分类号: **S 725**
密级:　**GK**

专业代码　: **095107**
学校代码　: **10298**
学号　: **6314204**

NANJING FORESTRY UNIVERSITY

全日制专业学位研究生学位论文

论文题目：

Effects of Planting Spacing on Tree Growth, Canopy Structure, and Understory Vegetation of Poplar Plantations

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2016 年 06 月

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Acknowledgements

I would first like to express my deepest thanks to my supervisor, Dr. Shengzuo Fang, Professor of Silviculture at Nanjing Forestry University for his close supervision and guidance throughout my study in China. The door to Prof. Fang's office was always open whenever I ran into difficulty or had a question about my research or preparing manuscript for my dissertation. Without his continuous support and kind encouragement, my research and dissertation could not have been successfully completed.

I would like to extend my profound gratitude to APFNet (Asia-Pacific Network for Sustainable Forest Management and Rehabilitation) for financial support to study in China. And, I gratefully acknowledge financial support from National Basic Research Program of China (973 Program) (2012CB416904) for my research works.

In addition, I am thankful to Ministry of Natural Resources and Environmental Conservation for giving me that chance to pursue master degree in China.

Also, a big thinks to all of my colleagues at the department of silviculture for their kind assistance in doing my experiments and social life as well. And, special thanks go to Mr. Zhang Fan for his enthusiastic cooperation during the field work and in doing experiments. I am also thankful to my classmates from different countries of Asia and Pacific region for their helpful advices and constructive comments on my research as well as for making an international family for me.

Grateful thanks are due to all of the teaching staff and supporting staff of Nanjing Forestry University for helping me broaden my knowledge and skills, and for their kind support throughout my stay in China.

Finally, I am most grateful to my family for their unfailing support and continuous encouragement.

摘要

杨树有许多适应人工种植的特点。为了提高杨树人工林的生产力，本次研究以 9 年生的 NL-95 无性系为研究对象，研究四种空间配置结构对林分冠层结构，林下植被多样性及生物量的生产，以及杨树人工林林木生长。结果表明，空间配置结构对杨树人工林的植物叶面积指数、平均叶倾角、光合有效辐射、杨树人工林的传输系数具有显著影响。林下植物 Shannon-Wiener 多样性指数和生物量在正方形配置中是更高的，而在 6m ×6m 的配置下 Pielou 均匀度指数更高，因此林下植被具有更大的均匀性。林下植被多样性及林下植被生物量均存在季节性变化，但多样性指数与林下植被生物量在正方形配置下更高。在 9 个生长季后，胸径（DBH）存在显著差异，但生物量、树木材积、树高生长没有显著变化。平均胸径随着配置密度增大而增大，在相同密度配置下，杨树人工林胸径在正方形配置（5m × 5m 和 6m × 6m）下高于长方形结构（3m × 8m，4.5m × 8m）。然而，在树龄为 9 年时，在 5m × 5m 的空间配置下表现出最高的总生物量和材积生长量。此外，间距配置确实影响杨树的干径圆度和冠层结构，在正方形配置（5m × 5m 和 6m × 6m）下具有更好的圆整度和冠层结构。结果表明，种植间距不仅对人工林的冠层结构特征、林下植被多样性、林下植被生物量有显著影响，并且对杨树人工林生产力和杨树木材质量具有显著影响，在相同条件下，5m × 5m 的正方形配置被考虑作为生产杨树胶合板才最好的配置。

关键词：杨树；栽植密度；生物量生产；叶面积指数；Shannon-Wiener 多样性指数；Pielou 均匀度指数；直径圆度

Abstract

Poplar has many characteristics that make it suitable for plantation forestry. In order to improve the productivity of poplar plantation, effects of four planting spacings on stand canopy structure characteristics, tree growth, and understory vegetation diversity, distribution pattern as well as its biomass production in 9-year-old poplar plantations were evaluated for clone Nanlin-95. The results showed that planting spacings significantly influenced leaf area index, mean leaf angle, photosynthetically active radiation, and transmission coefficient of the poplar plantations. Shannon-Wiener index and biomass of the understory were higher in poplar stands with square configuration forms, while the distribution of understory was much homogeneous under poplar stand with 6m × 6m with higher Pielou evenness index. There were seasonal variations in understory vegetation diversity and understory biomass production, but both the diversity indices and biomass of the understory were higher in poplar stands with square configuration forms. After nine growing seasons, there were significant differences in diameter at breast height (DBH), but no significant variations were found in biomass, volume growth, and tree height growth. The mean DBH increased with increasing planting spacings and the DBH in the plantations of square configurations (5m × 5m and 6m × 6m) was higher than rectangular configurations (3m × 8m, 4.5m × 8m) under the same stand density. However, the highest total biomass production and volume growth of the poplar plantation was achieved in the plantation of 5m × 5m spacing at age 9. Moreover, spacing configurations indeed affected stem diameter roundness and crown form of poplar trees, with better circularity percentage and crown formation in square configurations (5m × 5m and 6m × 6m). The obtained results suggest that planting spacing not only significantly affects canopy structure characteristics of the plantation, understory vegetation diversity and its biomass production but also poplar plantation productivity and wood quality, and the square spacing of 5m × 5m could be considered as a best option for poplar plywood timber production at a similar site.

Keywords: Poplar; Planting density; Biomass production; Leaf area index: Shannon-Wiener Index; Pielou evenness index; Diameter roundness

ABBREVIATION

ANOVA	Analysis of Variance
cm	Centimeter
DBH	Diameter at breast height (1.3 m)
FAO	Food and Agricultural Organization of the United Nations
FGHY	Fast-growing and high-yielding plantation project in China
FOC	Flora of China (http://www.efloras.org/flora_page.aspx?flora_id=2)
H	Tree height
h	Hours
ha	Hectare (1ha = 10,000 m^2)
IPC	International Poplar Commission
Kg	Kilogram (1 kg = 1,000 g)
LAI	Leaf Area Index
m	Meter
mg	Milligram
MLA	Mean Leaf Angle
NPC	National Poplar Commission of China
PAR	Photosynthetically Active Radiation
TC	Transmission Coefficient
tonne	1 tonne = 1,000 kg
Yr.	Year

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1. Introduction

China has the fifth most largest forest area around the globe with the total forest area of 208 million hectares in 2013 (State Forestry Adminstration of China, 2013). However, the forest area per capita is only 0.123 hectare, less than one-fourth of the world's average (Wan, 2009) because it's population is the largest around the world with over 1.3 billion. With economic blooming, China has undergone tremendous increase in wood consumption and estimated to triple between 2008 and 2020 (He and Xu, 2011). To satisfy some of this increasingly high timber consumption, China has launched the fast-growing and high-yielding (FGHY) plantation project since 2001. China has established large areas of forest plantations annually and the total area of forest plantations has reached 69.33 million ha (State Forestry Adminstration of China, 2013), that accounts for over one third of the total world's forest plantations in 2013.

Poplar has got growing interests and become preferred tree species for fast-growing plantations in China due to its good characteristics such as wide adaptability to different environmental conditions and silvicultural systems, fast growth rate, high timber yield and responsiveness to tree breeding (Kang et al., 2015; Yikun Wang et al., 2014). In 2012, the total area of poplar plantations around the world was reported as 8.6 million ha and 87.5 % or 7.57 million ha was in China (Yangyang Wang et al., 2014). In Jiangsu province (study site located in this province), poplar has become the major tree species both in plantation forestry and in agroforestry systems since some poplar clones were introduced in the 1970s (Fang et al., 1997).

With increasing establishment of poplar plantations, researches on suitable silvicultural techniques are necessary to get optimum yield and timber quality as well as to use site resources efficiently. Choosing initial spacing is the important first step for plantation programs because it determines efficient utilization of site, and subsequent selection and harvesting options (Smith and Brennan, 2006) and duration of production cycle (Fang et al., 2007). Planting densities and tree spacings have significant effects on the available growing spaces and resources to each planted tree, and crown characteristics (Armstrong et al., 1999; Fang et al., 1999), thereby it affects wood volume growth or biomass increment, and wood quality.

While fast-growing plantations are primarily considered an efficient mean of producing timber, there is increasing interest in their potential contribution to biodiversity conservation (Kanowski et al., 2005). Generally, fast growing species are planted in monoculture and they have obvious advantages over native plants in competition for light, nutrient and water resources (Li et al., 2014). Due to that factor, large-scale forest plantations cause adverse effects on biodiversity (Morris et al., 2008), but some studies pointed out that fast-growing forest plantations might have a balanced effect on biodiversity depends on habitat heterogeneity and differences in planting pattern or land-use history (del Pilar Clavijo et al., 2005). Changes of forest structure after plantation establishment can lead to different forest environments and understory vegetation (Yan et al., 2015). Therefore, changes in environmental conditions after establishment of fast-growing tree plantations were generally considered as key factors affecting understory plant diversity (Archaux et al., 2010; Boothroyd-Roberts et al., 2013; Franklin and Steadman, 2010). Another key factor that affects understory plant diversity are light gradient due to canopy stratification (Christian et al., 1994) and higher transpiration rate (Boothroyd-Roberts et al., 2013; Li et al., 2014). Therefore, the objective of this study was to find out the effects of spacing treatments on stand growth, canopy structure of poplar stands and understory vegetation community.

1.1 Rationale of the study

Due to fast-growing, fine wood quality, and good adaptation, poplar becomes one of preferred tree species for fast growing and high-yield timber plantation and have been the main timber producers in China (National Poplar Commission, 2003). With increasing establishment of poplar plantations, researches on different plantation management and silvicultural practices are important and urgently needed to do. Productivity of plantations mainly depends on choosing or planting suitable species/clones on suitable sites and appropriate silvicultural techniques (Fang et al., 1999). Planting density and spacing affect the growing resources available to each tree and the size and form of logs available at harvest (Thomas et al., 2009). Therefore, choice of the best optimal planting spacing is very important for the maximum production of wood volume or biomass increment and determination of duration of production cycle (Fang et al., 1999).

While sound silvicultural techniques, especially planting density, are focused for optimum yield and timber quality, it is also necessary to take into account impacts on biodiversity. Because, planting density affects on understory vegetation diversity through creating different canopy closure (Merila et al., 2002; Tan et al., 2008). However, researches on impacts of initial planting density and spacing on stand growth, canopy structure and understory vegetation community are quite limited.

1.2 Objectives of the study

Therefore, the main objective of this study is to assess the impacts of initial planting spacing and density on stand growth, canopy structure and understory vegetation in poplar plantations. The specific objectives are:

i. To investigate growth dynamic of poplar plantations with four spacing configurations at two levels of planting density.
ii. To examine differences in canopy structure and crown development patterns of poplar plantations with four spacing configurations at two levels of planting density.
iii. To evaluate changes in species diversity, distribution pattern, and biomass of understory vegetation communities under four poplar plantations along with different spacing configurations and planting densities.

1.3 Conceptual framework

The following conceptual framework was followed to reach the objectives of this study;

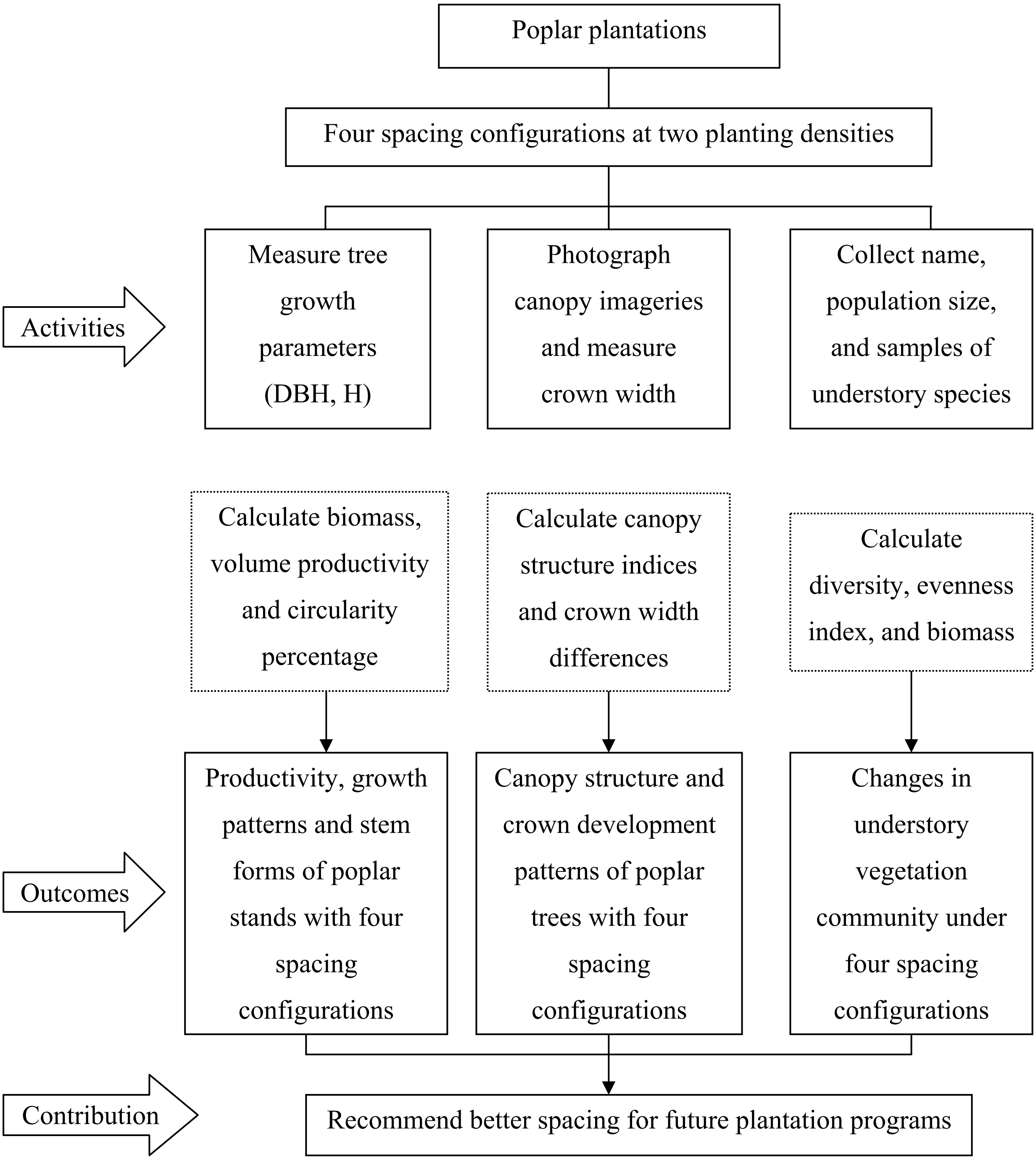


Figure 1. Conceptual framework of the study

2. Literature review

2.1 Ecology of *Populus*

Poplars is the collective name for species of genus *Populus* and widely distributed from sub-tropical to the temperate and boreal regions of northern hemisphere (Karačić, 2005; Zsuffa et al., 1993). According to Chao et al. (2009) , the taxonomical lineage of poplars is as follow;

Kingdom: *Plantae*
  Phylum: *Angiosperms*
    Class: *Eudicots*
      Order: *Malpighiales*
        Family: *Salicaceae*
          Subfamily: *Populoideae*
            Genus: *Populus*

Poplars are single-stem deciduous, broad leaf trees and light demanding that can grow on variety of soil types - yet the best performance is achieved only on deep fresh soils (FAO, 1958). Most of poplars are dioecious, wind pollinated and produce millions of extremely light, cottony seeds by a single tree and dispersed by wind to long distances (Karačić, 2005). Another unique character of poplars is that they can reproduce asexually; they can even sprout form root collar of killed trees or from abscised or broken branches that are embedded in the soil (Rae et al., 2007). Due to extensive interspecific hybridization and high levels of morphological variation among poplars, it is difficult to identify taxonomic units for comparative evolutionary studies and systematics (Hamzeh and Dayanandan, 2004; Rae et al., 2007). According to Eckenwalder (1996); Hamzeh and Dayanandan (2004), the genus *Populus* is classified into six sections - Leuce, Tacamahaca, Aigeiros, Turanga, Populus and Leucoides – that includes 29 species. However, the number of *Populus* species described in the literatures ranges from 22 to 100 plus hundreds of hybrids, varieties, and cultivars (Dickmann and Stuart, 1983; Eckenwalder, 1996, 1977; Hamzeh and Dayanandan, 2004).

2.2 Poplar resources around the world and in China

According to FAO (2012), the total area of natural poplars is over 75 million hectares and 96% of total area is possessed by Canada, Russia and USA. Due to its fast growth rate, fine wood quality and wide utilities, wide adaptability to varieties of ecological sites, poplars become one of the most economically important groups of forest trees (Hamzeh and Dayanandan, 2004; Stettler et al., 1996) and also one of preferred species for fast growing and high-yield timber plantation (NPC, 2003). In 2012, the total area of poplars plantations reached 8.6 million ha and of which 87.5 % (7.57 million ha) is in China. Poplars are cultivated around the world for a variety of purposes ranging from environmental protection to industrial raw materials. Poplars are widely used for pulp and paper, veneer/ plywood, sawn timber, fuelwood and energy, and packaging materials. Moreover, poplars are also used in environmental protection plantations such as windbreaks and erosion control, phytoremediation of environmental toxins and as bioindicators for ozone pollution in the environment (Rae et al., 2007).

According to FOC (1999), 71 poplars species out of totally about 100 species of the world were found in China and 47 of them are endemic to China. The poplar resource of China reported to IPC in 2012 is shown in Table 1.

Table 1. Poplar resource of China in 2012 (modified form IPC 2012 report, FAO)

		Area by function (ha)			
	Total area (ha)	Industrial roundwood	Fuelwood/ biomass	Environmental Protection	Others
Natural forest	2,530,000	-	-	2,403,500	126,500
Plantation	7,570,000	4,542,000	757,000	1,892,500	378,500
Agroforestry	2,800,000	840,000	140,000	1,680,000	140,000
Total	12,900,000	5,382,000	897,000	5,976,000	645,000

2. 3 Yield of poplar plantations with different planting densities

Due to its suitable qualities for plantation forestry, poplar is one of preferred species for short rotation and high-yield plantation programs. The commercial poplar cultivation started since half a century ago and mainly occurs in America, Canada, Europe, and China (Rae et al., 2007). The rotation for poplar plantations ranges from 2 to 30 years, depends on end-uses of poplar trees (FAO, 2012). According to IPC-FAO report, the growth rates of poplar plantations including highly productive poplar clones range from 2.75 to 41 m^3 ha^{-1} $yr.^{-1}$, averaging 17 m^3 ha^{-1} $yr.^{-1}$. In terms of biomass productivity, the mean annual production of poplar plantations in Europe ranges from 2 to 13.5 tonnes ha^{-1} $yr.^{-1}$ (Karačić, 2005). Although, 20 to 30 tonnes ha^{-1} $yr.^{-1}$ was reported for poplar plantations in small plots with irrigation and fertilization treatments, yet cannot be expected from plantations on operational scale (Karačić, 2005; Pontailler et al., 1999). Biomass productivity of poplar plantations with age and planting densities similar with this study ranges between 8.09 and 21.8 tonnes ha^{-1} yr.$^{-1}$ (Table 2). The productivity of poplar plantation is mainly affected by site conditions, planting materials and intensity of silvicultural system (Fang et al., 1999; Karačić, 2005).

Table 2. Productivity of poplar plantations with different initial planting densities

Poplar species/clones	Age	Planting density (stems ha^{-1})	Biomass (tonnes ha^{-1})	Productivity (tonnes ha^{-1} yr.$^{-1}$)	Location	References
Populus deltoides	9	500	92.9	10.32	India	(Das et al., 2011)
P. deltoides clones	10	500	117	11.7	China	(Fang et al., 2007)
P. deltoides clones	6	500	48.5 – 62.24	8.08 – 10.37	India	(Swamy et al., 2006)
P. deltoides	11	487	81.6	7.4	USA	(Bowersox and Ward, 1976)
P. deltoides clone D_{121}	8	400	170	21.8	India	(Lodhiyal et al., 1995)
Populus deltoides	8	-	89.7	11.2	USA	(Carter and White, 1971)

2. 4 Initial planting spacing effects on poplar and biodiversity

Tree growth is function of age, spacing and site quality (Nissen et al., 2001). Khan and Chaudhry (2007) investigated effects of spacing (3.7m × 6.1m; 3.7m × 9.1m; 3.7m × 12.1m) on growth of poplar (*Populus deltoides* clone AY-48) plantations. Their results showed that the spacing treatments had significant effect on DBH and crown width, but no significant effect on height and clean bole. Li et al. (2014) studied the effects of young poplar plantations on understory plant diversity in the Dongting lake wetlands in China. Actually, they compared understory diversities under poplar plantations versus reed areas, and poplar plantations had higher understory plant diversity. They concluded that light availability at ground level is key factor in determining understory plant diversity (148,000 plants/ha in reed areas and 1,666 trees/ha in poplar plantations. Fang et al. (1999) studied the growth dynamics and canopy characteristics of three poplar clones (NL-80351, I-69 & I-72) at four levels of spacing (3m × 3m; 3m × 4m; 4m × 4m; 4m × 5m). They found that spacing significantly affect on DBH and canopy characteristics but no significant effect on H. They stated that the greater the initial planting density, the slower the DBH increase with age. They also found that leaf area indices of three poplar clones increase with increase in planting density. These previous studies showed that spacing treatments or planting density have significant effects on growth and canopy characteristics of poplar stands, and understory diversity. But, these all are different from this study in treatment (spacing systems), site conditions (land use history, climate and soil), and studied species (species or clones).

3. Materials and methods

3.1 Study area

The study site is situated at Chenwei forest farm located in Sihong County, Jiangsu Province of China (33°19′ N, 118°18′ E) (Figure 2). The climate of this area is semi-humid climate in mid-latitude warm zones with long-period of illumination, high accumulated temperature and plentiful rainfall. It gets mean annual precipitation of 972.5 mm, occurring mostly from June to August. The mean annual illumination is 2, 250 ~ 2, 350 h and mean annual temperature is 14.4°C with variation of -7°C in January to 28°C in July. The soil is a clay loam derived from lacustrine sediments.

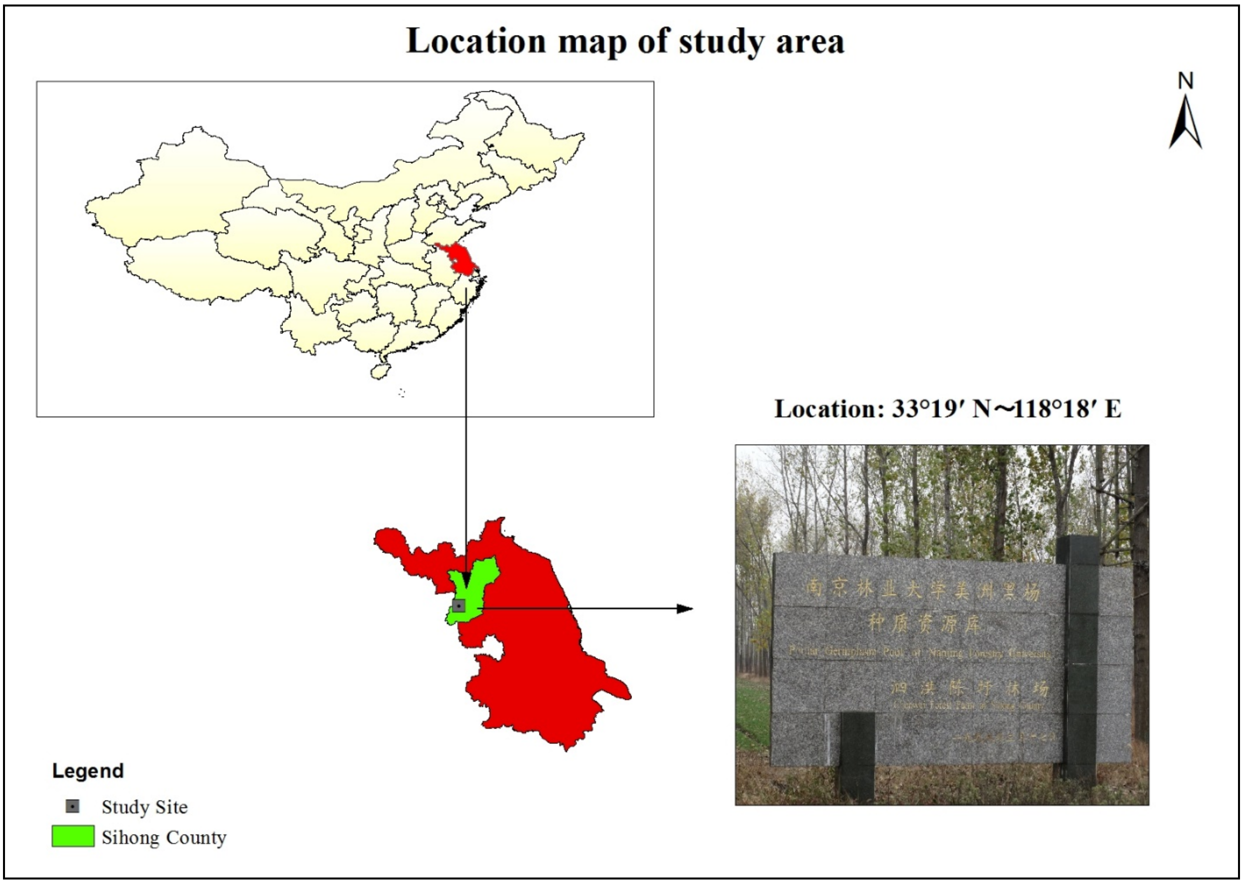


Figure 2. Location map of study area

3.2 Studied plantations

The studied plantation was established in March, 2007 for research purposes in a split-plot design with three poplar clones and four levels of spacing treatment. The planting materials are one-year old seedlings of three poplar clones: Nanlin-95, Nanlin-895 and Nanlin-797. This study was carried out in experiment plots of ‘Nanlin-95’, a hybrid of clone I-69 (*Populus* *deltoids* Bartr. cv. 'Lux') × clone I-45 (*P.* × *euramericana* (Dode) Guineir cv. I-45/51') bred by Nanjing Forestry University, China. Four levels of planting spacing are composed with two configuration forms: two rectangulars (4.5m × 8m and 3m × 8m) and two squares (6m × 6m, 5m × 5m). The spacing 4.5m × 8m and 6m × 6m have same planting density (278 stems ha^{-1}) while spacings of 3m × 8m and 5m × 5m were regarded as having same planting density of 400 stems ha^{-1} (417 and 400 stems ha^{-1}). The main understory plant species are *Bidens pilosa, Imperata cylindrical, Oplismenus undulatifolius, Erigeron annuus, Bromus japonicas, Achyranthes bidentata, Xanthium sibiricum, Enghinochola crusgalli, Cirsium setosum* and *Viola verecu*mba, and dominant families are Compositae, Graminaceae, Amaranthaceae and Violaceae. Three replicates of soil samples form three layers (0 – 10 cm; 10 – 20 cm; 20 – 40 cm) in each plantation were collected and the basic properties of soil were analyzed in soil laboratory of Silviculture Department, College of Forestry. The basic properties of soil under each poplar plantation were presented in Table 3.

Table 3. Basic soil properties of poplar plantations at the research site

Spacing	Soil layers	TN* (g. kg^{-1})	Ava. P (mg. kg^{-1})	Ava. K (mg. kg^{-1})	OM (g. kg^{-1})	pH	BD (g.cm^{-3})
6m × 6m	0 – 10 cm	0.9	6.1	94.3	23.0	6.7	1.38
	10 – 20 cm	0.6	2.7	73.5	20.5	7.1	1.48
	20 – 40 cm	-	2.0	58.9	14.9	7.3	1.48
4.5m × 8m	0 – 10 cm	0.7	3.2	95.8	20.2	6.6	1.29
	10 – 20 cm	0.4	2.4	68.1	15.3	7.1	1.33
	20 – 40 cm	-	2.0	52.5	13.6	7.3	1.36
5m × 5m	0 – 10 cm	0.9	4.1	90.8	21.7	6.6	1.39
	10 – 20 cm	0.5	2.4	52.3	19.0	6.7	1.47
	20 – 40 cm	-	1.5	38.5	13.0	7.2	1.47
3m × 8m	0 – 10 cm	0.9	3.5	108.3	22.1	6.1	1.33
	10 – 20 cm	0.5	1.9	66.6	19.2	6.5	1.40
	20 – 40 cm	-	1.7	60.5	15.9	7.1	1.40

* TN (total nitrogen) values were taken from (Yan et al., 2015); Ava. P = available phosphorus; Ava. K = available potassium; OM = soil organic matter; BD = Bulk density

3.3 Layout of experiment plots

Since plantation was established, three replicates for each spacing treatment were randomly arranged in 12 plots with single plot area of 1200-1800 m^2 containing 49-66 trees per plot. The growth parameters of poplar trees were collected in each plot, and five1m × 1m quadrants were formed in each plot to collect understory vegetation parameters (Figure 3).

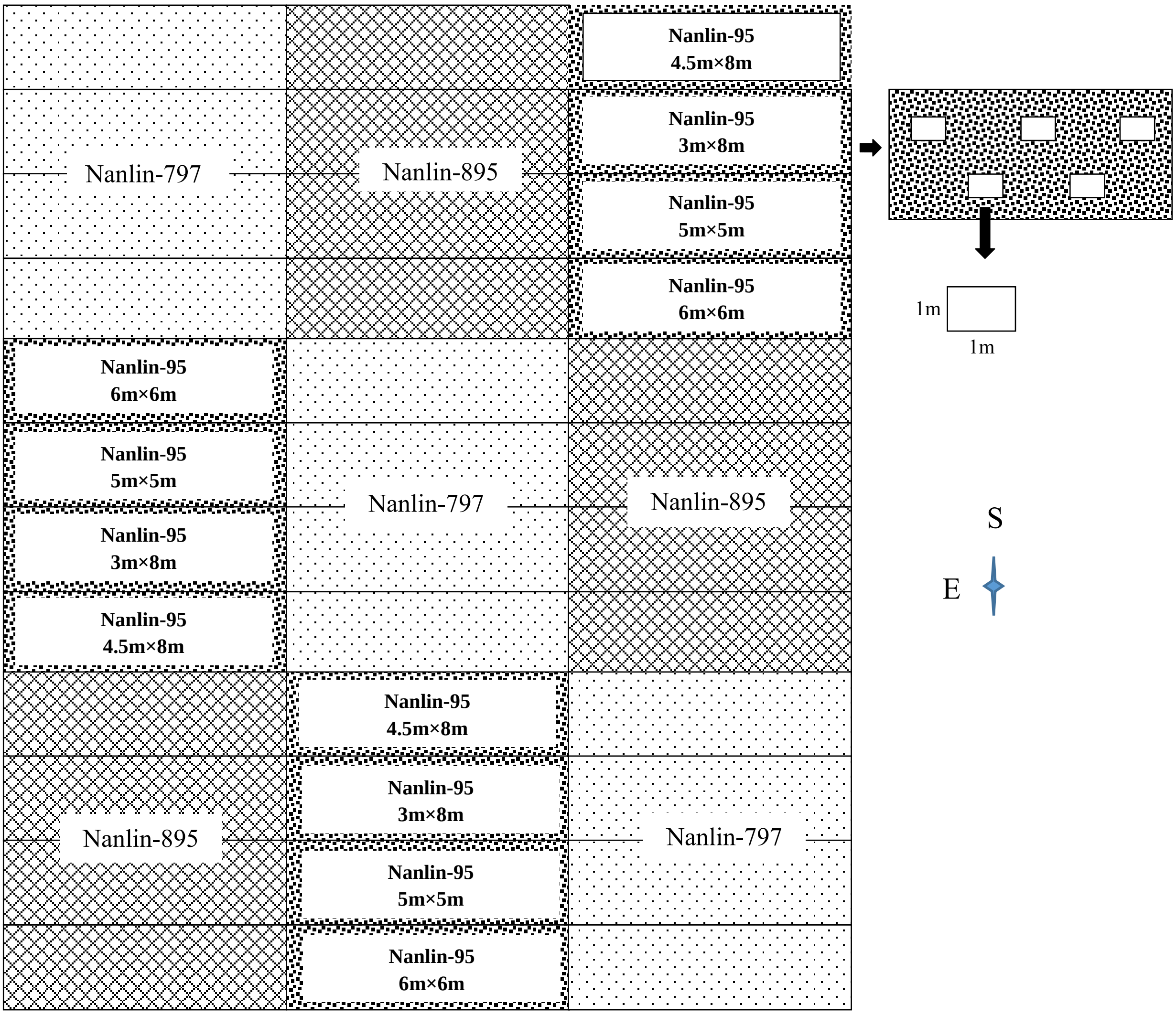


Figure 3. Layout of the studied plantations and sample plots

3.4 Stand growth and biomass measurement

This research is one part of project that has been carried out since plantation was established in 2007. The DBH and height growth data of past 8 years from this project were used to track the growth patterns of poplar stands.

After excluding trees at the outer rows to avoid edge effect, the diameter at breast height (DBH) of 1.3m above the ground level of all trees were measured in November, 2015 assumed as end of growing season. After mean DBH of each plot was calculated, five trees that have plot mean DBH were drawn out for total height measurement. Therefore, height of poplar trees were measured form 15 trees for each spacing treatment and totally 60 trees for four spacing treatments using height measure compass (CGQ-1) manufactured by Harbin Optical Instrument Factory, China. The acquired DBH and height data were used for calculating basal area, volume and biomass of each stand. Moreover, DBH and crown width of ten trees per plot (totally 30 trees per each treatment) were measured in two dimensions – narrow and wide space - to examine the effect of spacing configuration on stem form (circularity) and crown form. To examine the diameter roundness (circularity percentage) of poplar stems and the difference in crown width of two dimensions, the following equations were used:

$$\text{Circularity (\%)} = \frac{D_{min}}{D_{max}} \times 100 \text{ (Luo et al., 2013)} \qquad (1)$$

Where, D_{min} is minimum diameter and D_{max} is maximum diameter

$$\text{Difference (\%)} = \frac{(W_{max} - W_{min})}{\left[(W_{max} + W_{min})/_{2}\right]} \times 100 \qquad (2)$$

Where, W_{min} is maximum crown width and W_{min} is minimum crown width.

In this study, diameter and crown width of poplar trees in wide space (8m) are greater than that of narrow space (3 m and 4.5 m) in rectangular configuration. Therefore, D_{min} and W_{min} refer to DBH and crown width of narrow space – 3m and 8m, while D_{max} and W_{max} refer to DBH and crown width of wide space – 8m. In square configuration, the diameter and crown width of poplar trees did not show persistent difference between two dimensions as if rectangular configuration. Therefore, D_{min} and W_{min} simply refer to smaller values and D_{max} and W_{max} to bigger values between two dimensions.

After field data collection of tree parameters was finished, stand basal area was calculated using mean DBH of each plot and expanded to hectare basic. Biomass accumulation in tree components (W, Kg) – stem, branch, leaf, root - of a mean-tree for each spacing treatment was estimated using the following formulae proposed by Tang et al. (2004). Then, the total number of trees per hectare for each spacing treatment – 278 for 6m × 6m and 4.5m × 8m, 400 for 5m × 5m, and 417 for 3m × 8m - were used to expand mean-tree values to hectare basic.

$$\text{Log } W_{\text{leaf biomass}} = 0.4489 \text{ Log } (D^2H) - 1.1455 \quad (3)$$

$$\text{Log } W_{\text{branch biomass}} = 0.9911 \text{ Log } (D^2H) - 2.3791 \quad (4)$$

$$\text{Log } W_{\text{stem biomass}} = 1.0659 \text{ Log } (D^2H) - 2.1305 \quad (5)$$

$$\text{Log } W_{\text{root biomass}} = 0.7061 \text{ Log } (D^2H) - 1.2588 \quad (6)$$

Where, D is mean DBH (cm); H is mean tree height (m).

Similarly, stand volume was calculated using the following formula proposed by Ren (2010) and expanded to hectare basic using total number of trees per hectare.

$$V = \left[\frac{\pi D^2}{40000 \times 2.7356}\right] \times \left[\frac{H^{2.7356}}{(H-1.3)^{1.7356}}\right] \quad (7)$$

Where, V is volume (m^3); D is mean DBH (cm) and H is mean tree height (m)

3.5 Canopy structure measurement

Digital plant canopy imageries were obtained in a cloudless twilight afternoon with a little sunshine in August using a CI-110 Digital Plant Canopy Imager (CID Bio-Science, Inc., Camas, WA, USA). A fisheye lens was firstly attached to an observation rod and placed at 1.0 m above the ground in the center of the rows while taking the canopy imageries. Seven hemispherical imageries were taken for each plot to evaluate the canopy structure characteristics of each spacing treatment. The evaluated canopy structure indicators were leaf area index (LAI), mean leaf angle (MLA), intercepted photosynthetically active radiation (PAR), and transmission coefficient (TC) and these all data were calculated by CID's CI-110 image analysis software (Version 3.0.2.0, 16 August 2002).

3.6 Collection of understory vegetation parameters

The observations on understory vegetation community were carried out in May, August and October, 2015 to cover three seasons: spring, summer and autumn. The understory species of the studied poplar plantations are herbaceous species. To collect understory vegetation parameters, five 1m × 1m quadrants were formed in each plot. In each quadrant, name and number of each species were recorded and species identification was carried out in laboratory of Nanjing Forestry University. And, the full harvest method was applied to determine aboveground biomass accumulation of understory vegetation. The collected understory vegetation samples were oven-dried at 65 °C to constant weight for biomass estimation. Firstly, the understory biomass was calculated at plot-level and then, expanded to an area basic.

3.7 Statistical analysis

All biomass results were expressed on oven-dry weight basis and reported as mean (±standard deviation) of three field replications. One-way ANOVA was used to determine significance in detected indices among the four planting spacing treatments, and Duncan's test was performed for all pairwise comparisons. The Pearson correlation analysis was also performed to examine relationship between canopy structure indicators of poplar plantations. All analyses were carried out using SPSS 19 statistical software package (SPSS Inc., Chicago, IL, USA). The diversity and distribution patterns of understory vegetation under each spacing treatment were evaluated through Shannon-Wiener diversity index and Pielou evenness index (Li et al., 2014; Yang and Sun, 2013) using the following formulae:

（1） Shannon-Winer Index

$$H' = -\sum_{i=1}^{S}(pi \times ln\, p\, i) \tag{8}$$

（2） Pielou Evenness Index

$$E = H'/lnS \tag{9}$$

Where S is the number of species present per sub-plot, p_i is the ratio of species i (N_i) to the total number of species (N), which is $p_i = N_i/N$.

4. Results and discussion

4.1 Tree growth of poplar plantations

4.1.1 Diameter and height growth patterns

The basic stand structure of four studied plantations is presented in Table 4. Among four plantations, plantations with wide spacing configuration had greater mean DBH and mean height values, but smaller mean basal area values. However, mean basal area contributed by individual tree was higher in wide spacing plantations and 6m × 6m spacing treatment had the highest value with 0.045 m^2 and followed by 0.042 m^2 in 4.5m × 8m, 0.034 m^2 in 5m × 5m and 0.032 m^2 in 3m × 8m. Between configuration forms, mean DBH of the 6m × 6m spacing treatment was 14.35 % greater than 5m × 5m while 4.5m × 8m was 13.86% greater than 3m × 8m. The mean height of four spacing treatments ranged from 21.8m in 3m × 8m to 23.9m in 6m × 6m and the wide spacing plantations were greater than 1.35% in square configuration form and 4.59% in rectangular form.

Table 4. Basic stand structure of poplar plantations with four spacing configurations

Spacing	Planting density(trees/ha)	DBH (cm) Min: ~ Max:	Mean DBH (cm)	Mean Height (m)	Mean Basal Area (m^2/ha)
6m × 6m	278	16.2 ~ 28.5	23.9± 0.34	22.5±1.96	12.47± 0.35
4.5m × 8m	278	14.6 ~ 28.2	23.0± 0.69	22.8±0.83	11.55 ±0.69
5m × 5m	400	14.4 ~ 26.3	20.9± 1.31	22.2±1.45	13.69 ±1.71
3m × 8m	417	11.8 ~ 24.8	20.2± 0.80	21.8±0.91	13.23± 0.88

The distribution of poplar trees in different DBH classes showed different patterns between narrow and wide spacing plantations: more trees fell in big DBH classes in wide spacing plantations while more trees in middle and small DBH classes in narrow spacing ones. The ANOVA analysis showed that there were significant differences in diameter growth among four plantations ($p= 0.01; F= 14.069$). The Duncan's test showed that diameter growth between two planting densities was significantly different, but no significant difference between two configuration forms – rectangular and square – at same planting density (Figure 4). The height growth of four plantations was not significantly different according to ANOVA result ($p=0.80;$ $F=0.331$).

These results pointed out that the diameter growth has significant response to initial planting density, and diameter growth decreased with increased planting density (23.4 cm in 278 stems ha^{-1} and 20.5 cm in 400 stems ha^{-1}). These results were in line with other studies by Khan and Chaudhry (2007) and Fang et al. (1999) where the greater the initial planting density, the slower the DBH increment with age. The decreased tree growth with high planting density can be due to competition over growing resources such as light, water and nutrients and that will effect on crown size, leaf area and synthesis of carbohydrates and hormonal growth regulators (Misra et al., 1996).

However, the planting densities and spacing configuration in this study did not show significant effect on height growth of poplar stands (Figure 5b) and this result agreed with other studies (Bisaria et al., 1999; Fang et al., 1999; Khan and Chaudhry, 2007; Misra et al., 1996). Our results supported the point that tree height growth is not affected by increasing planting density within a certain planting density range, but significantly modified by site and genotype (Toillon et al., 2013).

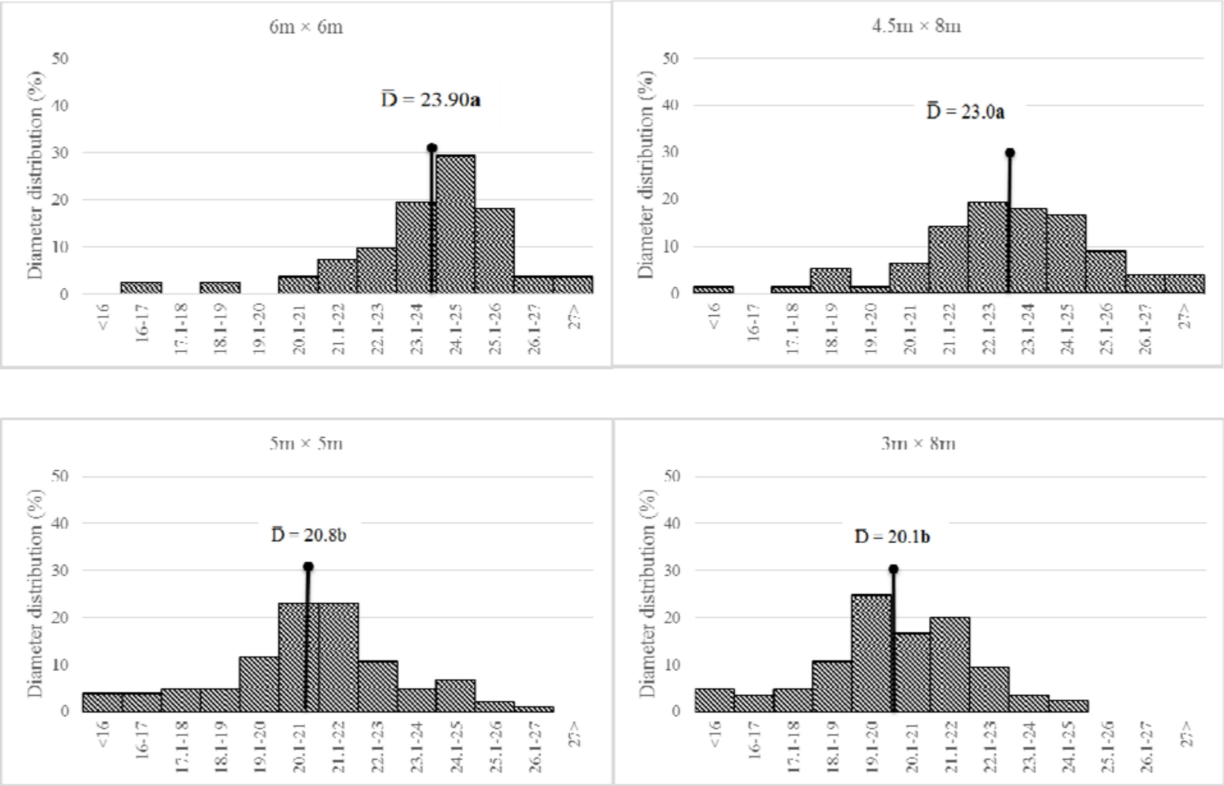


Figure 4. Relative distribution of diameter classes expressed as percentage of total in different spacing treatments. Different letters represent significant difference in diameter growth between spacing treatments according to Duncan's test at $p<0.05$.

The diameter growth over nine growing seasons showed two phases of growth pattern: the first phase before canopy closure and second one at canopy closure stage (Figure 5a). All of studied plantations – both wide and narrow spacing plantations - showed same pattern and reached the maximum mean annual diameter growth at fourth growing season and afterwards decreased with age. At the end of first phase, plantations with wide spacing reached maximum mean annual diameter growth of 3.58 cm yr.$^{-1}$ in 6m × 6m and 3.54 cm yr.$^{-1}$ in 4.5m × 8m and decreased to 2.66 cm yr.$^{-1}$ and 2.56 cm yr.$^{-1}$ at the end of ninth growing season. Meanwhile, plantations with narrow spacing had maximum mean diameter growth of 3.42 cm yr.$^{-1}$ in 5m × 5m and 3.36 cm yr.$^{-1}$ in 3m × 8m at the end of first phase and decreased to 2.42 cm yr.$^{-1}$ and 2.32 cm yr.$^{-1}$ at the end of ninth growing season.

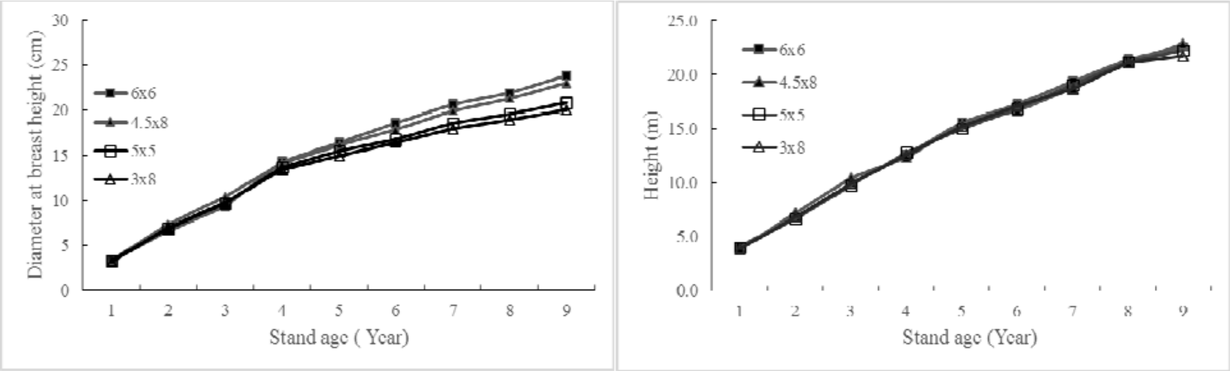
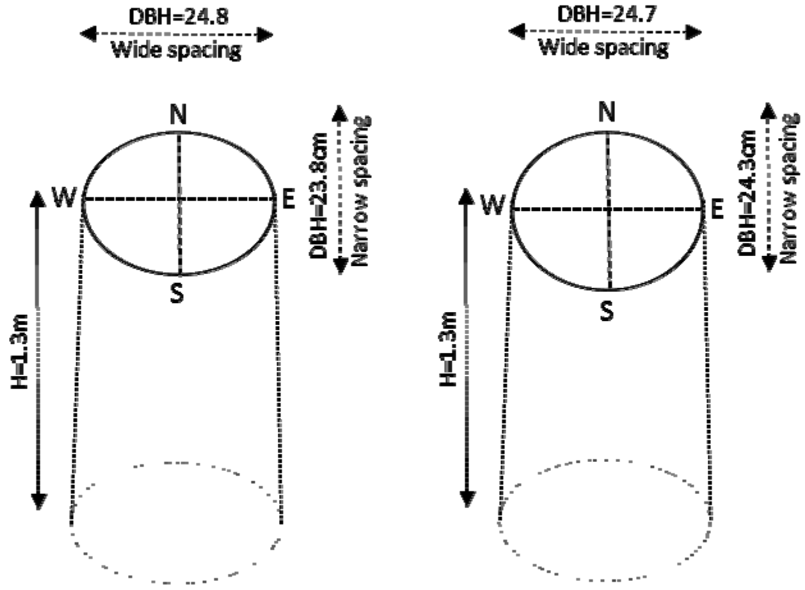


Figure 5. (a) Growth patterns of mean DBH and (b) mean height of poplar plantations with four spacing configurations over nine growing seasons

Before canopy closure stage, planting densities did not have significant effect on diameter growth, and difference between mean diameter of wide spacing and narrow spacing plantations was only 4.97 %. But, this difference became significant and increased to 13.21% after canopy of poplar trees touched. In another studies by Fang et al. (1999); Khan and Chaudhry (2007), the duration of first phase ranged from 3 to 5 years depend on initial stand density and they stated that the lower the density, the longer the time to canopy closure stage. Our result was in agreement with their findings because the planting densities in this study were within the range of their studies (230 stems ha^{-1} - 1111 stems ha^{-1}).

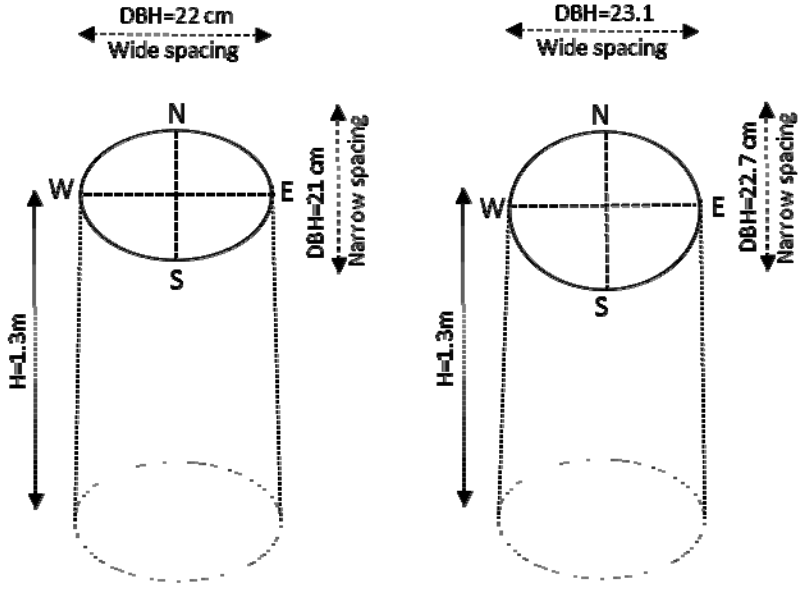
4.1.2 Diameter roundness (circularity percentage) of poplar trees

To investigate the effects of spacing configuration on stem form, diameter of poplar trees were also measured in two dimensions, e.g. DBHs were measured along with both 3m and 8m rows in the case of 3m × 8m spacing treatment. The mean DBH values of poplar trees in two dimensions were similar in square configuration (24.7 cm and 24.3 cm in 6m × 6m; 23.1 cm and 22.7 cm in 5m × 5m). However, in poplar stands with rectangular forms, DBH growth with wide space (8 m rows) was higher than narrow space (4.5 m and 3m rows). In 4.5m × 8m stand, mean DBH with wide space (8 m) was 24.8 cm and 23.8 cm in narrow space (4.5 m) while 22 cm and 21 cm in 3m × 8m stand (Figure 6).



a : 4.5m × 8m spacing
Circularity % = 95.9±3.10 %

b : 6m × 6m spacing
Circularity % = 98.4±2.48 %



c : 3m × 8m spacing
Circularity % = 95.2±3.76 %

d : 5m × 5m spacing
Circularity % = 98.1±2.27 %

Figure 6. The schematic diagram of diameter roundness under four spacing treatments

Also the two configuration forms revealed different circularity percentages: plantations with square configuration showed better diameter roundness with higher circularity percentage 98.4% in 6m × 6m and 98.1% in 5m × 5m than 95.9% in 4.5m × 8m and 95.2% in 3m × 8m. Results from this investigation suggested that the DBH growth was not significantly affected by spacing configuration forms with the same planting density, but spacing forms indeed affected stem diameter roundness of poplar trees. One of major utilizations of poplar wood in China is for plywood production, and stem roundness is important for peeling process of plywood timber because the stem roundness will affect production cost, rotation length and outturn percentage of plywood.

4.1.3 Stand volume growth

After nine years, plantations with more planting density had greater stand volume growth with 123.43 m^3 ha^{-1} by 5m × 5m and 116.65 m^3 ha^{-1} by 3m × 8m. Between each two configuration forms with same planting density, 5m × 5m configuration is greater than 8.4% of 113.86 m^3 ha^{-1} in 6m × 6m, and 3m × 8m configuration is greater than 9.3% of 106.73 m^3 ha^{-1} in 4.5m × 8m. Plantations with more planting density also had higher mean annual volume growth over nine growing seasons: 13.83 m^3 ha^{-1} in 5m × 5m spacing and followed by 13.39 m^3 ha^{-1} in 3m × 8m, 12.57 m^3 ha^{-1} in 6m × 6m and 11.65 m^3 ha^{-1} in 4.5m × 8m orderly (Figure 7b). However, ANOVA analysis showed that there were no significant differences among volume growth of four poplar plantations (*$p=0.349$; $F=1.267$*). And, Duncan's test also pointed out that there was no significant difference between two planting densities, and between two configuration forms (Figure 7a).

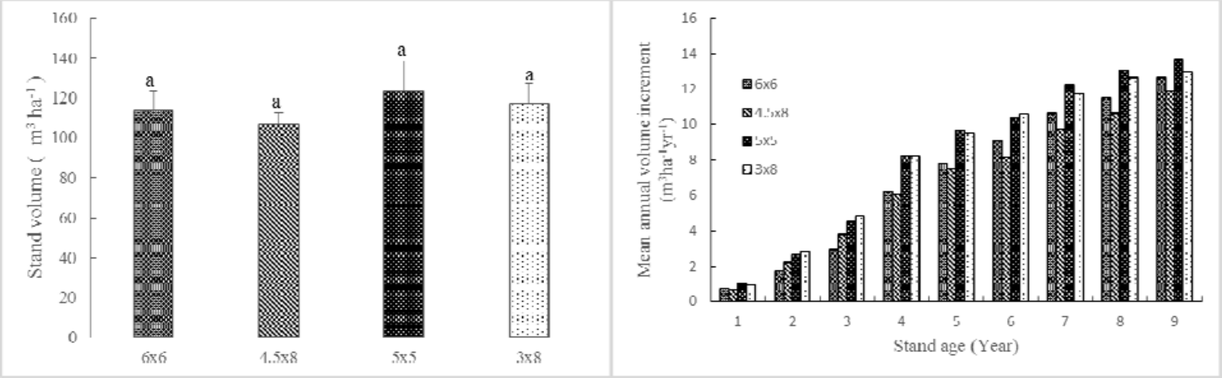


Figure 7. (a) Volume growth of poplar plantations with four spacing configurations; same letters indicate no significant difference in volume growth among four plantations at $p<0.05$

(b) Mean annual volume increment of poplar plantations over nine growing seasons

In this study, volume productivity of poplar plantations increased with increase in planting density because narrow spacing plantations had higher total volume production and mean annual volume increment. This result agreed with Khan and Chaudhry (2007) and the volume productivity of studied plantations are comparable with 8-year old poplar plantations that have similar planting density in their study: 12.11 $m^3ha^{-1}yr^{-1}$ (278 stems ha^{-1}) vs 12.2 $m^3ha^{-1}yr^{-1}$ (305 stems ha^{-1}).

4.1.4 Biomass production

The biomass accumulation by tree components and productivity of poplar plantations are presented in Table 5. The higher total biomass accumulation and productivity were found in narrow spacing plantations. Among four plantations, 5m × 5m spacing plantations possessed the highest biomass accumulation at the end of ninth-growing season with 89.23 tonne ha^{-1}, which is 9.7% greater than biomass accumulated by 6m × 6m spacing plantation. On the other hand, 3m × 8m spacing plantation accumulated 11.2% greater than 76.50 tonne ha^{-1} of 4.5m × 8m. However, ANOVA analysis showed that there were no significant differences in biomass accumulated by four poplar plantations ($p= 0.278; F= 1.540$) and between two spacing configurations forms.

Table 5. Biomass production and productivity of nine-year old poplar plantations (within a column, different superscripts indicate significant difference between spacing treatments according to Duncan's test ($p<0.05$))

Planting spacing (m)	Biomass production (tonne ha^{-1})					Productivity (tonne ha^{-1} $yr.^{-1}$)
	Stem	Branch	Leaf	Root	Total	
6 × 6	49.44 ^{a} ±4.907	13.74^{a} ±1.271	5.95^{b} ±0.253	12.21^{b} ±0.811	81.34^{a} ±7.24	9.04
4.5 × 8	46.15^{a} ±2.701	12.89^{a} ±0.702	5.78^{b} ±0.143	11.67^{b} ±0.454	76.50^{a} ±4.00	8.50
5 × 5	52.46^{a} ±7.071	14.89^{a} ±1.863	7.52^{a} ±0.419	14.35^{a} ±1.268	89.23^{a} ±10.62	9.91
3 × 8	49.43^{a} ±4.569	14.14^{a} ±1.213	7.52^{a} ±0.289	14.00^{a} ±0.852	85.09^{a} ±6.92	9.45

The ranking of biomass accumulation in tree components was stem > branch > root > leaf for all plantations. In percentage, stems contributed 58.1 – 60.8 % to total biomass and followed by branches with 16.6 – 16.9 %, roots with 15.0 – 16.5 % and leaves with 7.3 – 8.8%. The ANOVA analysis for mean biomass values accumulated by different tree components showed no significant differences, apart from leaf ($p= 0.000; F= 32.096$) and root component ($p= 0.015; F= 6.505$).

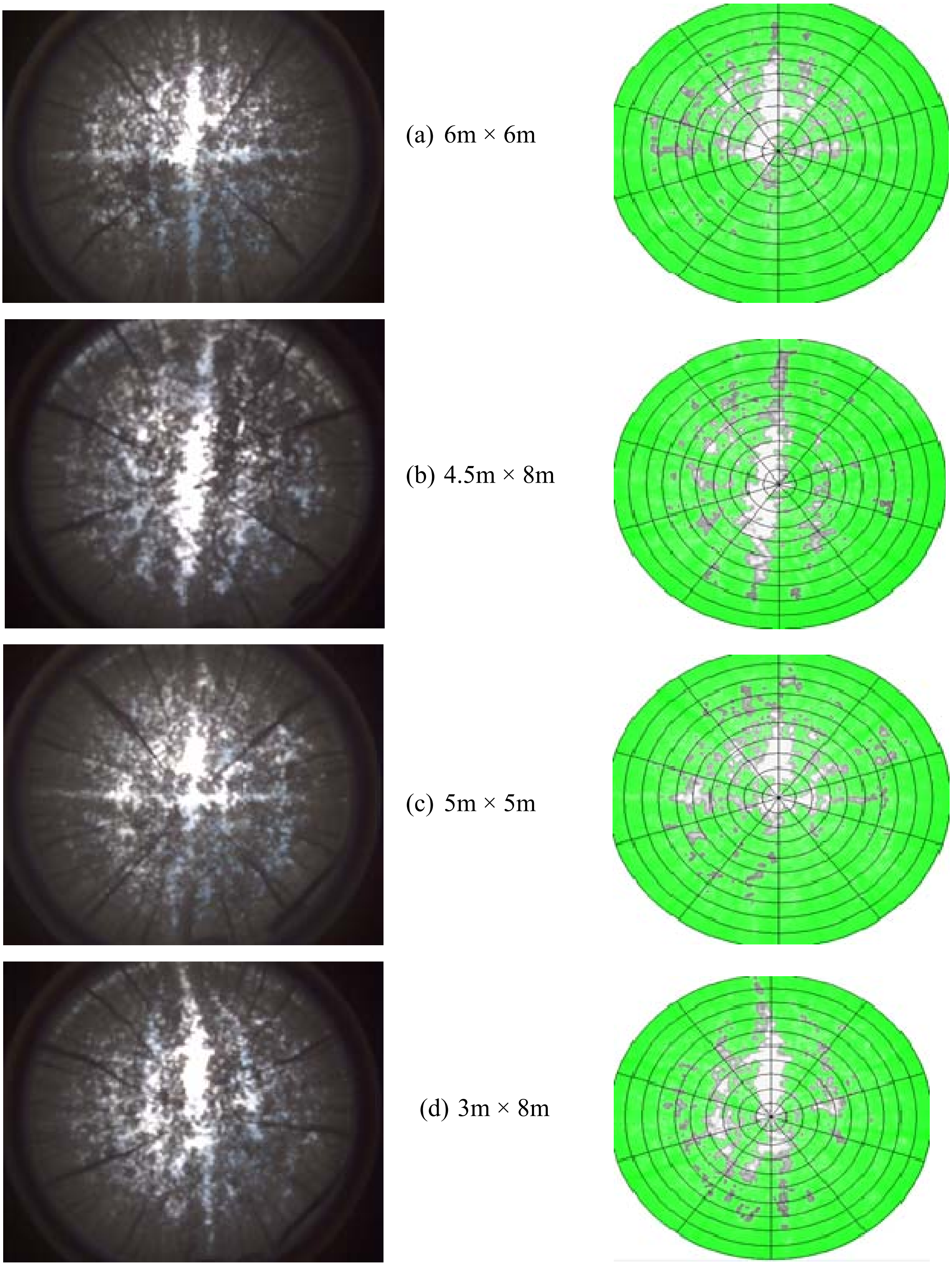
This study results showed that the initial planting density has effect on biomass accumulation and productivity, but no statistically significant. The ranking of biomass productivity among studied plantations was 5m × 5m (400 stems ha^{-1}) > 3m × 8m (417 stems ha^{-1}) > 6 m × 6m (278 stems ha^{-1}) > 4.5m × 8m (278 stems ha^{-1}). The biomass productivity increased with enhancing planting density, and this was in line with other studies by Fang *et al.* (1999, 2010). Compared to data of other studies (Ajit et al., 2011; Bowersox and Ward, 1976; Carter and White, 1971; Fang et al., 2010, 1999; Lodhiyal, L.S., Singh, R.P. & Singh, 1995; Swamy et al., 2006), the biomass accumulation and growth rate of this study fell within the range reported for poplar plantations. All of these studies reported that biomass productivity increased with higher planting density and thus, this study results were in agreement with their findings. The biomass productivity of this study is also comparable with productivity of 9 and 10-year-old poplar plantations in India (Das et al., 2011) and in China (Fang et al., 2007).

Among tree components, stems of poplar trees shared highest percentage of total biomass with average value of 59.5% over four plantations and followed by branches (16.8%), roots (15.7%) and leaves (8%) orderly. This distribution pattern is similar with another study in China by Fang *et al.* (2010), but the contribution by leave component to total biomass in their study was higher than this study (10.8%). Fang *et al.* (1999) stated that more dry matter (biomass) is distributed to foliage and branches, but less to stem wood and stem bark as spacing increased. The planting densities in their study are 94, 167 and 250 stems ha^{-1} and lower than this study of 278 and 400 stems ha^{-1}.

4.2 Canopy structure characteristics

4.2.1 Variation in canopy structure indices

The plant canopy imageries were taken in August to investigate the effect of planting spacing and density on canopy structure characteristics. The hemispherical canopy images of poplar plantations with four spacing configurations were shown in Figure 8. In these pictures, the different configuration patterns of tree canopies can be seen clearly. The evaluated canopy structure indices are leaf area index (LAI), mean leaf angle (MLA), transmission coefficient (TC) for diffuse radiation and intercepted photosynthetically active radiation (PAR). The ANOVA analysis showed significant differences among canopy indices of four poplar plantations: LAI ($p=0.000; F=25.679$); TC ($p=0.004; F= 7.17$); PAR ($p= 0.000; F= 39.435$) and MLA ($p= 0.005; F= 7.075$) (Table 6).



(a) 6m × 6m

(b) 4.5m × 8m

(c) 5m × 5m

(d) 3m × 8m

Figure 8. Hemispherical canopy images of poplar plantations with different four sapcing configurations (taken in August, 2015)

In the context of canopy structure characteristics, the significant differences were not found between two planting densities. However, significant differences were found in LAI and TC of two spacing configuration forms. Among four plantations, plantations with square configuration had higher LAI, PAR, and lower TC values.

Table 6. The canopy structure indices of poplar plantations with four spacing treatments (Within column, different letters indicate significant differences between four spacing treatments by Duncan's test at $p<0.05$))

Spacing	**LAI** (m^2m^{-2})	**MLA**	**TC**	**PAR** ($molm^{-2}s^{-1}$)
6m × 6m	2.513±0.19**a**	73.1±2.81**a**	0.200±0.01**b**	255.62±6.84**a**
4.5m × 8m	1.916±0.12**c**	57.0±8.09**b**	0.224±0.02**a**	214.95±0.62**c**
5m × 5m	2.483±0.06**a**	70.4±4.88**a**	0.198±0.01**b**	240.23±5.94**b**
3m × 8m	2.230±0.12**b**	72.1±6.65**a**	0.235±0.01**a**	232.94±7.61**b**

Canopy structure plays an important role in productivity and yield of forest plantations as it comprises leaf orientation and distribution, and thereby affecting canopy density, influencing on light interception and carbon assimilation (Broeckx et al., 2012). In this study, LAI is one-half of the total green leaf area per unit ground area and MLA is the average angles between the foliage and the horizon (Qin et al., 2014). On the other hand, PAR and TC are important indicators for the (solar) energy absorption capacity of a vegetation canopy (Fensholt et al., 2004; Schaefer et al., 2013). The LAI in this study ranged from 1.91 to 2.51 and fell within the range of 0.6 – 4.5 reported by other studies (Fang et al., 1999; Swamy et al., 2006). Plantations with higher LAI values had higher PAR and lower TC values, and these results are in line with other studies by Bolstad and Gower (1990); Luo et al. (2014). The 6m × 6m plantation had the highest mean leaf angle and followed by 3m × 8m > 5m × 5m > 4.5m × 8m orderly. The flux of solar radiation per unit leaf area is influenced by leaf angle, and steeper leaf angles increase light capturing by leaf surface at low sun angles (morning/ afternoon and winter), while decrease at high sun angles (midday and summer) (Falster et al., 2003).

4.2.2 Correlation between evaluated canopy structure indices

Leaf area index (LAI), mean leaf angle (MLA), transmission coefficient (TC) are the main indices for light radiation within the canopy and there is a close relationship among these indices (Hu and Lan, 2001, 1999). Therefore, the Pearson correlation analysis was carried out to evaluate the relationship among these canopy structure indices. The correlation analysis results showed that PAR is positively correlated with LAI and MLA, and negatively correlated with TC. Inversely, TC is negatively correlated with LAI and MLA (Table 7).

Table 7. Pearson correlation coefficients between leaf area index, mean leaf angle and transmission coefficient and photosynthetically active radiation

	LAI	**MLA**	**TC**
TC	-.624**	-.049	-
PAR	.811**	.696**	-.442

**. Correlation is significant at the 0.01 level (2-tailed).

These results were in line with the statement by Hu and Lan (1999); LiHuogen and HuangMinren (1998) where they stated that light interception by tree canopy is influenced by LAI and it rises along with the increasing LAI. And, the photosynthetic rate can be affected by light interception and photosynthetic capacity of tree canopy can increase with appropriate increase of light interception, and stand production will increase accordingly.

4.2.3 Crown development of poplar trees

Tree canopy is the interface between the land and atmosphere, and influences on process of fixing atmospheric carbon into biomass and releasing oxygen and water (Smith et al., 2008) and determines tree growth, carbon sequestration and shading (Pretzsch et al., 2015). Therefore, crown widths of poplar trees with different spacing configurations were investigated as in dimeter roundness investigation. Among four plantations, plantations with wide spacing configuration had greater mean crown width – 5.9 m in 4.5m × 8m; 5.7m in 6m × 6m – than narrow spacing plantations with 5.4m in 3m × 8m and 4.9m in 5m × 5m. This can be due to more space for crown development in wide spacing plantations. Similar with diameter roundness results, spacing configuration forms had significant effect on crown development. Crown width in wide space – e.g. crown width in 8m row of rectangular spacing forms – was greater than that in narrow spaces. In 4.5m × 8m plantation, mean crown width in 8m row was 6.76 m and 5.12 m in 4.5m row while 6.36 m in 8m row versus 4.49 m in 3m row of 3m × 8m plantation. However, there were no significant differences in crown width of poplar trees in square spacing plantations: 5.67 m versus 5.73 m in 6m × 6m; 5.08m versus 5.25 m in 5m × 5m. Accordingly, the difference percentage values between crown width of two dimensions – wide and close – were higher in rectangular configuration forms. The highest value was found in 3m × 8m as 34.4% and followed by 4.5m × 8m with 27.4%. However, difference percentage values of two square configurations were quite low with 1.10% in 6m × 6m and 3.2% in 5m × 5m (Figure 9). Smith et al. (2008) stated that canopy structure and formation is influenced by arrangement of individual trees, differences in species morphology, light and soil nutrients availability and many other factors.

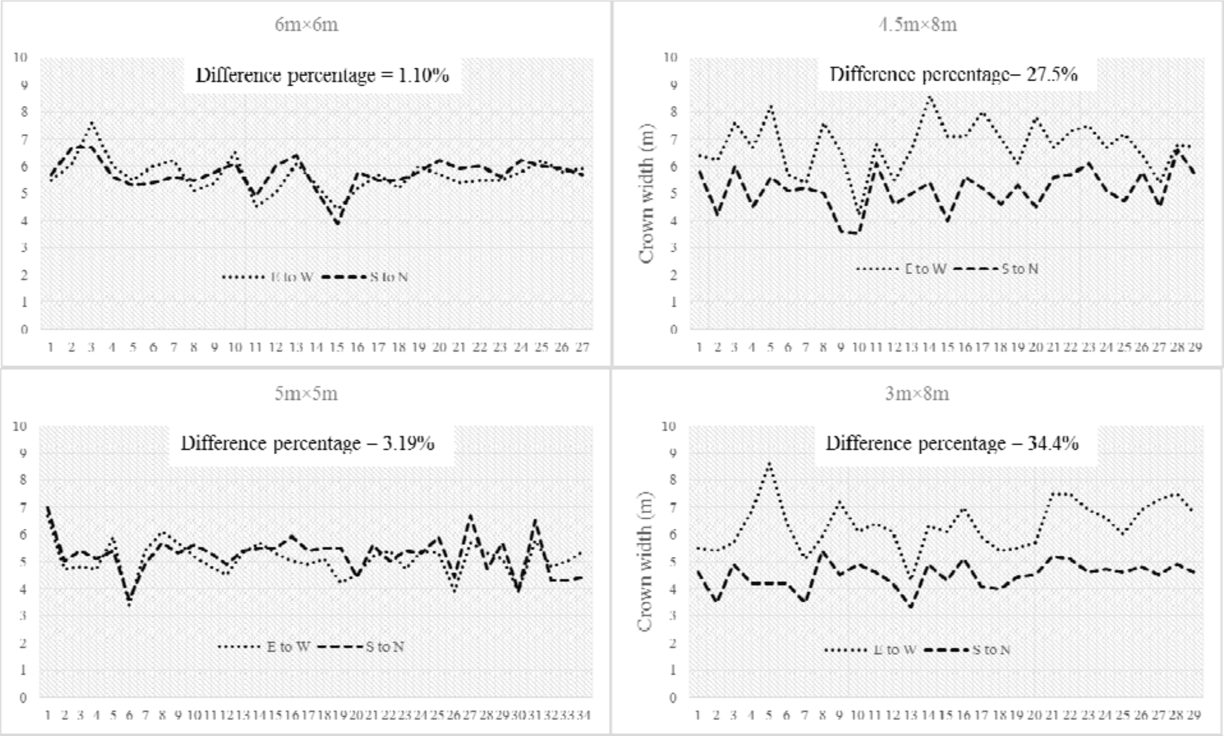


Figure 9. Crown development patterns of poplar trees with four spacing configurations (E to W (east to west) = wide space; S to N (south to north) = narrow space)

4.3 Understory vegetation diversity, distribution pattern, and biomass production

Understory vegetation parameters were collected for three months – May, August, and October – to cover three seasons: spring, summer and autumn. The Shannon-Wiener's index and Pielou's index were calculated to examine changes of diversity and distribution of understory vegetation along with different planting densities and spacing configurations. Biomass of understory vegetation community was also calculated to examine the effects of spacing configurations and planting densities on understory vegetation community.

4.3.1 Diversity of understory vegetation

The ANOVA analysis showed that there were significant differences in diversity indices among four plantations for August (*$p= 0.04; F= 4.705$*), but no significant differences for another two months (spring and autumn). According to Duncan's test, the diversity indices of two spacing configuration forms were significantly different each other in summer, but not in another two seasons (Figure 10). Among four plantations, the 6m × 6m spacing plantation had the highest diversity index with 1.32 and followed by 5m × 5m with 1.21, 3m × 8m with 1.03 and 4.5m × 8m with 1.01 respectively. For two configuration forms, the square configuration stands had higher diversity indices than rectangular ones. The diversity indices of four plantations showed seasonal variations and the highest diversity index value was found in summer and the lowest in spring.

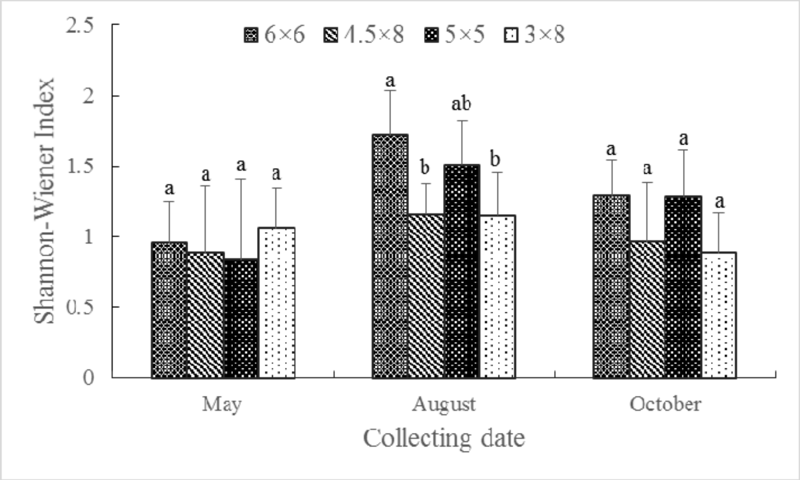


Figure 10. The Shannon-Wiener Indices of understory vegetation under four poplar plantations over three seasons. Different letters indicate significant differences between diversity indices of poplar plantations according to Duncan's test at *p<0.05*.

4.3.2 Distribution patterns of understory vegetation

The distribution patterns of understory vegetation were examined using Pielou's evenness index. The ANOVA analysis showed that there were no significant differences in Pielou's indices of four poplar plantations (Figure 11). But, the highest evenness value was found in 6m × 6m plantation and the ranking order is 6m × 6m (0.823) > 3m × 8m (0.809) > 4.m × 8m (0.774) > 5m × 5m (0.717). The evenness indices also showed seasonal variation: the highest value was in autumn while the lowest in spring.

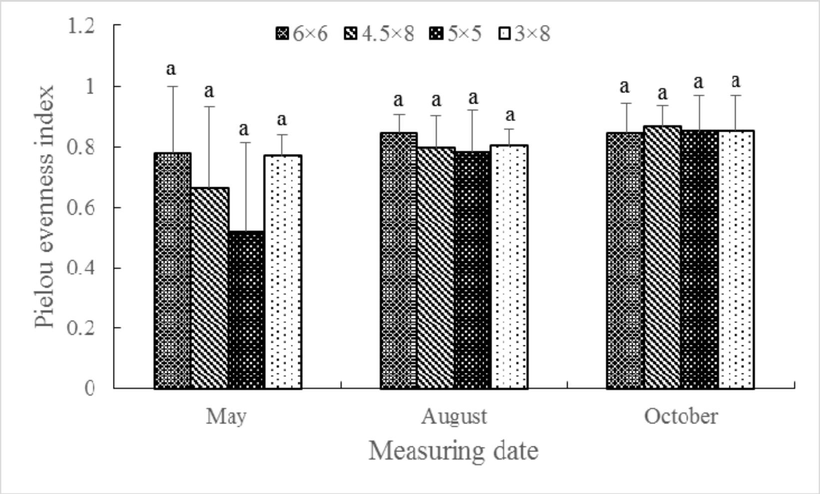


Figure 11. The Pielou's evenness indices of understory vegetation under poplar plantations with four spacing treatments over three seasons. Same letters indicate no significant differences in evenness indices of poplar plantation according to Duncan's test at *p<0.05*.

4.3.3 Biomass production of understory vegetation

The biomass accumulations by understory vegetation in each poplar plantation were also calculated to examine the effects of spacing and planting density treatments. The ANOVA analysis results showed that there were significant differences in biomass productivity of understory vegetation community among four plantations in all seasons: May ($p=0.000; F=26.47$); August ($p= 0.000, F= 49.63$) and October ($p= 0.000, F= 15.03$). The significant differences between each four plantations according to Duncan's test were shown in Figure 12. The understory vegetation community in 6m × 6m plantation possessed the highest biomass accumulation and the ranking order is 6m × 6m (320.1 kg ha^{-1}) > 5m × 5m (203.3 kg ha^{-1}) > 3m × 8m (157.8 kg ha^{-1}) > 4.5m × 8m (148 kg ha^{-1}). According to these results, the square configuration forms had higher understory vegetation biomass than rectangular forms. The understory vegetation biomass productivity also showed seasonal variations: the highest biomass productivity was found in autumn and the lowest in summer. And, understory vegetation biomass of this study was quite lower than another study (Lodhiyal et al., 1995) in India (1.8 tonnes ha^{-1} versus 0.32 tonne ha^{-1}).

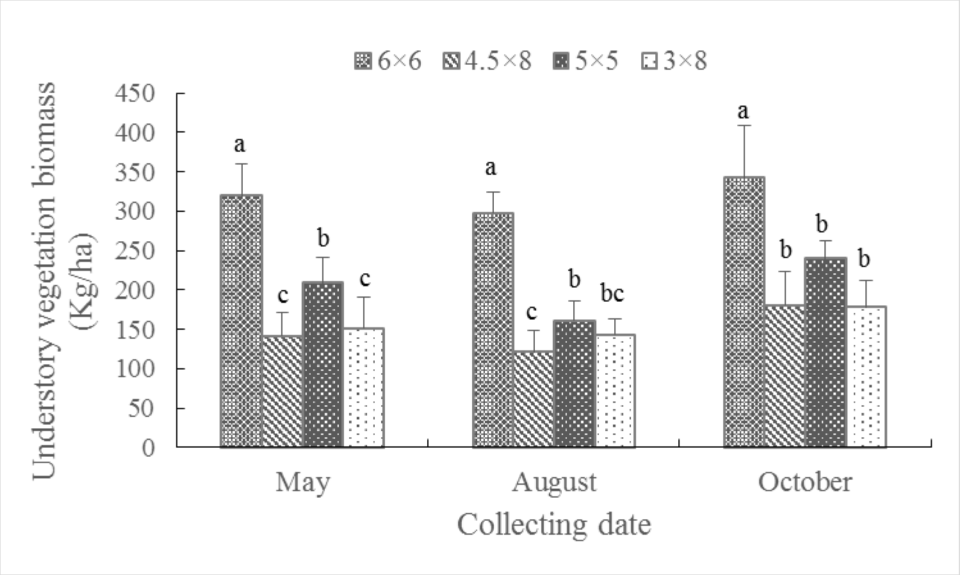


Figure 12. Biomass accumulation by understory vegetation in four poplar plantations over three seasons. Different letters indicate significant differences in understory vegetation biomass between poplar plantations according to Duncan's test at $p<0.05$.

The detected understory vegetation parameters showed seasonal variations, and the distribution indices and biomass accumulation were found highest in autumn while highest diversity indices were found in summer. Plantations with square configurations had higher diversity and biomass of understory vegetation, and 6m × 6m plantation had the highest values for detected understory vegetation parameters: diversity, evenness, and biomass. This result agreed with the result reported in China by Li et al. (2014) where they noted that high stand density increases canopy density and thereby causes more plant competition for light resources and decreasing diversity. In this study, the canopy characteristics indices and understory vegetation parameters showed contradict results with Swamy et al. (2006) where they stated that plantations with narrow spacing configurations had higher LAI, which means more interception of photosynthetically active radiation (PAR) and thereby low transmittance of PAR to understory vegetation so that it affects the understory vegetation diversity. In this study, 6m × 6m plantation had higher LAI and lower TC yet it had highest species diversity, better distribution patterns and biomass accumulation by understory vegetation. After forest plantations are established, the environment is changed through creating light gradient along with canopy stratification (Christian et al., 1994) and changing soil water content along with increasing transpiration rates by planted trees (Boothroyd-Roberts et al., 2013; Licata et al., 2008). Therefore, Li et al. (2014) suggested to investigate species composition in different ecotypes (according to light and water requirements) accompanied with species diversity to reflect environmental changes after forest plantation establishment. The limitations of this study were that species composition of understory vegetation in different ecotypes could not investigated and changes in canopy structure characteristics were evaluated for only one season.

5. Conclusion and recommendations

This study tried to examine effects of spacing configuration and plating density on planted poplar trees and understory vegetation communities in nine-year old poplar plantations. To evaluate effects on poplar trees, changes of growth performance, stem forms and canopy structure characteristics along with different configuration forms and planting densities were investigated. Between two configuration forms, square configuration forms (6m × 6m; 5m × 5m) had better growth performance because these plantations had higher biomass and volume productivity. Among four plantations, 5m × 5m plantation had the best growth performance with highest biomass productivity and volume yield. All poplar plantations showed same biomass contribution patterns by different tree components as stem > branch > root > leaf. And, all plantations grew with same diameter and height growth patterns over nine growing seasons and maximum diameter increment was found at fourth-growing season. In another study in China by Fang et al. (1999) showed different patterns for planting densities ranging from 500 to 1111 stems ha^{-1}. Plantations with square configuration forms also showed better stem forms with highest circularity percentage, and 6m × 6m and 5m × 5m plantations revealed similar circularity percentage with 98.4 % and 98.1 % respectively. The stem form (diameter roundness) is important for poplar plantation intended for plywood/ veneer production because it can effect on quality of end-products, outturn percentage and production cost in peeling process.

In the context of canopy structure characteristics, square configurations had higher leaf area and better light interception ability because these two plantations had higher LAI and PAR values, and lower TC values. Also, they possessed better crown development form with less difference in crown width of two dimensions (1.10 % for 6m × 6m and 3.19 % for 5m × 5m). The balanced crown development is important for better resistance to wind-damage and better tree forms. Also, it was found that relationship between stem form and crown development form of poplar trees in this study. Because, trees with symmetrical crown form (in square configuration) had better stem form. Polmion et al. (2011) stated that trees with asymmetrical crown shape cause reaction wood and thereby, affect on stem form.

The detected understory vegetation parameters showed that plantations with square configurations had higher species diversity and biomass accumulation by understory vegetation. Among four spacing treatments, higher species diversity and biomass accumulation were found in 6m × 6m and 5m × 5m orderly and understory vegetation distributed more homogeneously under 6m × 6m plantation.

According to results of this study, square configuration with 5m × 5m spacing are suggested for plywood production of poplar plantations at similar sites. More fixed detecting points for taking tree canopy imageries and collecting understory vegetation parameters are recommended for further study in order to evaluate more efficiently the seasonal changes and effects of spacing configurations and planting density. And examining the composition of understory species in different ecotypes according to their light and water requirement are recommended for more understanding about environmental changes by planting density and configuration form.

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