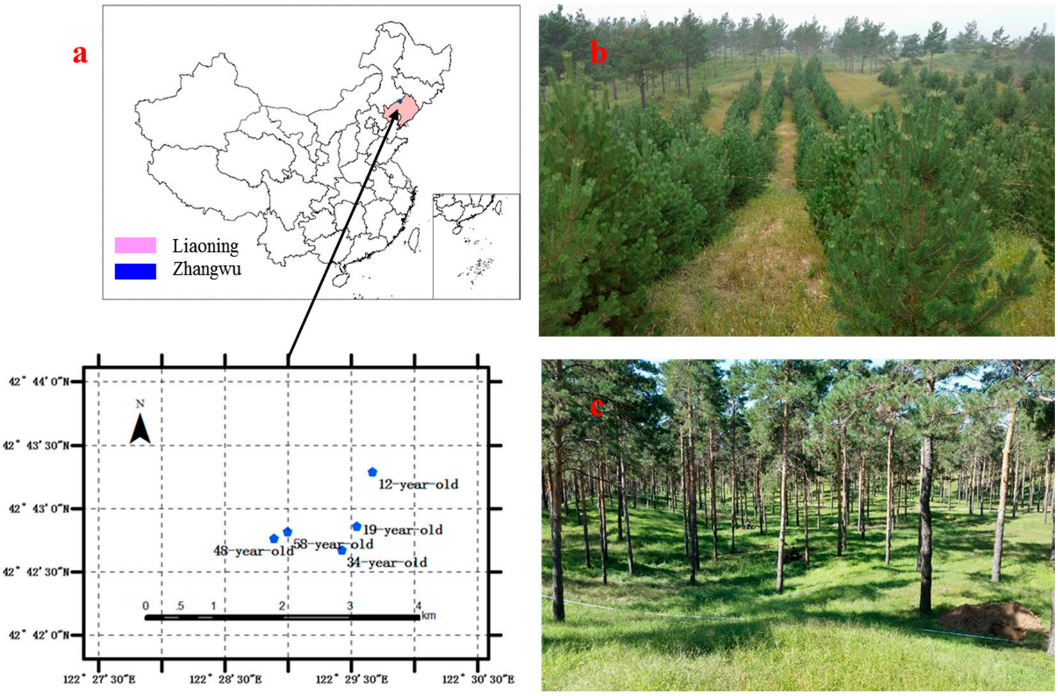

Figure 1. Location of the five Mongolian pine stands (**a**) and pictures of the 12-year-old (**b**) and 58-year-old (**c**) Mongolian pine stands.

In this study, an age sequence of 12-, 19-, 34-, 48-, and 58-year-old Mongolian pine stands was selected in the Zhanggutai region. Stands were not replicated in the age sequence because it is difficult to locate replicated stands of the same age, especially for the older stands (i.e., 48- and 58-year-old stands). The distances between the 12-, 19-, 34-, 48-, and 58-year-old stands were within 2 km (Figure 1). In the 12-year-old stand, the texture of the surface soil (0–10 cm) was sandy soil with a sand content of 86.8%. For the 19-, 34-, 48-, and 58-year-old stands, the textures of surface soil were loamy sand or sandy loam soil, with sand content of 68.2%, 68.5%, 68.9%, and 73.1%.

2.2. Forest Inventory and Measurements

From August to September 2017, four 25 × 25-m plots were selected in each stand. Within each plot, tree position, tree height and tree diameter at breast height (D) were recorded for every tree (Table 1). There were almost no other woody plants or shrubs in those stands.

To determine the biomass of understory plants and forest floor, three quadrats (1 m × 1 m) were established within each age-sequence stand. In each quadrat, the coverage, plant type, quantity and height were recorded. In half of the quadrat (0.5 m^2), the aboveground part of understory plants was destructively sampled by clipping from the bottom, and the forest floor (containing sound, intermediate and rotten woody debris) was also collected [26]. Fresh weights of the aboveground biomass of understory plants and forest floor were measured in situ by electronic balance, and subsamples of each component were dried at 65 °C to determine the ratio of fresh weight to dry biomass [14]. Then, the subsamples were mechanically ground to pass through a 0.5-mm mesh and used for carbon concentration analysis. In nine out of the 15 quadrats, roots of the understory plants were also sampled, cleaned of soil, and weighed. The ratio of belowground biomass to aboveground biomass was determined and used to calculate belowground biomass of understory plants.

Table 1. Stand characteristics (the mean value with the standard error) of the 12-, 19-, 34-, 48-, and 58-year-old Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) plantations.

Stand Age (Years)	Location	Altitude (m)	Number of Trees	Mean Height (m)	Range (m)	Mean D (cm)	Range (cm)	Soil Bulk Density (g cm^{-3})					
								0–10 cm	10–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm
12	42.7215° N, 122.4946° E	231.4	324	2.22	0.70–3.50	5.9	4.33–7.09	1.56 ± 0.02	1.60 ± 0.04	1.59 ± 0.03	1.60 ± 0.02	1.62 ± 0.02	1.61 ± 0.02
19	42.7143° N, 122.4925° E	230.4	168	4.15	1.50–7.30	9.95	4.30–14.20	1.61 ± 0.02	1.64 ± 0.04	1.63 ± 0.03	1.61 ± 0.01	1.58 ± 0.02	1.56 ± 0.04
34	42.7112° N, 122.4905° E	235.4	91	8.06	6.00–10.50	17.3	10.30–26.00	1.58 ± 0.12	1.59 ± 0.02	1.56 ± 0.02	1.56 ± 0.01	1.56 ± 0.01	1.59 ± 0.02
48	42.7127° N, 122.4816° E	247.5	61	11.08	8.00–12.70	23.68	13.00–31.50	1.53 ± 0.04	1.59 ± 0.01	1.55 ± 0.00	1.58 ± 0.02	1.61 ± 0.07	1.63 ± 0.07
58	42.7136° N, 122.4834° E	225.5	77	12.2	10.50–15.60	23.56	15.30–35.30	1.62 ± 0.05	1.57 ± 0.06	1.58 ± 0.01	1.57 ± 0.05	1.57 ± 0.03	1.56 ± 0.02

Notes: D, diameter at breast height.

2.3. Soil Measurements and Sampling

In addition to each quadrat, a soil profile with a depth of 100 cm was dug, for a total of 15 profiles in five stands. In each of the soil profiles, the soil bulk density in the layers of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm was measured. In each layer, three soil cores were sampled by a cutting ring with a volume of 100 cm^3 and were oven-dried at 105 °C to calculate the soil bulk density (the ratio of dry mass to sample volume). Another set of soil samples was collected, air-dried, and used to analyze soil organic carbon (SOC). Considering the homogeneous soil within the stand, soil samples within the same layer were pooled together in each stand and ground to pass through a 0.25-mm sieve.

2.4. Destructive Tree Sampling

In late April 2018, one standard tree was selected and logged in each stand for biomass determination using the segmenting method. The number of logged trees was low due to forestry administrative department imitations and the scarcity of Mongolian pines older than 50 years old. Another three trees logged in nearby stands were also used to establish the allometric equation for Mongolian pine; those trees were 34, 36, and 40 years old. Before cutting the tree, the tree DBH and crown in four directions were measured, and the north direction of the tree was chalked. The tree was cut by a chainsaw from the bottom, with the north side facing up. The crown was divided into several sections at 1-m intervals. In each section, the branches were clipped from the tree and divided into branch, foliage, and fruit. The stem of each tree was divided into 1-m-long sections and divided into wood and bark. The roots of each sampled tree were excavated manually at approximately 1 m depth within a radius of 1 m from the tree center [21] and sorted into three size classes: pile and coarse roots (diameter > 2.0 cm), medium roots (diameter between 0.5 and 2.0 cm), and fine roots (diameter < 0.5 cm) [13]. Standard trees were divided into six components: stem wood, stem bark, branch, foliage, fruit, and root. The fresh weights of all components were measured in situ, and samples of every component in each standard tree were collected and oven-dried at 65 °C for moisture content and carbon concentration analysis. The carbon concentrations of the components from the tree, ground vegetation, forest floor and SOC were determined by the potassium dichromate oxidation method [37].

2.5. Allometric Biomass Equations for Tree Components

The allometric equations used to determine the biomass of tree components take the form of a power function with diameter at breast height (D) as the variable:

$$y = a(D)^b \tag{1}$$

where y is the dry weight of tree components (kg), a and b are parameters. Limited by the numbers of logged trees (one for each stand), it is impossible to establish stand-specific ABE; therefore, if Equation (1) does not fit well for some tree components, tree age (A) was considered as another variable to show the possible effects of age:

$$y = a(D)^b(A)^c \tag{2}$$

where c is another parameter.

2.6. Biomass and Carbon Density

The equation for calculating biomass density (B, Mg ha^{-1}) of tree components is:

$$B = \frac{\sum_{i=1}^{n} y_i}{62.5} \tag{3}$$

where y is the dry weight (kg) determined by Equation (1) or Equation (2), n is number of trees in the plot. The plant biomass carbon density was calculated as follows:

$$C_p = B \times C_f \tag{4}$$

where C_p is vegetation carbon density (Mg ha^{-1}) and C_f is the plant biomass carbon concentration (%).

Soil carbon density (C_s, Mg ha^{-1}) was calculated by [14]:

$$C_s = \sum_{i=1}^{n} C_i \times \rho_i \times h_i \times (1 - \theta_i) \times 0.1 \tag{5}$$

where C_i is the carbon concentration (g kg^{-1}), ρ_i is the bulk density (g cm^{-3}), h_i is the thickness of the soil horizon (cm), θ_i is the volumetric percentage of the coarse fraction (>2 mm), and n is the soil layer.

2.7. Statistical Analysis

During analyzing the difference significance of the biomass of ecosystem components among the five stands of different ages, multiple comparisons following Duncan test and Tamhane test in one-way analysis of variance (ANOVA) were used in the case of homogeneity and inhomogeneity of variance respectively.

Statistical analysis, including mean value, standard error, ANOVA and regression analysis were completed by the common software package IBM SPSS Statistics 22 (IBM, Armonk, NY, USA).

3. Results

3.1. Tree Biomass and Its Distribution

The allometric equation in the form of a power function is applicable to determine the biomass of individual tree components (Table 2). Compared to ABEs with the D as a single variable, ABEs with two variables (i.e., D and A) had a better fitting degree, and the R^2 values of ABEs for all components increased. For total tree, aboveground, stem, stem wood, stem bark, and root biomass, ABEs with a single variable (i.e., D) can give accurate results, and the R^2 values of the equations were all greater than 0.97. Although R^2 values increased slightly after considering the age effect in ABEs, for the sake of simplicity and accuracy, equations with D as a single variable were recommended for biomass determination of the above components and were used in the subsequent analysis. For the biomass of branch, foliage and fruit, the results of ABEs with a single variable were poor, with R^2 values of 0.91, 0.83, and 0.59, respectively; the R^2 values increased to 0.95, 0.91, and 0.92 after considering the age effect, indicating that the biomass of these components was significantly affected by age. The bivariate ABEs with D and A were used to determine branch, foliage and fruit biomass in the following analysis.

Table 2. Allometric biomass equations for individual components of Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.).

Biomass of Tree Components (kg)	Parameters in Equation (1)				Parameters in Equation (2)				
	a	*b*	R^2	Significance	*a*	*b*	*c*	R^2	Significance
Total tree	0.630	1.852	0.975	0.000 **	1.515	2.644	−0.902	0.987	0.000 **
Aboveground	0.373	1.922	0.974	0.000 **	0.954	2.769	−0.965	0.986	0.000 **
Tree stem	0.052	2.415	0.992	0.000 **	0.065	2.608	−0.220	0.993	0.000 **
Stem wood	0.035	2.515	0.991	0.000 **	0.042	2.683	−0.192	0.991	0.000 **
Stem bark	0.033	1.830	0.993	0.000 **	0.035	1.892	−0.071	0.993	0.000 **
Branch	0.192	1.671	0.913	0.000 **	0.781	2.939	−1.444	0.948	0.001 **
Foliage	0.610	1.036	0.835	0.002 **	2.265	2.220	−1.348	0.907	0.003 **
Fruit	3.616×10^{-7}	4.187	0.595	0.045 *	4.836×10^{-12}	0.139	6.412	0.920	0.011 *
Root	0.286	1.676	0.977	0.000 **	0.585	2.323	−0.737	0.987	0.000 **

Note: the expressions for equations 1 and 2 are $y = a(x_1)^b$ and $y = a(x_1)^b(x_2)^c$, respectively, where y is the dry weight of tree components, x_1 is the diameter at breast height (cm), x_2 is the tree age (years); * and ** indicate significance less than 0.05 and 0.01, respectively.

Using the ABEs established in Table 2, the biomass of individual tree components was determined in the 12-, 19-, 34-, 48-, and 58-year-old Mongolian pine stands (Table 3). With increasing stand age, the biomass of most tree components increased, including total tree, aboveground, stem, stem wood, stem bark, fruit, and root biomass. The total tree, aboveground and root biomass was 23.10, 15.77, and 7.32 Mg ha^{-1} in the 12-year-old stand and increased to 61.49, 44.44, and 17.05 Mg ha^{-1} in the 58-year-old stand. Branch biomass increased gradually with increasing stand age and decreased slightly in later stages. Branch biomass increased from 5.28 Mg ha^{-1} in the 12-year-old stand to 7.66 and 7.43 Mg ha^{-1} in the 48- and 58-year-old stands. In contrast to other components, foliage biomass decreased with age, with values of 5.30, 4.71, 3.84, 3.26, and 3.19 Mg ha^{-1} in the 12-, 19-, 34-, 48-, and 58-year-old stands.

The biomass distribution varied in the five stands of different ages (Figure 2a). The biomass distribution pattern for tree components was root > foliage > branch > stem > fruit for the 12-year-old stand and stem > root > branch > foliage > fruit for the other four stands. For all stands, the proportion of fruit biomass was lowest, less than 1%. Except for the 12-year-old stand, the stem had the largest proportion of biomass among all components. With increasing stand age, the proportion of stem biomass increased gradually with values of 22.2%, 31.1%, 43.9%, 51.7%, and 54.2% in the 12-, 19-, 34-, 48-, and 58-year-old stands. With increasing age, the proportion of branch biomass and foliage biomass decreased from 22.9% and 23.3% in the 12-year-old stand to 12.1% and 5.2% in the 58-year-old stand. The contribution of root biomass to total tree biomass was 31.7%, 30.5%, 28.7%, 26.6%, and 27.7% in the five stands, showing a decreasing trend with the exception of the 58-year-old stand.

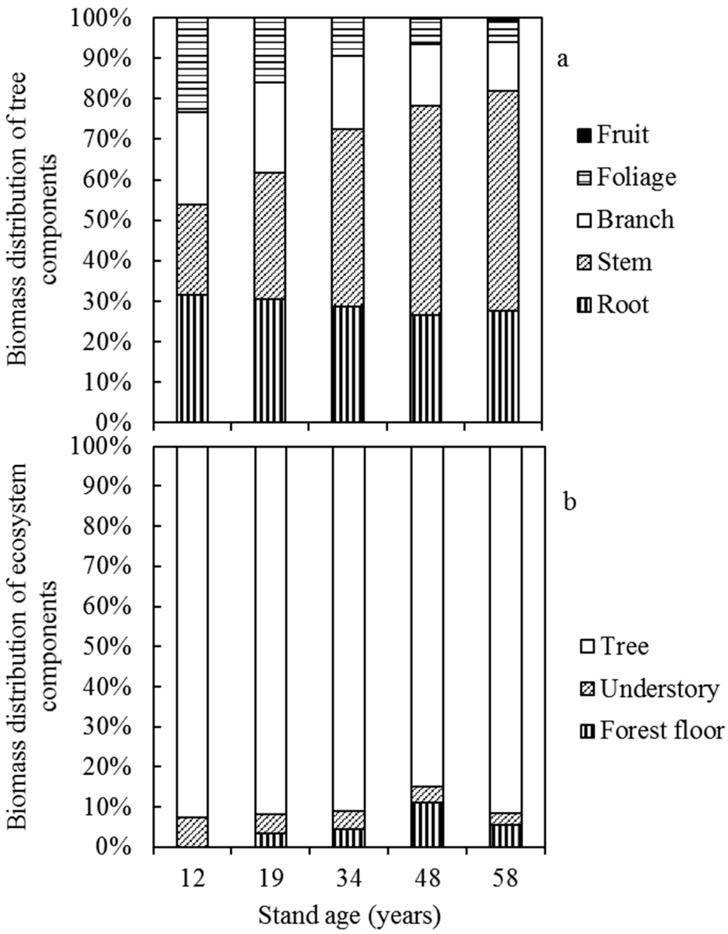

Figure 2. Biomass percentage distribution of tree individual components (**a**) and ecosystem components (**b**) in the 12-, 19-, 34-, 48-, and 58-year-old Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) plantations.

Table 3. Biomass of the ecosystem components (the mean value with the standard error followed by different uppercase letters are significantly different at $p < 0.05$, Mg ha^{-1}) (including tree components, understory and forest floor) in the 12-, 19-, 34-, 48-, and 58-year-old Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) stands.

Ecosystem Components	Stand Age (Years)				
	12	19	34	48	58
Total Tree	23.10 ± 2.83 B	29.32 ± 5.95 AB	41.37 ± 5.28 A	50.88 ± 8.56 A	61.49 ± 20.66 AB
Tree aboveground	15.77 ± 1.99 C	20.39 ± 4.06 BC	29.51 ± 3.18 AB	37.35 ± 5.78 A	44.44 ± 14.60 ABC
Tree stem	5.12 ± 0.64 B	9.13 ± 1.83 B	18.18 ± 2.10 A	26.32 ± 4.19 A	33.35 ± 11.00 AB
Tree stem wood	4.01 ± 0.51 B	7.66 ± 1.53 B	16.05 ± 1.75 A	23.77 ± 3.69 A	30.14 ± 9.88 AB
Tree stem bark	1.11 ± 0.13 A	1.47 ± 0.31 A	2.12 ± 0.36 A	2.54 ± 0.50 A	3.21 ± 1.12 A
Tree branch	5.28 ± 0.70 B	6.54 ± 1.27 AB	7.48 ± 0.61 A	7.66 ± 1.02 A	7.43 ± 2.34 A
Tree foliage	5.37 ± 0.66 A	4.71 ± 0.96 AB	3.84 ± 0.51 BC	3.26 ± 0.56 C	3.19 ± 1.08 C
Tree fruit	0.00 ± 0.00 B	0.00 ± 0.00 A	0.02 ± 0.01 AB	0.11 ± 0.04 AB	0.47 ± 0.19 AB
Tree root	7.32 ± 0.84 A	8.93 ± 1.90 A	11.86 ± 2.17 A	13.53 ± 2.82 A	17.05 ± 6.07 A
Total Understory	1.87 ± 0.74 A	1.47 ± 0.32 A	2.02 ± 0.62 A	2.45 ± 1.83 A	1.99 ± 0.50 A
Understory aboveground	1.32 ± 0.53 A	0.90 ± 0.20 A	1.24 ± 0.38 A	1.50 ± 1.12 A	1.22 ± 0.30 A
Understory belowground	0.54 ± 0.22 A	0.57 ± 0.12 A	0.78 ± 0.24 A	0.95 ± 0.71 A	0.77 ± 0.19 A
Forest Floor	0.00 ± 0.00 B	1.12 ± 0.97 AB	2.04 ± 0.64 AB	6.69 ± 4.49 AB	3.65 ± 0.18 A
Total Ecosystem	24.97	31.91	45.43	60.02	67.13

3.2. Biomass of Understory and Forest Floor

In the 12-, 19-, 34-, and 48-year-old pine stands, forest floor biomass increased with increasing stand age, with values of 0.00, 1.12, 2.04, and 6.69 Mg ha^{-1}, respectively. The biomass of the forest floor in the 58-year-old stand was 3.65 Mg ha^{-1}, less than that in the 48-year-old stand. The biomass of the understory did not have an obvious relationship with stand age, with the lowest value (1.47 Mg ha^{-1}) and the highest value (2.45 Mg ha^{-1}) occurring in the 19- and 48-year-old stands, respectively. With increasing stand age, the proportion of forest floor biomass to ecosystem biomass showed an increasing trend with the exception of the 58-year-old stand, and the percentages were 0.0%, 3.5%, 4.5%, 11.1%, and 5.4% in the five stands (Figure 2b). With increasing stand age, the proportion of understory biomass to total ecosystem biomass decreased from 7.5% in the 12-year-old stand to 3.0% in the 58-year-old stand.

3.3. Carbon Concentration

There were significant differences in carbon concentration among different ecosystem components (Table 4). Carbon concentration was highest in the lignified tree components, and the values were 56.23%, 54.50%, and 55.68% in the stem wood, branch and root, respectively, which were significantly ($p < 0.05$) larger than the carbon concentration of the other components with exception of tree foliage. The carbon concentrations of tree foliage and stem bark were 53.98% and 51.53%, respectively, significantly ($p < 0.05$) larger than those of tree fruit, aboveground understory and forest floor. The carbon concentration of belowground understory was lowest with the value of 38.77%, significantly ($p < 0.05$) lower than all other components.

Table 4. Carbon concentration (%) of different ecosystem components in the 12-, 19-, 34-, 48-, and 58-year-old Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) stands.

Ecosystem Components	Stand Age (Years)					Average
	12	19	34	48	58	
Tree stem wood	55.96	56.19	55.42	57.07	56.49	56.23 ± 0.62 A
Tree stem bark	52.31	53.04	49.05	53.28	49.96	51.53 ± 1.91 B
Tree branch	52.55	52.96	56.84	56.01	54.13	54.50 ± 1.88 A
Tree foliage	53.20	51.44	53.74	55.45	56.05	53.98 ± 1.84 AB
Tree fruit			47.81	47.21	49.22	48.08 ± 1.03 C
Tree root	52.65	54.77	57.64	56.04	57.27	55.68 ± 2.03 A
Understory aboveground	44.22	46.37		44.02		44.87 ± 1.30 C
Understory belowground	36.42	38.31		41.57		38.77 ± 2.61 D
Forest floor	41.31	45.79		48.15		45.08 ± 3.48 C

Note: The average data are presented as the mean value with the standard error (SE) followed by uppercase letters indicating the difference significance at $p < 0.05$.

3.4. Soil Carbon Density and Ecosystem Carbon Pools

Figure 3a shows the soil carbon concentration at layers of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm in the 12-, 19-, 34-, 48-, and 58-year-old stands. The carbon concentration of the upper 0–10 cm soil layer was the highest in all five stands, and the values for each stand were 4.4, 6.0, 11.1, 15.2, and 7.2 g kg^{-1}, respectively. The results also showed a decreasing trend of carbon concentration with depth in all five stands. For the 12-, 19-, 34-, and 48-year-old stands, the carbon concentration of the 0–10, 10–20, and 20–40 cm soil layers increased with increasing stand age, indicating an obvious accumulation process of organic carbon in the surface soil layer after afforestation. The soil carbon density observed in the 0–100 cm soil layer was 27.1, 56.4, 68.1, 57.0, and 50.3 Mg ha^{-1} in the 12-, 19-, 34-, 48-, and 58-year-old stands, respectively (Table 5). The carbon density of the 19-year-old stand was much larger than that of the 12-year-old stand, indicating an obvious increase in soil carbon density during these years with an annual accumulation rate of 4.2 Mg C ha^{-1}. The uppermost 40 cm of soil stored a large proportion of carbon, and the soil carbon density in the 0–40 cm soil layer accounted for 60, 47, 53, 72, and 49% of the total carbon density in the 0–100 cm soil layer for the five stands.

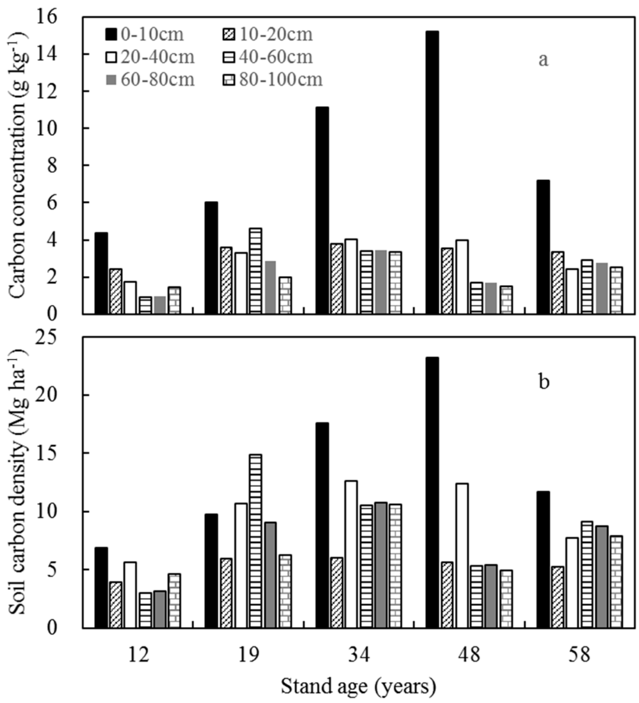

Figure 3. Distribution patterns of the carbon concentration (**a**) and carbon density (**b**) at different soil depths in the 12-, 19-, 34-, 48-, and 58-year-old Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) stands.

The total ecosystem carbon density was 40.2, 73.4, 92.9, 89.9, and 87.2 Mg ha^{-1} in the 12-, 19-, 34-, 48-, and 58-year-old plantations, and displayed a sigmoidal pattern, first rapidly growing and then gradually decreasing (Table 5). The carbon sequestration rates of the ecosystem were 4.7 and 1.3 Mg ha^{-1} year^{-1} during the 12th–19th and 19th–34th years, respectively. In all five pine stands, the proportion of carbon density in the soil was larger than 55%, with specific values of 67.4, 76.8, 73.2, 63.4, and 57.7%, respectively (Table 5). Except for in the 12-year-old stand, the proportion of carbon stored in soil decreased with increasing age and the proportion stored in vegetation increased.

Table 5. Carbon density (Mg C ha^{-1}) and the percentage (%) of ecosystem components (including tree components, understory and forest floor) in the 12-, 19-, 34-, 48-, and 58-year-old Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.) stands.

Ecosystem Components	Stand Age (years)									
	12		19		34		48		58	
	Carbon Density	Percentage	Carbon Density	Percentage	Carbon Density	Percentage	Carbon Density	Percentage	Carbon Density	Percentage
Total Tree	12.31	30.63	15.87	21.61	23.10	24.85	28.66	31.88	34.43	39.47
Tree aboveground	8.46	21.04	10.98	14.95	16.26	17.50	21.07	23.44	24.67	28.27
Tree stem	2.82	7.03	5.08	6.92	9.94	10.69	14.92	16.60	18.63	21.35
Tree stem wood	2.24	5.58	4.30	5.86	8.90	9.57	13.57	15.09	17.02	19.51
Tree stem bark	0.58	1.45	0.78	1.06	1.04	1.12	1.36	1.51	1.60	1.84
Tree branch	2.77	6.90	3.47	4.72	4.25	4.58	4.29	4.77	4.02	4.61
Tree foliage	2.86	7.11	2.42	3.30	2.06	2.22	1.81	2.01	1.79	2.05
Tree fruit	0.00	0.00	0.00	0.00	0.01	0.01	0.05	0.06	0.23	0.26
Tree root	3.86	9.59	4.89	6.66	6.83	7.35	7.58	8.44	9.77	11.19
Total Understory	0.78	1.95	0.64	0.87	0.86	0.92	1.05	1.17	0.85	0.97
Understory aboveground	0.59	1.46	0.42	0.57	0.56	0.60	0.66	0.73	0.55	0.63
Understory belowground	0.20	0.49	0.22	0.30	0.30	0.33	0.39	0.44	0.30	0.34
Forest Floor	0.00	0.00	0.51	0.70	0.92	0.99	3.22	3.58	1.65	1.89
Soil Carbon Stock	27.10	67.42	56.41	76.82	68.06	73.23	56.97	63.37	50.32	57.68
Ecosystem Carbon Stock	40.20	100.00	73.42	100.00	92.93	100.00	89.90	100.00	87.25	100.00

4. Discussion

4.1. Allometric Biomass Equation for Tree Components

The results of this study showed that the ABE with D as the sole variable could accurately determine the stem and root biomass of Mongolian pine at different ages. However, to determine branch, foliage and fruit biomass, the influence of stand age should be considered. This result is consistent with the results of many previous studies. A study of Chinese pine at three different ages found that the ABEs for branch and foliage were age-specific and that stem, root, aboveground and total tree biomass was independent of age [14]. Compared to the ABE with only one variable of D, R^2 values of bivariate ABEs with D and height (or age) were increased for the biomass of branch and foliage of white pine [13]. Previous studies also concluded that better results could be obtained using the variable D^2H or D with age-specific parameters [13,14,38–40]. Compared with the univariate ABE with D, the ABE with height as a second variable could give better results. A reasonable explanation was that the influence of age was taken into account to some extent by considering both the D and height of trees [41].

In general, accurate measurement of tree height is more difficult than D measurement during plot inventory. Planted forests have consistent age that can be easily determined by historical data or tree rings. In this study, we tested age as the second variable of the ABE, and the biomass results of individual components were all improved, especially for branch, foliage and fruit. This study confirmed that the ABEs with D and age instead of height could also accurately determine the biomass of tree components in an age-sequence stand.

4.2. Biomass Distribution

Age is the most important factor affecting the magnitude and distribution of biomass in plantation ecosystems [13,42]. With increasing stand age, the total tree, aboveground, stem and root biomass of Mongolian pine increased, displaying a linear increase in this study (Figure 4). Similar results were reported in previous studies [19,21]. A linear positive correlation between age and total tree, aboveground, stem and root biomass could be extracted for the white pine plantations with ages of 2 to 65 years [13], and the total tree, aboveground and stem biomass increased with age following power functions for Mongolian pine [28]. For Korean pine in Li et al. [26], total tree biomass increased rapidly from the 8th to the 35th year and increased slowly during the 35th to the 51st year, and the relationship between root biomass and age showed a sigmoidal pattern with a decreasing trend of root biomass from the 35th to 51st year. This change pattern after planting could also be found in many previous studies [21,27,42,43]. From the 12- to the 48-year-old stand in this study, the tree branch biomass increased, and there was a slight decline in the 58-year-old stand, which could be described by a polynomial equation (Figure 4). The same pattern was also observed in previous studies [13,26,28]. Tree foliage biomass decreased from the 12th to the 58th year in this study and decreased from the 15th to the 65th year in white pine [13]. However, for Korean pine, foliage biomass increased from the 8th to the 35th year and decreased slightly in the 51st year [26]. These inconsistent relationships between foliage biomass and age might be due to differences in climate, soil condition, tree species and stand structure.

With increasing stand age, the proportion of stem biomass to total tree biomass increased in this study, which was consistent with the results of many previous studies [26]. Stem biomass accounted for a proportion between 22% and 54% in the five stands of this study, which was consistent with the range reported in the literature. The proportion of stem biomass to total tree biomass was in the range of 27% to 67% for the 10-, 18-, 25-, and 30-year-old Mongolian pine [28] and of 27% to 70% for the 2-, 15-, 30-, and 65-year-old white pine [13]. For the proportion of branches, foliage and root biomass with age, there were some inconsistent results. In this study, the proportion of these three components decreased with age. Several papers found that the proportion of branch biomass to total biomass first increased and then decreased with age increment [13,26,28]. The divergence of results may be caused by differences in tree species and ages among these studies and biomass distributions among branch, foliage and root being more susceptible to stand structure and environmental conditions than stem biomass.

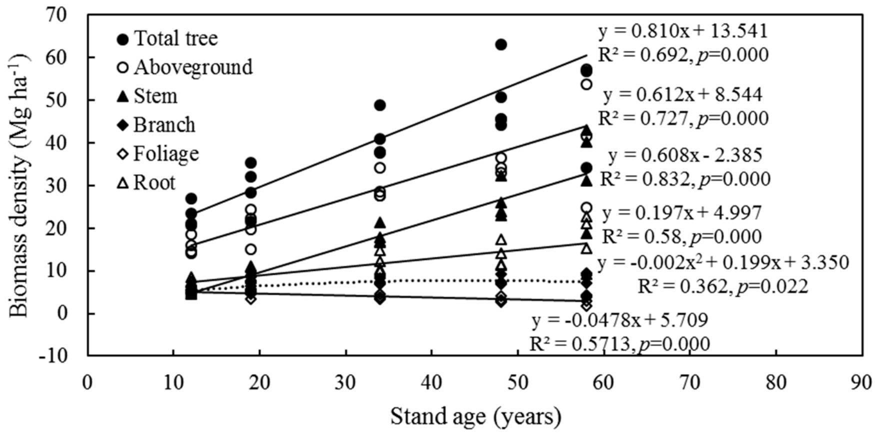

Figure 4. Biomass density of tree components versus stand age of Mongolian pine (*Pinus sylvestris* L. var. *mongolica* Litv.). The solid line and dotted line represent linear regression and polynomial regression, respectively.

Forest floor biomass increased from the 12- to 48-year-old stands and slightly decreased in the 58-year-old stand. The maximum proportion of forest floor biomass to ecosystem biomass was 11% of the 48-year-old stand. Some previous studies also showed similar trends, with forest floor biomass first increasing and then decreasing with stand age [21,26,41]. Other previous studies showed that forest floor biomass continued to increase with age, as in the forest floor biomass in 25-, 65-, and 105-year-old Chinese pine plantations and in Chinese pine plantations with trees at young, middle-age, immature and mature development stages [14,22]. In most previous studies, there was no obvious trend for understory biomass with age, similar to this study [20,22]. Some studies showed that with increasing stand age, understory biomass decreased [14], first increased and then decreased [26], first decreased and then increased [23] or increased only in late stages [21]. These inconsistencies in understory biomass might be caused by the differences in age, structure, climate and soil conditions among these studies.

4.3. Changes in Soil Carbon Density

In the five age-sequence pine stands of this study, the soil carbon concentration was the highest in the surface 0–10 cm soil layer and showed a decreasing trend with increasing depth. Previous studies about soil carbon concentration with depth yielded the same results as our study [14,20,22,26]. Due to the lack of repeated stands of the same age and measurements of carbon concentration, the effect and significance of age on soil carbon density could not be analyzed. However, the mixed soil sample from three sampling sites was used for concentration analysis and calculating soil carbon density, which could represent the overall carbon density of the pine stand at that age.

With increasing stand age, the soil carbon density displayed a sigmoidal pattern, increasing during the 12th to 34th year and slightly decreasing during the 34th to 58th year (Table 5). There were varied results regarding the changes in soil carbon density after afforestation among previous studies in the literature. Some studies reported no significant changes in soil carbon density with increasing stand age [20,23]. Some studies have shown an increasing trend of soil carbon density with increasing age [14,22]. Some studies revealed that there was an initial decrease in soil carbon density after afforestation followed by a gradual increase [21,24,26]. These inconsistent results could be explained by the fact that, in addition to age, many other important factors influence soil carbon density, such as climate, soil properties, forest type and previous land use, all of which may overshadow the effect of stand age [23]. In our study, in which the soil was semifixed sand before plantation, an obviously increasing organic carbon concentration and decreasing sand content (0.05–2 mm) could be observed in the 19-year-old stand compared with the 12-year-old stand, resulting in an accumulative process of soil organic carbon during the first 34 years after planting. For Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) plantations converted from natural broadleaf forest, the soil carbon density decreased with age increment during the first 16 years and remained 30% lower than the soil carbon density of natural forest in the plantation at 88 years old [21]. The above two examples illustrate the different patterns of soil carbon density with age after afforestation affected by previous land use. Nevertheless, soil carbon density accounted for the largest proportion of ecosystem carbon reservoirs, especially the carbon density in the upper 40-cm layer, which had proportions of 60, 47, 53, 73, and 49% of total soil carbon (0–100 cm) in the 12-, 19-, 34-, 48-, and 58-year-old plantations.

4.4. Carbon Density and Distribution for Ecosystem Components

Carbon concentration is a crucial parameter for converting biomass into carbon content or density, which is usually regarded as a constant with a value of 0.5 in carbon reservoir estimation on a regional or national scale [44]. However, to further improve the accuracy of carbon content or density of vegetation biomass, using component-specific carbon concentration values is usually recommended [22]. Among tree components, the carbon concentration values of stem wood, branch and root were highest, with average values of 0.56, 0.55, and 0.56, respectively, in the five age-sequence plantations (Table 4). Foliage had the highest carbon concentration, except for the lignified part, with an average value of 0.54. This order of the magnitude of carbon concentration among tree components are the same as results in Zhao et al. [22]. The magnitude of the carbon concentration of the forest floor depended on the degree of decomposition, in the order of undecomposed > semidecomposed > fully decomposed [22], and the carbon concentration of the forest floor was 0.45 in our study. The carbon concentration values of the ecosystem components ranged from 0.39 to 0.56, which was consistent with the range of carbon concentrations found in pine plantations [14,23,26]. Most related studies concluded that carbon concentration was primarily component-specific and not significantly related to age, thus, a set of component-specific values is enough to accurately determine carbon storage in stands of different ages.

With increasing stand age, total tree, tree aboveground and tree root carbon density increased, which was the same result as in most previous studies on age-sequence stands [14,16,23]. The carbon density of understory vegetation was not significantly related to stand age, which was similar to the results of Zhao et al. [22], and some other studies revealed a decreasing trend with age increment [14,27]. In most stands, the proportion of carbon in the understory was the smallest, with the greatest proportion of 1.9% in the 12-year-old stand. With increasing age, the carbon density of the forest floor increased, with the exception that the 58-year-old stand showed an increase, which was slightly different from results from previous studies [14,22]. The forest floor carbon density was dependent on the quantity and decomposition rate of litter, and it also showed an increasing trend in 2-, 15-, and 65-year-old white pines, with the exception of a slight decrease in the 30-year-old stand [23]. Compared with understory vegetation, forest floor carbon density accounted for a relatively large proportion of carbon in ecosystems, with the largest proportion of 3.6% in the 48-year-old stand. The proportion of forest floor carbon was even larger in other studies, with a value of 9.4% in the 15-year-old white pine in Peichl and Arain [23] and 11.4% in the 25-year-old Mongolian pine in Yuan et al. [28], indicating that the forest floor should be regarded as an important carbon pool in plantation ecosystems.

Among the ecosystem components (i.e., tree, understory, forest floor and soil), soil contained the largest proportion of carbon density, with values of 67.4%, 76.8%, 73.2%, 63.4%, and 57.7% in five plantations. With increasing age, the soil carbon density increased from 27.1 Mg ha^{-1} in the 12-year-old stand to 68.1 Mg ha^{-1} in the 34-year-old stand and decreased to 57.0 and 50.3 Mg ha^{-1} in the 48- and 58-year-old stands. The values of soil carbon density in this age sequence were slightly smaller than the values of 38.7, 36.3, 64.5, and 71.55 Mg ha^{-1} in 10-, 18-, 25-, and 30-year-old Mongolian pine plantations, from a study conducted in an area adjacent to this study area [28]. The values of soil carbon density were slightly larger than those of 37.62, 13.98, 19.21, 37.58 and 32.91 Mg ha^{-1} in 8-, 19-, 30-, 35-, and 51-year-old Korean pines [26]. In conclusion, soil carbon density in this study was within the range of soil carbon density after vegetation restoration reported by previous studies.

Tree carbon density was 12.3, 15.9, 23.1, 28.7, and 34.4 Mg ha^{-1} in the 12-, 19-, 34-, 48-, and 58-year-old plantations in this study. The results of Yuan et al. [28] showed that the carbon density of trees in 18- and 30-year-old Mongolian pines was 29 and 31 Mg ha^{-1} and greater than that of stands with similar ages in this study, which might be caused by a higher tree density of the stands in Yuan et al. [28]. With the exception of the 12-year-old stand, the proportion of tree carbon density increased from 21.6% in the 19-year-old stand to 39.5% in the 58-year-old stand. The proportion of tree carbon density was in the range of 8% to 42% and 39% to 50% reported by Yuan et al. [28] and Han et al. [45], both conducted in adjacent areas.

The ecosystem carbon density in the 34-, 48-, and 58-year-old stands was more than twice that in 12-year-old stands, indicating a considerable carbon sequestration potential during Mongolian pine development. From the 34th year after plantation, the ecosystem carbon density began to decrease with values of 92.9, 89.9 and 87.3 Mg ha^{-1} in the 34-, 48-, and 58-year-old stands (Table 5). The decline in ecosystem carbon density was caused by the decrease in soil carbon density and resulted in the continuous growth of pine plantations after 34 years losing the ability to sequester carbon. The results could also be found in previous studies. Soil carbon density decreased from 37.6 Mg ha^{-1} in 35-year-old Korean pine to 32.9 Mg ha^{-1} in the 51-year-old pine, and the ecosystem carbon density of the 51-year-old stand was only slightly larger (approximately 5 Mg ha^{-1}) than that of the 35-year-old stand [26]. There were also no significant differences in ecosystem carbon between 40- and 88-year-old Chinese fir plantations [21]. The phenomenon that the carbon density of overmature forest stopped increasing could provide a theoretical basis for the evaluation and management of planted forests with respect to carbon sequestration.

5. Conclusions

Allometric biomass equations for some tree components are age-specific, thus, using age as a second variable in ABEs with *D* is a simple, practical and accurate method for plantation biomass estimation. With increasing stand age, the biomass and carbon density of total tree, tree aboveground, tree stem and tree root increased, and those of tree foliage decreased. The biomass and carbon density of the tree branch and forest floor first increased with age, followed by a slight decrease in the later stage. There was a decreasing trend of soil carbon concentration with depth in all five pine stands. For the four younger stands, the carbon concentrations of the 0–10, 10–20, and 20–40 cm soil layers increased with stand age, indicating obvious carbon accumulation in shallow surface soil layers. The soil carbon density displayed a sigmoidal pattern with stand age with an increasing trend toward 34 years after afforestation followed a decline in the 48th and 58th years. Influenced mainly by soil carbon density, the ecosystem carbon density of 48- and 58-year-old stands were both lower than that of the 34-year-old stand, revealing the functional loss of carbon sequestration in plantations older than 34 years on the ecosystem scale. This study was conducted in a single region, and the Mongolian pine stands of the same ages were not repeated, which might have led to uncertainty in some conclusions. Multisite studies are further needed to fully elaborate patterns of biomass and carbon density of individual trees and ecosystems of Mongolian pine plantations by stand age.

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