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Biomass production and carbon stocks of poplar-based agroforestry with canola and wheat crops: a case study

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Abstract

Poplar (*Populus deltoides* Bartr. ex Marsh.) produce a large amount of biomass per unit area and is important fast-growing species in different planting systems. However, the appropriate space between poplar trees is essential to high-performance productivity in diverse regions. The present study monitored the effect of different spacing configurations (A: 4 × 3 m; B: 4 × 3 m (pure poplar); C: 6 × 3 m; D: 8 × 3 m; E: 10 × 3 m and F: pure crop) of poplar-based agroforestry with two canola (*Brassica napus* L.) and wheat (*Triticum aestivum* L.) cropping system on biomass production and carbon storage. Over the eight years, the total poplar biomass production was significantly different ($P \leq 0.05$) in poplar-based configurations and ranged from 9.1 to 13.4 mg ha^{-1}. The highest carbon storage of 6.5 mg ha^{-1} was observed in configuration E. Crop production of canola and wheat in configurations B, C, D, and E, did not show a significant difference with pure crop cultivation, while configuration A was significantly lower. Our result indicated that configuration E, with the highest total biomass production but no significant difference in crop production, is the optimum system of poplar-based agroforestry in regions with similar temperate climate conditions of Northern Iran. Finally, poplar-based agroforestry provides high efficiency of carbon sequestration in trees which can conserve all market and non-market benefits.

Keywords: aboveground biomass, carbon concentration, crop yield, productivity, *Populus deltoides*, Northern Iran

Introduction

Terrestrial ecosystems, particularly forest ecosystems, play an essential role in a large and long-term carbon pool (Djomo et al. 2011). Worldwide, the average amount of carbon stored in forest biomass is 283 Gt (FRA 2005). A portion of this amount of carbon storage is related to the tree plantations. Globally, plantations are about 5% of forest cover (Wang et al. 2013). Therefore, plantations have a high potential to sequestrate atmospheric CO_2 and store carbon in the biomass of tree components.

The Kyoto Protocol (based on the United Nations Framework Convention on Climate Change 1992) encourages countries to afforestation under the Clean Development Mechanism, CDM (IPCC 2007). In these emission reductions and sequestrate CO_2 targets, agroforestry systems have a considerable carbon sequestration capacity (Fang et al. 2010). Carbon stored in the agroforestry systems was estimated to be between 40–50 mg ha^{-1} (IPCC 2006). Agroforestry systems provide a mix of market and nonmarket goods and services such as food, fuel, wood products, water, and air quality improvement, soil conservation and nutrients enrichment, biodiversity conservation, and scenic beauty (Alavalapati et al. 2004). Thus, agroforestry is one of the best ways to improve environmental and socioeconomic sustainability.

Acacias, eucalyptus, and poplars as fast-growing tree species are appropriate for different agroforestry practices (Puri and Nair 2004, Swamy et al. 2006, Chauhan et al. 2012). Poplar, particularly *Populus deltoids* Bartr. ex Marsh. (hereafter *P. deltoides*) is a deciduous tree that produces a large amount of biomass per unit area and time (Zabek and Prescott 2006). Easy establishment, straight cylindrical bole, high merchantable bole volume, and short rotation time (typically about eight to ten years) are other potentials of poplar species (Eslamdoust 2022). These potentials make poplar suitable for planting trees under agroforestry systems (Das and Chaturvedi 2005).

Iran was ranked 10th globally among the other countries based on the size of planted forests (Del Lungo et al.

2006). Northern Iran (a greenbelt of 800 kilometers) is a large and prominent region with high environmental and economic abilities due to its location between the high mountains of Alborz and the Caspian Sea. In recent years *P. deltoides* received popularity among farmers in northern Iran due to its fast growth and ability to attain substantial biomass production in a short rotation of up to ten years.

Although several authors have published research regarding agroforestry with poplars around the world (Ralhan et al. 1992, Puri et al. 2001, Swamy et al. 2006, Fang et al. 2007, Singh and Sharma 2007, Singh and Lodhiyal 2009, Fang et al. 2010, Chauhan et al. 2012), yet, despite the perfect climate condition of northern Iran for poplar-based agroforestry, our domestic information is rare. The selection of an appropriate poplar-based configuration (different tree densities and spacing arrangement) is necessary to demonstrate a highly productive configuration. Therefore, this study attempts to understand the pattern of biomass production and carbon (C) stock in different configurations of poplar-based agroforestry. The objectives of this study were: (1) to compare the effects of different configurations with different tree densities and spacing arrangements on biomass production and C stocks, (2) to determine the biomass allocation in tree components according to the age, and (3) to estimate crop production under different configurations of poplar-based agroforestry.

Materials and methods

Study sites

The study was conducted at the Research Station of Poplar Baye-kola, Mazandaran province, the north of Iran. The four distinct agricultural seasons of the year are rainy (September–December), winter (December–March), spring (March–June), and summer (June–September). The experimental site is situated at 36°43' N and 52°13' E and 15 m above the mean sea level. The annual average rainfall during 2010–2020 was 630 mm, with more than 80% falling between October and December. The mean annual temperature is 16.8°C. The soil texture is clay loam, with some chemical characteristics in Table 1.

Table 1. The characteristic of the soil at the study site (Baye-Kola)

Soil characteristics	Depth (cm)	
	0–30	30–60
Texture	Clay-loam	Clay-loam
Electrical conductivity (EC) (dS/m)	2.19	1.20
pH_{H2O}	7.67	7.86
Total neutralizing value * (TNV)-(%)	9.88	10.01
Saturation percentage (%)	33.85	32.30
Organic carbon (%)	0.39	0.49
Total N (%)	0.04	0.05
Available P (mg kg^{-1})	2.80	3.80
Available K (mg kg^{-1})	179.00	171.00
Available B (mg kg^{-1})	0.40	0.30

Note: * TNV is an index representing the limestone percentage capable of neutralizing acid.

Experimental design and treatments

A complete randomized block design was used in this study, with three blocks. Each block contained six experimental plots of five configurations as A: 4 × 3 m; B: 4 × 3 m (pure poplar); C: 6 × 3 m; D: 8 × 3 m, and E: 10 × 3 m for tree space treatments and one pure cultivated crop (F).

The area of each experimental plot was 0.12 ha (30 m × 40 m in size). Table 2 shows the characteristics of configurations.

P. deltoides

One-year-old poplar plants of *P. deltoides* were transplanted in March 2012. At the time of planting, the seedling's height ranged from 1.5 to 2 m, and the collar diameter of the seedlings ranged from 1.5 to 2.5 cm. During the eight-years experiment, no other management practices were applied, except the pruning of *P. deltoides* trees, which was applied from the third year after planting (tree stem was pruned during the 2nd–3rd; 3rd–4th, and 4th–5th year). The survival rate of 94% was observed in A and B configurations, while in other configurations, all trees survived (100% survival rate). Table 3 shows the tree characteristics in all configurations at different years.

Crops

Based on worldwide and regional interest, followed by Sari Agricultural University, Sari (Iran) recommendations, we selected canola and wheat to cultivate for poplar-based agroforestry. Oilseed rape (*Brassica napus* L. var. Hayola 401) is one of the world's most widely cultivated oil crops (FAOSTAT 2010). Also, wheat (*Triticum aestivum* L. var. N-8119) is one of the most cultivated crops in the daily diet of 36% of the world population (Neiverth et al. 2014). Crop cultivation was conducted in all configurations except for configuration B (pure poplar stand) for three years. In the middle of November 2015, Canola

Table 2. Information of six different configurations at intercropping in Baye-kola, Northern Iran

Configurations	Interval distance (m)	Plot area (m^2)	Trees per plot (pcs.)	Trees per hectare (pcs.)	Removal area by tree planting (m^2 ha^{-1}) *
A	4 × 3	1200	100	833	533.3
B	4 × 3 Pure stand	1200	100	833	0
C	6 × 3	1200	65	542	347.2
D	8 × 3	1200	50	416	266.7
E	10 × 3	1200	40	333	213.3
F	Pure crops	1200	-	-	0

Note: * The sum of areas of tree planting holes (0.64 m^2 for each tree) that is out of crop cultivation.

Table 3. Collar diameter (CD) (cm), diameter at breast height (DBH) (cm), and height (H) (m) of *P. deltoides* in the configurations in different years

Years		Treatments				
		A (3 × 4 m)	B (3 × 4 m P)	C (6 × 3 m)	D (8 × 3 m)	E (10 × 3 m)
1	CD	2.81 ± 0.06	2.76 ± 0.06	2.97 ± 0.06	2.82 ± 0.08	2.65 ± 0.08
	H	2.41 ± 0.05	2.38 ± 0.05	2.57 ± 0.05	2.46 ± 0.07	2.30 ± 0.06
2	CD	3.26 ± 0.21	3.34 ± 0.23	3.10 ± 0.25	3.21 ± 0.26	3.71 ± 0.32
	H	3.79 ± 0.14	3.90 ± 0.15	3.73 ± 0.16	3.81 ± 0.14	4.12 ± 0.19
3	DBH	6.38 ± 0.29	6.44 ± 0.35	6.47 ± 0.38	6.78 ± 0.38	7.10 ± 0.46
	H	6.76 ± 0.24	6.72 ± 0.27	6.51 ± 0.28	6.64 ± 0.31	6.60 ± 0.31
4	DBH	9.90 ± 0.36	9.71 ± 0.45	10.30 ± 0.47	10.46 ± 0.46	10.71 ± 0.54
	H	9.99 ± 0.25	9.62 ± 0.32	9.79 ± 0.32	9.42 ± 0.32	9.73 ± 0.34
8	DBH	18.57 ± 0.69	18.37 ± 0.78	19.93 ± 0.76	21.40 ± 0.96	22.87 ± 0.63
	H	15.60 ± 0.20	15.20 ± 0.48	15.18 ± 0.33	15.22 ± 0.49	15.89 ± 0.16

Note: Data represent the mean ± Standard deviation.

was sowed with 8 kg ha^{-1} of the seeding rate. For the next year, in early November 2016, wheat (hereafter: wheat_1) was sowed with a seeding rate of 200 kg ha^{-1}. In early November 2017, wheat (hereafter: wheat_2) was sown for the second time with a seeding rate of 200 kg ha^{-1}. For all cultivated crops, the standard management practices were the same. For supplementary nutrients, 50 kg ha^{-1} of the Urea $(NH_2)_2CO$, and for pest control, 3–4 kg of Sevin SL Carbaryl in 1,000 L of water have been used for all crop cultivation configurations.

Observations

Tree biomass and carbon

All *P. deltoides* trees in each configuration were measured from July to September for their diameter (collar diameter, CD, for plants of one and two-years age and diameter at breast height, DBH, for plants of three-, four- and eight-year age), total height, bole height, and crown width during the different years of this study. The biomass of tree components was derived by fitting the tree CD or DBH and height variables in the allometric equations developed by Eslamdoust (2015) for the same climate conditions of Northern Iran.

Twelve poplar trees were randomly selected and destructively sampled to determine the carbon concentration of tree components. We cut a five cm-thick stem disc of each tree. We used hand tools to separate the bark and then measured the fresh weight of the wood and bark of each stem disc to determine the portion of the bark disc. Also, we randomly sampled separated branches, twigs, and leaves. Approximately 300 g of a fresh sample of each tree component was collected, labeled and transported in plastic bags to the laboratory. Samples of each component were weighed the same day on an electronic balance (accuracy 0.1 g) and dried at 70°C until they reached a constant weight. The total dry biomass for each component was calculated by multiplying the fresh weight by the dry/wet ratio. We used the dynamic combustion method to measure the carbon content of tree components. Samples were burned at 1150°C in a combustion chamber by Vario ELIII elemental analyzer. The total carbon storage per hectare was computed by multiplying the actual carbon value with the total dry biomass.

Crop biomass and yield

The yield of the cultivated crops was measured after full maturity by placing six plots of 1 m^2 per each replication of configurations (18 plots for each configuration, 90 plots for each cultivated crop). The total biomass of cultivated crops was measured by cutting, grain sifting, drying, and weighing all the plant material within the plot. The aboveground wheat biomass was divided into two components (straw and grain), while the biomass of Canola was only corn components. Random samples of each component of crops were collected and transported to the laboratory, and moisture content was measured using the same method used for tree components. The total crop biomass of all configurations was calculated from the crop biomass sampling measurement and moisture content for each year and expanded to the unit of area (ha).

Statistical analyses

Data were analyzed using the one-way analysis of variance (ANOVA) procedures of the SPSS statistical software program (IBM 2010). Dunnett's tests were performed to separate means when ANOVA results indicated the presence of significant differences at $P \leq 0.05$.

Results

Biomass in poplars

In all configurations, biomass production of the *P. deltoides* component was ordered to stem wood > stembark > leaves > branches > twigs. Aboveground tree biomass (mg ha^{-1}) of two-year configurations followed the order C > A > D > B > E. However, in *P. deltoides* aged 3, 4, and 8 years, there were no significant differences in configurations. Finally, *P. deltoides* at the end of its 8 years was har-

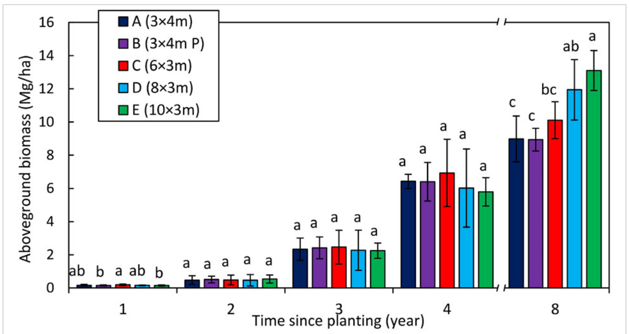

Figure 1. Aboveground tree biomass of poplar configurations in different years. Statistically significant differences in tree biomass among the configurations are indicated with lowercase characters ($P \leq 0.05$)

vestable, the total aboveground biomass of configurations followed the order E > D > C > A > B. At age of 8 years, biomass production in configuration E was 46.1%, 46.8%, 29.7%, and 9.75% higher than in configurations A, B, C, and D, respectively (Figure 1).

Carbon concentration

The mean carbon concentration in tree aboveground components varied from 43.6 to 49.6% of dry weight (Table 4). The maximum carbon concentration was observed in the stem (49.6%), and that was 4.2, 5.7, 8.1 and 12.1% higher than in branches, twigs, stembark, and leaves, respectively. A significant difference was observed in carbon concentration between leaves with the lowest carbon concentrations and another component with the higher carbon concentration in stem wood, branch, twig, and stembark.

Carbon stocks in poplar

Figure 2 shows the dynamics of total aboveground carbon storage to better different and understandable variations in different configurations at different ages. Carbon stored in different configurations varied from 4.44 to 6.50 mg ha^{-1} at age 8 years of *P. deltoides* with a maximum amount of carbon in stem wood. As the result shows, configuration E has the highest total aboveground carbon storage at age 8 years with the lowest tree density (333 stems ha^{-1}). Nevertheless, configurations A and B have the lowest total aboveground carbon

Table 4. Carbon content in different aboveground biomass components of *P. deltoides* (n = 3)

Components	C (%)
Stemwood	49.6 ± 1.3 a
Branch	47.5 ± 2.1 a
Twig	46.8 ± 1.2 a
Stembark	45.6 ± 2.4 a
Leaf	43.6 ± 1.4 b
Total Tree	46.6 ± 2.8 a

Note: Data represent the mean ± Standard deviation. The different lowercase characters indicate significant differences among components ($P \leq 0.05$).

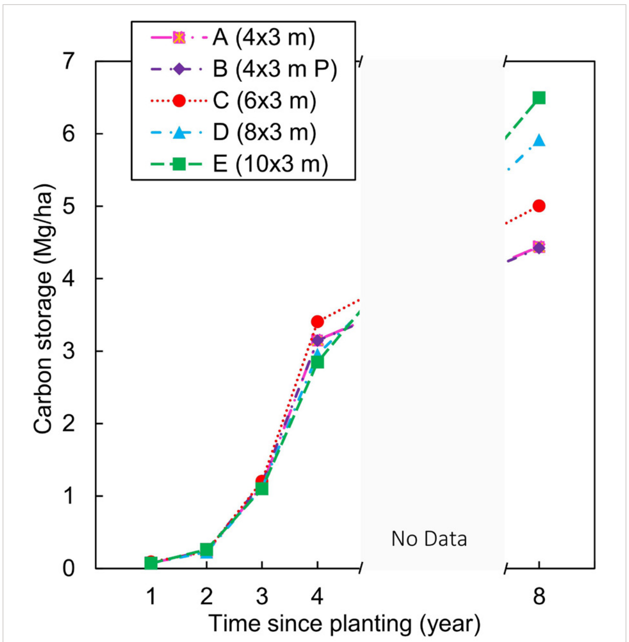

Figure 2. Dynamics of carbon storage (mg ha^{-1}) in aboveground biomass of five configurations with various planting densities

storage with the highest tree density (833 stems ha^{-1}). Over the eight years, the total aboveground carbon stocks in the configurations were in the order of E > D > C > A > B with 6.5, 5.9, 5.0, 4.4, and 4.4 mg ha^{-1} of carbon, respectively. The configuration tree density was in the order of A, and B > C > D > E with 833, 542, 416, and 333 stems ha^{-1}, respectively. Carbon was stored in the components of *P. deltoides* in all configurations based on biomass production, and the carbon concentration of each component was estimated at different years.

Productivity of crops

The performance of the cultivated canola in the open condition (configuration F) was better than other poplar-based configurations but not significantly (Table 5). The difference in canola plant height, number of bags, and seed weight were not statistically significant. However, the difference in the number of seeds per bag was statistically significant. Compared to configuration F as control (pure canola cultivativation), configurations A, C, D, and E were 14.6, 12.5, 9.0, and 3.5% lower, respectively. The effect of different configurations on characteristics of the wheat_1, sown in 2016–2017, was not statistically significant, except for the number of wheat plants (Table 6). Compared to configuration F as pure wheat cultivation, the number of wheat plants was significantly lower of 25.1, 33.7, 8.0, and 30.8% for poplar-based configurations of A, C, D, and E, respectively. Also, the characteristics of wheat_2, sown in 2017–2018, were not significantly different in poplar-based configurations and pure wheat cultivation (configuration F).

Total canola yield in pure cultivation (configuration F) was higher than yield productivity in other pop-

Table 5. Characteristics of canola (*Brassica napus* L. var. Hayola 401) in different configurations

	A (4 × 3 m)	C (6 × 3 m)	D (8 × 3 m)	E (10 × 3 m)	F (pure canola)	Sig.
Plant height (cm)	91.13 ± 9.96	91.97 ± 14.65	85.83 ± 6.75	101.53 ± 12.93	105.40 ± 1.61	0.199 ns
Number of bags	22.90 ± 3.68	28.43 ± 4.76	30.67 ± 4.70	28.50 ± 1.59	36.07 ± 11.28	0.206 ns
Number of seeds per bag	17.97 ± 0.23 b	18.40 ± 0.61 a	19.13 ± 0.81 a	20.30 ± 1.87 a	21.03 ± 1.46 a	0.043 *
Seed weight (g)	2.27 ± 0.23	2.20 ± 0.20	2.27 ± 0.31	2.47 ± 0.12	2.60 ± 0.35	0.330 ns

Note: Data represent the mean ± Standard deviation; ns show no significant differences between configurations; * show significant difference ($P \leq 0.05$) and lowercase characters represents differences among configurations.

Table 6. Characteristics of wheat (*Triticum aestivum* L. var. N-8119) in different configurations

Years		A (4 × 3 m)	C (6 × 3 m)	D (8 × 3 m)	E (10 × 3 m)	F (pure wheat)	Sig.
Wheat_1 (2016–2017)	Plant height (cm)	92.67 ± 7.57	88.67 ± 4.16	92.00 ± 1.73	87.00 ± 3.46	94.67 ± 4.04	0.312 ns
	Number of wheat plants (per 1 m^2)	175.00 ± 46.57 a	155.00 ± 5.00 b	215.00 ± 36.04 a	161.67 ± 14.57 a	233.67 ± 36.50 a	0.047 *
	Number of grains per ear	29.67 ± 2.08	33.00 ± 3.61	31.33 ± 6.11	32.67 ± 3.22	30.00 ± 3.00	0.763 ns
	1,000 grain weight (g)	51.33 ± 2.31	52.33 ± 4.51	54.33 ± 1.15	54.33 ± 2.52	51.67 ± 3.21	0.590 ns
	Straw yield (mg ha^{-1})	6.72 ± 2.62	6.92 ± 1.42	8.63 ± 2.04	7.46 ± 2.12	8.97 ± 0.84	0.527 ns
Wheat_1 (2017–2018)	Plant height (cm)	73.27 ± 6.29	80.33 ± 4.51	75.17 ± 3.33	85.17 ± 0.76	78.33 ± 6.43	0.81 ns
	Number of wheat plants (per 1 m^2)	194.33 ± 75.16	213.00 ± 4.93	216.33 ± 39.53	204.33 ± 55.05	215.00 ± 16.70	0.979 ns
	Number of grains per ear	26.67 ± 0.58	26.67 ± 1.53	26.00 ± 1.00	27.33 ± 3.51	26.33 ± 2.08	0.943 ns
	1,000 grain weight (g)	27.13 ± 5.48	30.17 ± 0.21	27.10 ± 5.37	23.90 ± 5.28	30.40 ± 0.17	0.358 ns
	Straw yield (mg ha^{-1})	5.73 ± 1.96	8.20 ± 0.35	7.47 ± 2.25	8.33 ± 2.08	6.06 ± 4.055	0.647 ns

Note: Data represent the mean ± Standard deviation; ns show no significant differences between configurations; * show a significant difference ($P \leq 0.05$) and lowercase characters represents differences among configurations.

lar-based configurations. No significant differences were in configurations C, D, E, and F with 0.65, 0.74, 0.66, and 0.86 mg ha^{-1}, respectively. The yield product in configuration A was significantly lower than in the other configurations with 0.39 mg ha^{-1} (Figure 3). The difference in grain yield of the wheat_1, sown in 2016–2017, was not statistically significant (Figure 3). The maximum grain yield was recorded in configuration D (3 × 8 m interval planting space) with 2.81 mg ha^{-1}. The total yield of wheat grain in configurations A, C, E, and F was 37.0, 38.8, 28.8, and 13.9% lower than the grain yield in configuration D. For wheat_2 in 2017–2018, the total grain yield in configuration A was significantly lower than in configurations C, D, E, and F with 1.83 mg ha^{-1}. Total grain yield in configurations C, D, E, and F was 4.60, 3.63, 4.13, and 4.10 mg ha^{-1}, respectively (Figure 3).

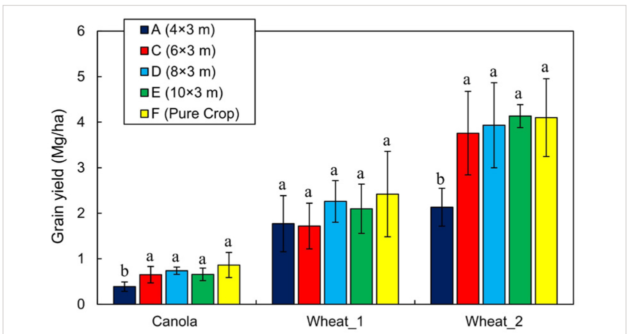

Figure 3. Effects of five poplar configurations on the grain and seed biomass of wheat and canola. The means with the same character for the same crop are not significantly different among the configurations ($P \leq 0.05$)

Discussion

In this study, we monitored biomass production and carbon storage in five different configurations of poplar for eight years. We observed the effect of tree spacing began after three years of planning. Biomass production and carbon storage derived from tree growth and followed the same trend of increase with age. In general, trees planted in wider spacing have a larger diameter than those in closer spacing (Misra et al. 1996, Singh and Sharma 2007). In our study, the biomass production in poplar aged 8 years ranged from 9.1 to 13.4 mg ha^{-1}, which is consistent with the result reported by Fang et al. (2010), where the total poplar biomass ranged from 8.8 to 15.1 mg ha^{-1}. Tree DBH in configuration E was higher than in others. Configuration E with the lowest tree density (333 tree stems ha^{-1}) provides a better condition for lighting and, consequently, more growth in tree DBH and total volume. Furthermore, the competition between trees is another reason which has a significant impact on tree growth (Castagneri et al. 2022). Narrow space configurations A and B at ages 1, 2, 3, and 4 years have higher aboveground biomass because of more trees were planted out per unit area and, accordingly, they experienced greater competition, making them fast grow and tall. At the end of the eighth year, there were significant differences in the total aboveground biomass of configurations. Configuration E had the highest total aboveground biomass (13.4 mg ha^{-1}) with the lowest tree density (333 stems ha^{-1}), which is 46.1% higher than configuration A with the highest tree density (833 stems ha^{-1}). In closer spacing stands, trees compete for light, nutrients, and moisture, affecting survival and production (Srinidhi et al. 2007, Chauhan et al. 2012, Eslamdoust and Sohrabi 2018).

In each configuration, more than 50% of total aboveground biomass is in the tree stems, followed by stem bark, branches, leaves, and twigs, which is consistent with earlier studies showing more biomass allocation by woody components in plantations (Puri et al. 2001, Chauhan et al. 2009). According to Bastien-Henri et al. (2010), site condition significantly influences biomass allocation in tree components. Another factor influencing biomass allocation is tree age (Mello et al. 2012). The proportion of stem wood biomass becomes more critical with age (Peichl and Arain 2006, Nogueira et al. 2008, Sanquetta et al. 2011). In this study, the carbon storage in 8-year old poplar plantations ranged from 4.4 to 6.5 mg ha^{-1}, which is much lower than the result reported by Peichl et al. (2006) that total mean aboveground poplar components were 15.1 mg ha^{-1} at 13-year old plantations. While it was similar to Fang et al. (2010), who reported carbon storage ranged from 4.5 to 7.8 mg ha^{-1}.

The carbon content of the tree components is related to the chemical composition. The chemical composition may be affected by the type of wood, geographical location, pedoclimate condition, and origin (Pettersen 1984, Romberger et al. 2004, Didier Bert 2006). Our study has the same condition for all configurations in different years. The mean carbon content for tree components ranged from 43.6 to 49.6%. IPCC (2006) proposed the standard 47% coefficient to convert tree component biomass into carbon. Using the standard 47% coefficient instead of actual carbon concentration have a relative overestimation of 0.8, 5.3, 6.8, 9.7, and 14.7% for the stem, branch, twig, stem bark, and leaf, respectively. Fang et al. (2010) reported that carbon concentration ranged from 46.0 to 52.7%, which is greater than the carbon content in our study. Nevertheless, the carbon content in our study is like values of that reported by Mandre et al. (2012). The literature revealed that carbon content in different tree components had been recorded between 45 and 50% of the dry weight (Wang and Feng 1995, Chauhan et al. 2009, Rizvi et al. 2011, Verma et al. 2014, Eslamdoust and Sohrabi 2018). However, using the accurate carbon content of tree components is appropriate for a better and more dependable result.

Our result indicated that the grain yield of canola was higher in configuration F as a pure crop (control) than in other configurations. In contrast, configuration A had the lowest grain yield, which may be because of tree shading and competition affected by trees, reducing crop growth and production in direct proportion to the canopy size (Wadud et al. 2002). It is considered that in configuration A, the removal area by tree planting is 533.3 m^2 ha^{-1}. This area was out of crop production and may be one of the main factors to lower grain yield in those configurations that had been planted with poplar.

Generally, as the distance increases from the tree line, crop growth and yield have considerably improved (Singh et al. 1998). The grain yield of wheat_1 and wheat_2 in configuration A was the lowest among the configurations, mainly due to removal area, competition, and tree shading (Srinidhi et al. 2007). In this study, the total wheat grain yield ranged from 1.7 to 4.6 mg ha^{-1}, which is in agreement with Fang et al. (2010) and Chauhan et al. (2012). However, our result shows that grain yield in poplar planted configurations is varied and sometimes higher than grain yield in pure crop configurations. These results are not in line with Sharma et al. (2000), Puri et al. (2001), and Chauhan et al. (2012), who reported that grain yield in the pure crop (control) is more than grain yield under poplar-based agroforestry systems.

Conclusion

The results of the current study demonstrated that different tree planting space in poplar-based agroforestry affects the growth, biomass production, and carbon storage of *P. deltoides* trees. Based on our data, configuration E, with the lowest tree density (333 tree stems ha^{-1}), had the highest biomass production and carbon storage after eight years compared to other configurations mainly due to higher available lighting and lower root competition between trees. Meanwhile, the crop production (canola and wheat) was not significantly different between all configurations and pure sown crops (control). These findings suggest that configuration E for agroforestry systems substantially improves biomass production and carbon storage with no decrease in crop production. Our finding recommends using poplar-based agroforestry in regions with similar temperate climate conditions in Northern Iran.

Finally, the farmers can gain additional economic benefits from carbon sequestration by carbon trading under the Clean Development Mechanism (CDM) by shifting from traditional agriculture to *P. deltoides*-based agroforestry. However, to find out more about the efficiency of carbon sequestration in the longer growth of poplar trees, long-term monitoring of experiments as well as tree effects and soil fertility are needed in future studies.

Conflict of interest

The authors declare no conflict of interest.

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