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Effects of different planting configurations and clones on biomass and carbon storage of 12-year-old poplar ecosystem in southern China

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Abstract

The main objective of this study was to compare the effects of two densities (278 stems ha⁻¹ with two spacings of 6 m × 6 m or 4.5 m × 8 m, 400 stems ha⁻¹ with two spacings of 5 m × 5 m or 3 m × 8 m) and three poplar clones (NL95, NL895, and NL797) on productivity and carbon (C) sequestration of poplar ecosystems. Results showed the planting density significantly affected the biomass of a single tree. Mean tree biomass of NL95 was higher in all spacings than the other clones, with a significant difference for the 6 m × 6 m spacing. The biomass of poplar trees ranged from 78.9 to 110.3 Mg ha⁻¹, with the highest tree biomass observed in the square configuration. Soil C concentration (0–100 cm) increased after 12 years of management. Soil C storage ranged from 138.1 to 164.3 Mg C ha⁻¹, and the highest soil C storage was in the NL797 poplar plantation with 6 m × 6 m spacing. Our results suggested that NL95 and NL797 clones should be chosen for planting, with a planting density of 278 stems ha⁻¹ and spacing of 6 m × 6 m.

Keywords: biomass production, C sequestration, plant density, plant spacing, poplar clone

1. Introduction

The continuous increase in atmospheric carbon dioxide (CO₂) concentration is the primary factor of climate change (Zhang et al. 2020). The two main causes of CO₂ increase are worldwide fossil fuel burning and deforestation (Coleman et al. 2004; Zhuang et al. 2015), and the atmospheric CO₂ level was higher than the critical 400 ppm limit in 2016 (Ardebili et al. 2020). Global warming has already become a major environmental challenge, with the greenhouse effect having a profound impact on the environment and world economy (Korkanç 2014). Sequestering carbon (C) in the biomass and soils can be an effective method to help mitigate global climate change (Teklay and Chang 2008). Forests play a major role in global terrestrial C cycling (Deng et al. 2020); the global annual C uptake in gross primary production of the terrestrial biosphere is estimated to be 120 Gt C (Ferré et al. 2014). The establishment of large-scale short-rotation woody crop plantations is an effective method for sequestering CO₂ and mitigating increased atmospheric CO₂ levels (House et al. 2002; Duffy et al. 2020) via increasing long-term C storage in woody biomass and the soil (Arevalo et al. 2011).

Since the last century, many plantations have been established in China because of ecological demand, and the total area of plantations has reached up to 79.54 million ha (Wang et al. 2011; National Forestry and Grassland Administration 2019). Poplars (*Populus* spp.) have many advantageous characteristics, such as fast growth, easy reproduction, high yield, and strong adaptability, making them one of the most important multipurpose afforestation trees in China (Jia et al. 2013; Goehing et al. 2017). Poplars are widely planted in China (Calfapietra et al. 2010; Li et al. 2018). The Chinese 9th national forest resources inventory data showed that the area of poplar plantation is 7.57 million ha, accounting for 9.51% of the total area of national plantations, especially in Jiangsu province, which is the largest timber production base in China (Tun et al. 2018; Jing et al. 2019). Due to the economic and environmental potential of poplar plantations, many studies have been conducted to estimate and increase biomass production and C storage in poplar plantations (Fang et al. 1999; Li et al. 2009; 2014; Xing et al. 2014). Fang et al. (1999) suggested that higher planting density (1111 stems ha⁻¹ and 833 stems ha⁻¹) caused higher biomass production in short-rotation (6 years) poplar plantations. Truax et al. (2018) reported that planting density had a large effect on poplar stem dimensions, but a minor effect on poplar stand volume, and increasing planting density stimulated C accumulation in the soil. Fang et al. (2007) reported that, for the four planting densities (1111, 833, 625, and 500 stems ha⁻¹) tested, the C storage potential was best when the trees were planted at 1111 and 833 trees ha⁻¹ and grown over 5- and 6-year cutting cycles, respectively. Many new poplar clones have been selected to meet increasing

ecological demand, and a great variation in the C sequestration potential has been observed due to plantation species, growth environment, and management (Fang et al. 2007; Yan et al. 2017). In tree plantations, studies have generally focused on tree growth and productivity to determine the best management practices to promote higher timber yield, whereas soil, understory vegetation, and litter C storage have been less investigated. Soil C content accounts for a major part of total C storage at the ecosystem level (Chomel et al. 2014). The choice of the best spacing and configuration system is very important for maximum wood production or C storage, and the response of soil organic pools to management practices such as planting spacing remains poorly understood (Six et al. 2000; Fang et al. 2007; Schwerz et al. 2020). Therefore, further studies are required to maximize the biomass of poplars and C sequestration to ensure that suitable clones are planted at appropriate sites to meet planting demands.

In the present study, the three poplar clones utilized were NL95 (*P. × euramericana* ‘Nanlin 95’), NL895 (*P. × euramericana* ‘Nanlin 895’), and NL797 (*P. × euramericana* ‘Nanlin 797’), which are hybrids of clone I-69 (*P. deltoides* Bartr. ‘Lux’, male parent) × clone I-45 (*P. × euramericana* (Dode) Guineir ‘I-45/51’, female parent). These three clones are new poplar clones that have been widely planted in south China in recent years; however, the suitable spacing of the three new clones remains unclear. Four different spacings were selected in the present study to meet the demand of biomass production and C sequestration in the poplar ecosystem. The objective of the study was to investigate the effects of different clones, stand densities, and configurations on poplar growth and C storage of poplar ecosystems to provide a better understanding of the role of poplars in C sequestration and gain a basis for the management of poplar plantations.

2. Material and methods

2.1. Experimental design, treatments, and site characteristics

Our experimental site was located at the Chenwei Forestry Farm, Suqian city, Jiangsu province, China (118°18' E, 33°15' N), a typical poplar site in southern temperate China. This site was farmland before the establishment of the poplar plantation. This site belongs to the mid-latitude semi humid climate region, with a rainfall of 985.5 mm, mean temperature of 14.4 °C, and annual sunshine duration of 2215.9 hours per year. The soil type of the study location is clay-loam texture. A total of three composite soil samples were randomly collected before the establishment of the plantation, and the soil basic properties (0–100 cm) have been listed as follows: soil C concentration was 8.0 g kg⁻¹, hydrolyzed nitrogen content was 6.0 mg kg⁻¹,

available potassium content was 137.9 mg kg⁻¹, and available phosphorus content was 15.6 mg kg⁻¹. The main understory vegetation species at this site include *Arthraxon hispidus*, *Saccharum arundinaceum*, *Bidens pilosa*, *Phytolacca acinosa*, *Ophiopogon japonicus*, *Lycoris radiata*, *Conyza canadensis*, *Glycine soja*, *Setaria viridis*, *Humulus scandens*, and *Achyranthes bidentata*.

Poplar plantations were established by hand planting 1-year-old seedlings in March 2007, with the plantation not receiving fertilizer during the time of planting. The configuration and clones in the study entailed four planting spacings, and three poplar clones (NL95, NL895, and NL797) arranged in a split-plot randomized complete design with three replications and 36 plots. There were approximately 80 poplars in each plot with two tree rows as a buffer and all investigations were conducted with inner trees to minimize any edge effects. The four planting spacings were 6 m × 6 m (278 stems ha⁻¹), 4.5 m × 8 m (278 stems ha⁻¹), 5 m × 5 m (400 stems ha⁻¹), and 3 m × 8 m (approximately 400 stems ha⁻¹), with each planting density comprised of two different shapes (square configuration and rectangular configuration). The densities were chosen for large-diameter timber production, and the spacings were useful for agroforestry management activities. Peanut (*Arachis hypogaea* L.) and wheat (*Triticum durum* Desf.) were intercropped in 2007, 2008, and 2009. There was no weed management in the poplar plantation.

2.2. Survey and sampling method

The survey of poplars, understory vegetation, and litter was conducted in July 2018 in 36 plots at Chenwei Forestry Farm. The survival rate, height, and diameter at breast height (DBH) of the trees, except for the buffer rows, were recorded. Total leaf, branch, stem (including bark), and root biomass was determined by combining DBH and tree height inventory data using previously existing allometric equations developed for the clone I-69 (Tun et al. 2018):

$$\lg W_{\text{leaf}} = 0.4489 \lg(D^2 H) - 1.1455 \quad (1)$$

$$\lg W_{\text{branch}} = 0.9911 \lg(D^2 H) - 2.3791 \quad (2)$$

$$\lg W_{\text{stem}} = 1.0659 \lg(D^2 H) - 2.1305 \quad (3)$$

$$\lg W_{\text{root}} = 0.7061 \lg(D^2 H) - 1.2588 \quad (4)$$

where, $\lg$ is $\log_{10}$, W is the biomass of different poplar tree components in kg, D is the DBH of a poplar tree in centimeters, and H is the height of a poplar tree in meters.

Nine sample trees (three trees per clone) of medium DBH were cut and divided into leaf, branch, and stem (including wood and bark). The roots were excavated from cardinal directions (north, south, east, and west) with an excavation angle of 30°, excavation depth of 1 m, and excavation length of half of the row spacing. In total, one-third of the area (120°) was excavated. The thickness grades of roots were divided into < 2 mm, 2–5 mm, 5–10 mm, 10–50 mm, and > 50 mm. The roots (> 2 mm) were excavated and weighed after cleaning. Fine roots were collected randomly around the sample trees using an auger borer (5 cm in inner diameter and 100 cm in length), transported to the laboratory, and cleaned carefully using a sieve. After cleaning, the roots were mixed based on the weight of the roots with different thickness grades, and then the roots and all aboveground fractions were oven-dried and ground for subsequent analysis.

Three sampling points were randomly selected to measure each plot. Soil C was evaluated by separately sampling three soil horizons (0–20 cm, 20–50 cm, and 50–100 cm). The soil bulk density was measured using a 100-cm³ cylinder, and each layer was oven-dried at 105 °C (Zhang et al. 2011); then, the soil samples were air-dried and sieved (2 mm) for homogenization and removal of fine plant roots. Three understory vegetation subplots (1.5 m × 1.5 m) were randomly chosen in each plot. A total of 108 subplots were selected in the survey, with location subplots controlled to not be too close to the trunk. The understory vegetation, including all aboveground and belowground parts, was weighed and sampled in each subplot (1.5 m × 1.5 m) at an excavation depth of approximately 30 cm. The samples were transported back to the laboratory for cleaning and to determine their dry weight (samples were oven-dried at 105 °C for half an hour and 80 °C to constant weight). Based on the weight of the samples, we estimated the biomass of understory vegetation in each plot, and the vegetation samples were sieved (2 mm) to homogenize the samples for subsequent analysis.

Aboveground litter was collected directly from the ground in three 1 m × 1 m subplots in each plot and weighed. The samples were then analyzed using the same technique as for the vegetation samples.

2.3. Sample analysis

C content in the poplar clones, understory vegetation, litter, and soil was determined using an elemental analyzer (Elementar Analysensysteme GmbH, Rhein, Germany). C storage in the poplar biomass was calculated by summing the C in various tree fractions. The C storage of the 100-cm soil samples was estimated using the following equation (Chen et al. 2009):

$$S_d = \sum D_i C_i V_i \quad (5)$$

where, S_d is the C storage at d depth per unit area and is represented in units of Mg C ha^{-1} , D_i is the soil bulk density of the i^{th} layer in Mg m^{-3} , C_i is the C content (%) of the soil layer I, and V_i is the volume of the i^{th} layer depth. C storage in the poplar plantation was calculated by adding the poplar biomass C, soil C, understory C, and litter C.

2.4. Data analysis

The data were calculated and plotted in Microsoft Office Excel 2016, and all data were subjected to analysis of variance (ANOVA) using IBM SPSS Statistics 19.0 (SPSS Inc., Chicago, IL, USA) at a significance level of 0.05. Results are presented as the mean value $\pm$ standard deviation ($M \pm SD$). To determine whether there was a significant interaction among the densities and clones on tree height, DBH, total tree biomass, total vegetation biomass, soil C storage, vegetation C storage, and total C storage, a multivariate ANOVA test was performed. When there were no significant interaction effects, differences between data were evaluated by one-way ANOVA followed by Duncan's multiple-range test.

3. Results

3.1. Interaction analysis

As shown in Table 1, the poplar clone had significant effects on DBH, total tree biomass, vegetation biomass, and vegetation C storage, and the planting spacing had significant effects on DBH, whereas their interaction did not significantly affect all indicators.

3.2. Tree height and DBH

As shown in Figure 1, the mean tree DBH in different treatments ranged from 21.4 cm to 27.1 cm, and the mean tree height in different treatments ranged from 21.6 m to 25.6 m for 12-year-old trees. The mean tree DBH (27.1 cm) was the highest in the NL95 poplar plantations with $6 \text{ m} \times 6 \text{ m}$ spacing. There was a significant difference between poplar plantations with lower densities ($6 \text{ m} \times 6 \text{ m}$ and $4.5 \text{ m} \times 8 \text{ m}$) and higher densities ($5 \text{ m} \times 5 \text{ m}$ and $3 \text{ m} \times 8 \text{ m}$) for the mean tree DBH ($P < 0.05$). For the same planting density, the square configuration plantations ($6 \text{ m} \times 6 \text{ m}$ and $5 \text{ m} \times 5 \text{ m}$) showed higher mean DBH than that in rectangular configuration plantations ($4.5 \text{ m} \times 8 \text{ m}$ and $3 \text{ m} \times 8 \text{ m}$), although there was no significant difference between the two configurations ($P > 0.05$). Among all poplar clones, the highest mean tree height was found in NL95, and the mean tree height in spacings followed the order of $6 \text{ m} \times 6 \text{ m} > 4.5 \text{ m} \times 8 \text{ m} > 5 \text{ m} \times 5 \text{ m} > 3 \text{ m} \times 8 \text{ m}$.

3.3. Biomass distribution in different poplar tree components

The single tree biomass of different poplar plots was evaluated according to equations 1, 2, 3, and 4. As shown in Figure 2, the average biomass of the 12-year-old single poplar ranged from 204.1 to 410.3 kg tree⁻¹ among all treatments. The stem biomass was the largest for different poplar components, followed by branch, root, and leaf, accounting for approximately 65%, 18%, 15%, and 2% of the total poplar tree biomass, respectively. For poplar plantations with different planting densities, the biomass of leaf, stem, branch, root, and total tree were in the order of 6 m × 6 m > 4.5 m × 8 m > 5 m × 5 m > 3 m × 8 m. Therefore, planting density significantly affected the biomass of a single poplar tree ($P < 0.05$), and the single tree biomass in poplar plantations with lower densities (4.5 m × 8 m and 6 m × 6 m) was higher than those with higher densities (5 m × 5 m and 3 m × 8 m). The single tree biomass with a square configuration was higher than that with a rectangular configuration at the same planting density.

3.4. Total distribution of biomass in the different poplar plantations

As shown in Table 2, the survival rate of poplar ranged from 92.93% to 98.33%, and the total biomass of vegetation under different poplar plantations was 85.7–116.8 Mg ha⁻¹, of which 90.6–95.4% was tree biomass. The biomass of litter and understory vegetation accounted for only 3.65%–8.76% and 0.77%–1.81% of total vegetation biomass, respectively. Total vegetation biomass of the poplar plantation with three clones under different spacing was in the order of NL95 > NL895 > NL797, and the highest total vegetation biomass was in the NL95 poplar plantation with 5 m × 5 m spacing. Overall, the results showed that the rectangular spacing decreased the vegetation biomass at the same planting density: 6 m × 6 m > 4.5 m × 8 m, and 5 m × 5 m > 3 m × 8 m. Poplar clones significantly affected the total vegetation biomass in the poplar plantations with 6 m × 6 m spacing ($P < 0.05$).

3.5. Soil C concentration and storage

Table 3 shows that the soil C contents decreased with an increase of soil depth, the soil concentration in 0–20 cm, 20–50 cm, and 50–100 cm layers ranged from 18.2 to 23.9, 9.85 to 12.9, and 5.68 to 8.07 g kg⁻¹, respectively. The soil C storage in the 0–20 cm, 20–50 cm, and 50–100 cm layers was 47.3–62.1, 42.7–56.0, and 37.6–58.6 Mg C ha⁻¹, respectively. The soil C storage in the NL797 poplar plantation with 6 m × 6 m spacing was higher than that in the other poplar plantations, and the soil C storage in the poplar plantation planted with 4.5 m × 8 m spacing was lower than that in the other plantations, although this difference was not statistically significant ($P > 0.05$).

3.6. Poplar tree C storage

The total tree C storage of different 12-year-old poplar plantations ranged from 39.5 to 55.2 Mg C ha⁻¹, of which 63.0%–66.2% was attributed to poplar tree stem, whereas the poplar tree leaf accounted for only 1.4%–2.1% of the total tree C storage. The tree C storage in the NL95 poplar plantation was higher than that in the other plantations. For different planting spacing, the tree C storage in the poplar plantations with a configuration of 6 m × 6 m was higher than that in the poplar plantations with other configurations (Fig. 3). The total tree C storage in poplar plantations with a square configuration was higher than that in plantations with a rectangular configuration at the same planting density. However, there was no significant difference in the total tree C storage between different poplar clones, densities, or configurations, except for the NL95 poplar plantation with 6 m × 6 m spacing ($P > 0.05$).

3.7. Vegetation C storage

Table 4 shows that the C storage of vegetation under different poplar plantations ranged from 42.4 Mg C ha⁻¹ to 57.9 Mg C ha⁻¹, of which 92% was attributed to poplar tree C storage. The tree C storage under different poplar plantations of the same clone was generally in the order of 5 m × 5 m > 6 m × 6 m > 3 m × 8 m > 4.5 m × 8 m. Comparing the three poplar clone plantations with the same planting spacing, the C storage of different poplar clones plantations was in the order of NL95 > NL895 > NL797. At the same stand density, the C storage of the vegetation layer in the poplar plantations with a square configuration (6 m × 6 m and 5 m × 5 m) was higher than that with a rectangular configuration (3 m × 8 m and 4.5 m × 8 m). However, the C storage in the understory vegetation and litter only accounted for 0.48%–1.44% and 3.15%–7.64%, respectively, of the total vegetation C storage in the poplar plantations.

3.8. Total C storage under different poplar plantation

Figure 4 shows that the total C storage ranged from 183.8 to 211.7 Mg C ha⁻¹ at the survey time. The average C storage of the vegetation and soil layers was 49.7 Mg C ha⁻¹ and 150.5 Mg C ha⁻¹, accounting for 24.8% and 75.2% of the total C storage, respectively. The total C storage in the NL797 poplar plantation was higher than that in the other two poplar plantations. In addition, the total C storage with a square configuration (6 m × 6 m and 5 m × 5 m) was higher than that with a rectangular configuration (3 m × 8 m and 4.5 m × 8 m) at the same density.

4. Discussion

Fast-growing hybrid poplars promote rapid C stock accumulation in plant biomass compared to other farm land uses (Arevalo et al. 2009). Forest biomass plays an important role in understanding the productivity, nutrient cycling, and C sequestration of forest ecosystems and influences global climate change research (Dixon et al. 1994; Somogyi et al. 2007; Garkoti 2008). Forest stand biomass is associated with forest age, site class, stand density, and other biotic and abiotic factors (Fang et al. 2001).

In our study, a 12-year-old poplar plantation with clay-loam texture soil was selected, with the total biomass of poplars ranging from 78.9 to 110.3 Mg ha⁻¹, which is consistent with Jiang et al. (2007), who found that the biomass of the 29-year-old *P. × xiaohei* on sandy land ranged from 88.64 Mg ha⁻¹ to 104.90 Mg ha⁻¹ in the Shanxi Province (northwest China) and Wu et al. (2001), who showed the biomass of 11-year poplar plantation on beach land was 90.2 t·ha⁻¹ in Anhui Province (south China). Our results were lower than Tang et al. (2004), who reported the biomass of poplars in Hubei Province (south China) ranged from 57.6 Mg ha⁻¹ to 201.9 Mg ha⁻¹. In general, our biomass value was within the normal range, with the difference between our production and the former study mainly due to the site characteristics, land-use types, species involved, stand age, and management practices (Xie et al. 2017).

Our results suggest that stand density significantly affects the average single poplar biomass and higher density resulted in lower single poplar biomass, which is consistent with the results of Bo et al. (2020), who also found that the DBH and volume of the average single poplar increased with a decrease in density. Poplars require more space for crown development than many other species as they are a strongly light-demanding species (Hart 1991). High stand density will induce inter-tree competition for light, moisture, and soil fertility (Vospernik and Sterba 2015; Dash et al. 2019). However, the lowest total biomass value per hectare of the poplar plantation in the present study was observed in the 4.5 m × 8 m spacing for all poplar clones, although there was no statistical significance. This highlights the trade-off between yield per unit area and single tree size. In addition, we found that plant configuration influenced total poplar biomass. A possible reason for this is that competition for light occurs more intensely in a rectangular configuration with narrow stem spacing (3 m or 4.5 m) than in a square configuration. Poplar is a photophilic species, where shade and low extension space caused by narrow configuration have negative effects on the canopy structure and stem roundness (Truax et al. 2018; Tun et al. 2018). Neighboring poplars in narrow spacings can also increase the belowground competition for water and nutrient resources (Truax et al. 2018), and excessive intraspecific competition can lead to an increase in tree mortality, decreasing the number of trees and poplar production.

Maximum production can be achieved by the selection of suitable clones and proper management in poplar cultivation (Johansson and Karacic 2011). Survival is an important selection criterion that is affected

by the environment and planting density (Chambers and Borralho 1997; Ceulemans and Deraedt 1999). Our results indicated that the three poplar clones exhibited a high survival rate and good biomass production compared with former studies in this region. Li et al. (2009) reported the biomass of 4-year-old poplar plantation (*P. deltoids* “35”) with a density of 250 stem ha⁻¹ was 14.83 Mg ha⁻¹. The difference in biomass of the different clones of the same age is closely related to the biological characteristics of poplar clones, which was in agreement with Guo and Zhang (2010); NL95 had the highest biomass among the three clones tested and was suitable for timber production in the southern temperate China.

Understory vegetation is an integral part of the forest ecosystem, and plays an ecophysiological role in nutrient storage and cycling, the maintenance of biodiversity, and the development of the forest ecosystem (Fabião et al. 2002; Chastain et al. 2006; Taylor et al. 2006). However, in our study, at the same site, the biomasses of undergrowth vegetation within poplar stands of different densities and clones were not significantly different, which is consistent with the observations of Zhang et al. (2019) for the *Pinus massoniana* plantation. However, Cho et al. (2017) reported that understory vegetation density was negatively correlated with canopy density. Additionally, shade was found to be the main factor affecting the growth and development of understory vegetation (Barbier et al. 2008). In general, high forest stand density leads to insufficient light in the forest, and light is commonly considered the major limiting factor of forest vegetation cover. However, low stand density induces a larger-sized poplar, which enhances the competition with undergrowth vegetation for water and fertilizer, inhibiting the growth and development of understory vegetation. The biomass of understory vegetation is affected by various factors, which require further study in the future.

Understory vegetation and litter are not only part of the C pool in the forest ecosystem and play an important role in C cycling in forest ecosystems (Hättenschwiler et al. 2005; Chastain et al. 2006). The highest soil C content was observed in the 0–20 cm soil layer, which might be due to the plant root density and decomposition of forest litter, soil microorganisms, and the high activity of enzymes (Li et al. 2004a; 2018). Soil organic C accounts for the largest terrestrial C pool, and it is estimated that the C stored in soils is approximately three times higher than that in the aboveground biomass (Scharlemann et al. 2014). We found the average soil C concentration (0–100 cm) of the 12-year-old poplar plantation was 1.09%, which exhibited a 0.29% enhancement after plantation establishment. The average C storage before plantation establishment was 116.0 Mg C ha⁻¹, and after 12 years of management, the average C storage was 150.5 Mg C ha⁻¹; therefore, the soil C accumulation rate was 2.88 Mg C ha⁻¹yr⁻¹. The increase in the soil C concentration was caused by fast-growing poplars producing a large amount of aboveground litter and underground litter

annually, increasing the soil organic input. Furthermore, our study site was close to the Hongze Lake, and the soil water content was high, which decreased the organic decomposition rate and was beneficial to the accumulation of soil organic C content (Ding et al. 2012). Site selection, terrain condition, forest type, and climatic condition were important factors affecting the soil C storage. The results indicated that under such site conditions, the management of a fast-growing poplar plantation was conducive to wood production and forest C stocks. Our results were consistent with Paul et al. (2003), who reported the *Eucalyptus grandis* and *E. globulus* plantation return the C from the forest biomass to the soil after 10 years of management. Wang et al. (2016) also reported the soil C concentration and sequestration rates of poplar plantation significantly increased with stand age in a coastal region. In our findings, the soil C storage of poplar plantations ranged from 138.1 Mg C ha⁻¹ to 164.3 Mg C ha⁻¹, accounting for approximately 75% of the total forest C storage. Based on the present study, soil C storage of poplar plantations in the region was slightly higher than that of the forestland in southeast China (118.4 Mg C ha⁻¹) (Zhao et al. 1997) and much higher than that of subtropical and tropical conifers (61.1 Mg C ha⁻¹) (Li and Zhao 2001). However, it was much lower than that of deciduous conifers (270 Mg C ha⁻¹) (Li et al. 2004b). There was no significant difference in C content among the different densities and clones due to the short planting time. Furthermore, NL797 achieved the highest soil C storage among the poplar clones tested, which might be due to the higher biomass of the understory vegetation and litter under the NL797 plantation (Table 2). Therefore, NL797 is a suitable clone for soil C sequestration.

The C distribution of the forest ecosystem varies with vegetational composition, forest age, site conditions, and stand characteristics (Zhang and Wang 2010; Zeng et al. 2014). In the present study, the poplar C storage of the different poplar plantations ranged from 39.5 Mg C ha⁻¹ to 55.2 Mg C ha⁻¹ (average 46.9 Mg C ha⁻¹, biomass C accumulation rate was 3.91 Mg C ha⁻¹yr⁻¹). This was much higher than the average value proposed for poplar plantations in China (23.7 Mg C ha⁻¹) (Jia et al. 2013) and the average plantation C storage in China (30 Mg C ha⁻¹) (Fang et al. 2001). The NL95 obtained the highest vegetation C storage among all poplar clones, whereas the highest poplar plantation C storage was observed in the NL797 clone. This was because NL797 had the most soil C storage, and soil C storage accounted for the largest fraction of the terrestrial C pool. Based on the C storage in vegetation biomass and soil, the C storage density in the poplar plantation was calculated to be 200.2 Mg C ha⁻¹, on average. This is higher than the average value in temperate forest biomass (forest age: 31–70 years) (189 Mg C ha⁻¹) (Pregitzer and Euskirchen et al. 2004). Based on the present study, the C density of poplar plantations in the region was substantially higher than that of Moso bamboo stand (14 years of cultivation history, stem ha⁻¹, 104.8 Mg C ha⁻¹), 14-year old

Chinese fir stand (3100 stem ha⁻¹, 95.7 Mg C ha⁻¹), and 14-year old Masson pine stand (2100 stem ha⁻¹, 96.5 Mg C ha⁻¹) in southeast China (Jiang et al. 2011), but slightly lower than that of the *Pinus sylvestris* var. *Mongolica* stand (204.3 Mg C ha⁻¹) in northeast China (Wang et al. 2018). Our results indicate that poplar plantations have high C storage and great potential for biomass and soil C sequestration. Furthermore, a square configuration is more beneficial for C storage than a rectangular configuration at the same planting density.

5. Conclusions

The biomass of an average single poplar (12-year-old) ranged from 204.1 to 410.3 kg tree⁻¹ and was significantly affected by planting density. Among all the treatments, the proportion of biomass in each fraction was in the order of stem > branch > root > leaf, and the largest average single biomass was observed in NL95 under the same density. The total biomass of poplars ranged from 78.9 to 110.3 Mg ha⁻¹, poplar biomass accounted for 90.6%–95.4% of the total biomass of the poplar plantation, and the square configuration was more beneficial for the total poplar biomass than the rectangular configuration at the same planting density. The soil C storage (0–100 cm) ranged from 138.1 to 164.3 Mg C ha⁻¹, accounting for 75.2% of the total C storage of the poplar plantation. The highest soil C storage was found in the 6 m × 6 m spacing for the NL797 plantation. The C storage density in the poplar plantation was calculated as 200.2 Mg C ha⁻¹. After 12 years of poplar cultivation, the soil C concentration increased by 0.29%. In general, our study plantations (poplar clones NL95, NL895, and NL797) had greater potential for C sequestration in southern temperate China than other tree species. We recommend that for poplar production and soil C sequestration at a similar site, NL95 and NL797 clones should be chosen for planting materials, with a planting density of 278 stems ha⁻¹ and a planting spacing of 6 m × 6 m.

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Table 1. Results (*P*-values) of two-way ANOVAs on the effects of poplar clone, planting spacing and their interaction on tree height, DBH, total tree biomass, vegetation biomass, soil carbon storage, vegetation carbon storage and total carbon storage.

	Tree height		DBH		Total tree biomass		Vegetation biomass		Soil carbon storage		Vegetation carbon storage		Total carbon storage	
	df	P	df	P	df	P	df	P	df	P	df	P	df	P
Clone	2	0.369	2	< 0.05	2	< 0.05	2	< 0.05	2	0.220	2	< 0.05	2	< 0.05
Planting spacing	3	0.152	3	< 0.05	3	0.371	3	0.454	3	0.385	3	0.504	3	0.504
Clone ×Planting spacing	6	0.986	6	0.993	6	0.787	6	0.899	6	0.723	6	0.940	6	0.940

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Table 2. Total vegetation biomass and distribution in different poplar plantations in 12-year-old (mean $\pm$ SD).

Poplar clone	Spacing (m)	Survival rate (%)	Poplar tree (Mg ha ⁻¹)	Understory vegetation (Mg ha ⁻¹)	Litter (Mg ha ⁻¹)	Total vegetation biomass (Mg ha ⁻¹)
NL895	6 $\times$ 6	95.68	98.2 $\pm$ 2.35bA	0.87 $\pm$ 0.13bA	6.30 $\pm$ 1.06aA	105.4 $\pm$ 2.85bA
	5 $\times$ 5	92.93	93.9 $\pm$ 3.98aA	0.74 $\pm$ 0.11abA	6.51 $\pm$ 1.21abA	101.2 $\pm$ 4.36aA
	3 $\times$ 8	95.83	91.7 $\pm$ 9.48aA	1.31 $\pm$ 0.50aA	5.23 $\pm$ 0.67abA	98.1 $\pm$ 10.19aA
	4.5 $\times$ 8	96.85	87.5 $\pm$ 8.92aA	1.23 $\pm$ 0.15aA	4.38 $\pm$ 0.98aA	93.1 $\pm$ 9.78aA
NL797	6 $\times$ 6	98.33	89.1 $\pm$ 4.41cA	0.78 $\pm$ 0.05bB	5.34 $\pm$ 1.62abA	95.2 $\pm$ 3.60cA
	5 $\times$ 5	97.47	87.2 $\pm$ 6.84aA	1.22 $\pm$ 0.23aAB	8.43 $\pm$ 1.17aA	96.9 $\pm$ 7.49aA
	3 $\times$ 8	97.62	82.9 $\pm$ 5.78aA	1.57 $\pm$ 0.29aA	6.96 $\pm$ 1.24aA	91.2 $\pm$ 7.19aA
	4.5 $\times$ 8	96.34	78.9 $\pm$ 3.71aA	0.81 $\pm$ 0.13aB	5.96 $\pm$ 2.24aA	85.7 $\pm$ 4.08aA
NL 95	6 $\times$ 6	96.91	110.3 $\pm$ 3.90aA	1.26 $\pm$ 0.19aA	4.20 $\pm$ 0.41bB	115.6 $\pm$ 3.34aA
	5 $\times$ 5	96.97	110.3 $\pm$ 14.2aA	0.66 $\pm$ 0.14bB	5.85 $\pm$ 1.04bA	116.8 $\pm$ 13.4aA
	3 $\times$ 8	94.64	98.9 $\pm$ 15.0aA	1.08 $\pm$ 0.23aAB	4.37 $\pm$ 0.41bAB	104.4 $\pm$ 14.7aA
	4.5 $\times$ 8	98.13	94.8 $\pm$ 12.5aA	1.10 $\pm$ 0.58aAB	4.45 $\pm$ 0.49aAB	100.4 $\pm$ 12.0aA

Data are the means $\pm$ SD of three replicates. Different capital letters indicate significant differences between different planting spacing with the same poplar clone; Different lowercase letters indicate significant differences between different clones with the same planting spacing; Based on Duncan's tests at the 0.05 level.

Table 3. Soil carbon concentration and storage at different soil layers in different poplar plantations in 12-year-old (mean ± SD).

Poplar clones	Spacing (m)	Soil carbon concentration (g kg ⁻¹)			Soil carbon storage (Mg C ha ⁻¹)			
		0–20 cm	20–50 cm	50–100 cm	0–20 cm	20–50 cm	50–100 cm	0–100 cm
NL895	6 × 6	20.4±2.07aA	9.85±2.20aA	7.83±1.99aA	53.1±5.39aA	42.7±9.53aA	57.5±14.6aA	153.3±22.1aA
	5 × 5	23.9±2.11aA	11.0±0.91aA	6.42±0.14aAB	62.1±5.49aA	47.7±3.95aA	47.1±1.01aA	156.9±4.24aA
	3 × 8	23.3±2.13aA	11.4±0.58aA	5.68±0.43aB	60.6±5.54aA	49.4±2.54aA	41.7±3.17bA	151.6±5.63aA
	4.5 × 8	20.6±3.19aA	11.5±1.70aA	5.76±0.49bB	53.5±8.29aA	50.0±7.37aA	34.7±10.3aA	138.1±20.2aA
NL797	6 × 6	21.4±3.31aA	11.6±2.83aA	7.95±0.82aA	55.6±8.60aA	50.3±12.3aA	58.4±6.03aA	164.3±25.4aA
	5 × 5	19.2±0.91bA	11.7±0.86aA	7.10±0.93aA	49.9±2.37bA	50.8±3.72aA	52.1±6.83aA	152.9±11.5aA
	3 × 8	18.9±0.58bA	11.7±2.40aA	7.98±1.83aA	49.2±1.50bA	50.5±10.4aA	58.6±10.4aA	158.3±13.6aA
	4.5 × 8	20.6±0.88aA	10.7±0.58aA	8.07±0.58aA	53.5±2.29aA	46.4±2.50aA	48.7±14.8aA	148.6±10.7aA
NL 95	6 × 6	18.3±0.58aB	10.2±2.04aA	7.27±1.13aA	47.6±1.51aB	44.2±8.84aA	53.4±8.30aA	145.2±16.2aA
	5 × 5	21.2±1.01abA	10.1±0.82aA	6.43±0.15aA	55.1±2.63abA	43.6±3.55aA	47.2±1.1aA	145.9±3.64aA
	3 × 8	19.9±1.58bAB	11.4±0.55aA	6.69±0.42aA	51.7±4.11abA	49.3±2.37aA	49.1±4.08abA	150.2±8.63aA
	4.5 × 8	18.2±1.21aB	12.9±1.96aA	6.25±0.54bA	47.3±3.14aB	56.0±8.48aA	37.6±11.1aA	140.9±9.60aA

Data are the means ± SD of three replicates. Different capital letters indicate significant differences between different planting spacing with the same poplar clone; Different lowercase letters indicate significant differences between different clones with the same planting spacing; Based on Duncan’s tests at the 0.05 level.

519 **Table 4.** Carbon storage of vegetation in different poplar plantations in 12-year-old (mean $\pm$ SD).

Poplar clones	Spacing (m)	Total carbon storage of poplar (Mg C ha ⁻¹)	Total carbon storage of understory vegetation (Mg C ha ⁻¹)	Total carbon storage of litter (Mg C ha ⁻¹)	Total carbon storage of vegetation (Mg C ha ⁻¹)
NL895	6 $\times$ 6	49.1 $\pm$ 1.18bA	0.36 $\pm$ 0.05abA	2.71 $\pm$ 0.55aA	52.2 $\pm$ 1.38bA
	5 $\times$ 5	46.9 $\pm$ 1.99aA	0.31 $\pm$ 0.05bA	2.81 $\pm$ 0.43abA	50.1 $\pm$ 2.15aA
	3 $\times$ 8	45.8 $\pm$ 4.74aA	0.55 $\pm$ 0.21aA	2.25 $\pm$ 0.23abA	48.6 $\pm$ 5.04aA
	4.5 $\times$ 8	43.5 $\pm$ 4.46aA	0.51 $\pm$ 0.06aA	1.89 $\pm$ 0.34aA	45.9 $\pm$ 4.83aA
NL797	6 $\times$ 6	44.5 $\pm$ 2.21cA	0.33 $\pm$ 0.02bB	2.30 $\pm$ 0.57abA	47.1 $\pm$ 2.35cA
	5 $\times$ 5	43.6 $\pm$ 3.42aA	0.51 $\pm$ 0.10aAB	3.63 $\pm$ 0.47aA	47.7 $\pm$ 3.70aA
	3 $\times$ 8	41.5 $\pm$ 2.89aA	0.65 $\pm$ 0.12aA	3.00 $\pm$ 0.44aA	45.2 $\pm$ 3.49aA
	4.5 $\times$ 8	39.5 $\pm$ 1.85aA	0.34 $\pm$ 0.06aB	2.57 $\pm$ 0.79aA	42.4 $\pm$ 2.14aA
NL95	6 $\times$ 6	55.2 $\pm$ 1.95aA	0.53 $\pm$ 0.08aA	1.81 $\pm$ 0.14bB	57.4 $\pm$ 1.71aA
	5 $\times$ 5	55.1 $\pm$ 7.08aA	0.28 $\pm$ 0.06bB	2.52 $\pm$ 0.49bA	57.9 $\pm$ 6.74aA
	3 $\times$ 8	49.5 $\pm$ 7.52aA	0.45 $\pm$ 0.09aAB	1.88 $\pm$ 0.14bAB	51.7 $\pm$ 7.38aA
	4.5 $\times$ 8	47.4 $\pm$ 6.25aA	0.46 $\pm$ 0.24aAB	1.92 $\pm$ 0.17aAB	49.8 $\pm$ 6.02aA

520 Data are the means $\pm$ SD of three replicates. Different capital letters indicate significant differences between
 521 different planting spacing with the same poplar clone; Different lowercase letters indicate significant
 522 differences between different clones with the same planting spacing; Based on Duncan's tests at the 0.05 level.

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Figure 1. Mean diameter at the breast height (DBH) and height of a single tree in different poplar plantations in 12-year-old.

Different capital letters indicate significant differences between different planting spacing with the same poplar clone; Different lowercase letters indicate significant differences between different clones with the same spacing; Based on Duncan’s test at the 0.05 level. (the same hereinafter); Bars indicate standard deviation (n=3).

Figure 2. Biomass distribution of tree components in different poplar plantations in 12-year-old.

Bars indicate standard deviation of the total biomass production (n=3).

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539 **Figure 3.** Carbon storage of tree components in different poplar plantations in 12-year-old.

540 Bars indicate standard deviation of the total carbon storage (n=3) (the same hereinafter).

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Figure 4. Total carbon storage in different poplar plantations in 12-year-old.

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