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Carbon stocks and biomass production of three different agroforestry systems in the temperate desert region of northwestern China

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Abstract Carbon sequestration potential of agroforestry systems has attracted worldwide attention following the recognition of agroforestry as a greenhouse gas mitigation strategy. However, little is known about carbon stocks in poplar–maize intercropping systems in arid regions of China. This study was conducted in the temperate desert region of northwestern China, a region with large area of poplar–maize intercropping systems. The objective of this study was to assess biomass production and carbon stock under three poplar–maize intercropping systems (configuration A, 177 trees ha^{-1}; configuration B, 231 trees ha^{-1}; and configuration C, 269 trees ha^{-1}). We observed a significant difference in the carbon stock of poplar trees between the three configurations, with the highest value of 36.46 t ha^{-1} in configuration C. The highest carbon stock of maize was achieved in configuration B, which was significantly higher than configuration A. The grain yield was highest in configuration A, but there was no significant difference from the other two configurations. In the soil system (0–100 cm depth), the total carbon stock was highest in configuration C (77.37 t ha^{-1}). The results of this study suggest that configuration C is the optimum agroforestry system in terms of both economic benefits and carbon sequestration.

Keywords Poplar–maize intercropping system · Carbon concentration · Carbon stock · Crop yield

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Introduction

Agroforestry systems are commonly considered to be carbon sinks because the integration of trees with farmland ecosystem results in greater CO_2 sequestration from the atmosphere and thus enhanced carbon storage in the permanent tree components (Albrecht and Kandji 2003; Nair et al. 2009b; Soto-Pinto et al. 2010; Verchot et al. 2007). The potential of agroforestry systems in tropical regions to accumulate carbon is estimated to be 12–228 Mg ha^{-1}, with an average of 95 Mg ha^{-1} (Albrecht and Serigne 2003). However, the amount of carbon in any agroforestry system depends on the structure and function of the different components within the systems (Schroeder 1994; Albrecht and Kandji 2003). In addition to the potential of agroforestry systems to accumulate and sequester carbon, widespread adoption of these systems may help to reduce deforestation rates in tropical zones, while also offering a wide variety of products and services to rural communities (Jong et al. 1995). In recent years, many studies have focused on carbon stock and sequestration of agroforestry systems in industrialized and developing countries (Takimoto et al. 2008; Soto-Pinto et al. 2010; Henry et al. 2009). However, to our knowledge, no studies have been reported regarding the carbon sequestration of agroforestry systems in arid regions, especially in northwestern China.

Poplar based agroforestry systems are reported to stock amounts of carbon and hence have the potential to mitigate climate change. In northwestern China, the poplar is one of the most widely planted trees to serve a windbreak function. Poplar agroforestry systems cover an estimated area of over 51,600 km^2 in the Hexi Corridor desert oasis. Liao et al. (2006) showed that poplar agroforestry in this region significantly reduced the influence of disaster weather (cloudy, sandy and others) and protected thirty-one million hectares of farmland. In this region, previous research has focused on crop productivity and competition for light (Ding and Su 2010), and it is imperative that the carbon sequestration potential for agroforestry practices is also investigated. Considering that the ecological production potential of this dry ecosystem is inherently low compared with that of ''high-potential'' areas of better climatic and soil conditions, the extent to which poplar intercropping systems can contribute—if at all—to carbon sequestration in such regions is in itself an important issue. The objective of this study was to compare the effects of three different poplar–maize intercropping systems on carbon sequestration in biomass and soils within the desert oasis ecosystem.

Materials and methods

Site description

The study was conducted within a desert oasis (39°21′N 100°02′E, 1400 m a.s.l.) in Linze County in the middle of the Hexi Corridor region, Gansu Province, northwestern China. The region has a temperate arid desert climate, with an average annual precipitation of 117 mm and a mean annual evaporative demand of over 2390 mm. Rainfall mostly (70 %) occurs between June and September. The average temperature is 7.6 °C, while the absolute maximum may reach 39 °C and minimum −27 °C, with the frost-free period lasting around 165 days (Li et al. 2013).

Experimental design

Poplar (*Populus gansuensis* C.Wang et H.L.Yang.) as a shelter forest tree was planted in later 1980s and 20 year-old poplar trees were selected for this study. Three poplar–maize intercropping patterns were designed (Fig. 1), and planting densities for the poplar trees were 177 trees ha^{-1} (configuration A), 231 trees ha^{-1} (configuration B) and 269 trees ha^{-1} (configuration C), respectively. In 2013, a randomized block design was used to establish the trial with three replicates, and the area of each block ranged from 3800 to 4400 m^2.

The maize variety planted was *Zea mays* L., cv Dongfu 22, which produces grain that is used as seed for commercial purposes. Maize was sown with the seed rate of 30 kg ha^{-1} and the plant density was 120,000 plants ha^{-1}. The 120 kg N ha^{-1} as urea, 75 kg P ha^{-1} as single super phosphate and 75 kg K ha^{-1} as muriate of potash were applied at the jointing stage and grain-filling stage, and 60 kg N ha^{-1} as urea was applied at the maturing stage. During the growing season, the total water input was 8000 m^3 ha^{-1}.

Poplar biomass and carbon estimation

Data were collected in September 2013, and two-thirds of the poplar trees were investigated randomly in each block. Data recorded for aboveground biomass were: (1) diameter at breast height (D) of each tree; and (2) tree height (H). Poplar biomass (B) was divided into leaf, branch, stemwood, stembark and root, and they were estimated using the following formulas from Li (2010). The carbon content in the biomass was estimated to be half of the dry biomass, following IPCC (2003).

$$B_{leaf} = 0.0351 \times (D^2H)^{0.6821} \quad (1)$$

$$B_{branch} = 0.0430 \times (D^2H)^{0.7183} \quad (2)$$

$$B_{stemwood} = 0.0373 \times (D^2H)^{0.8629} \quad (3)$$

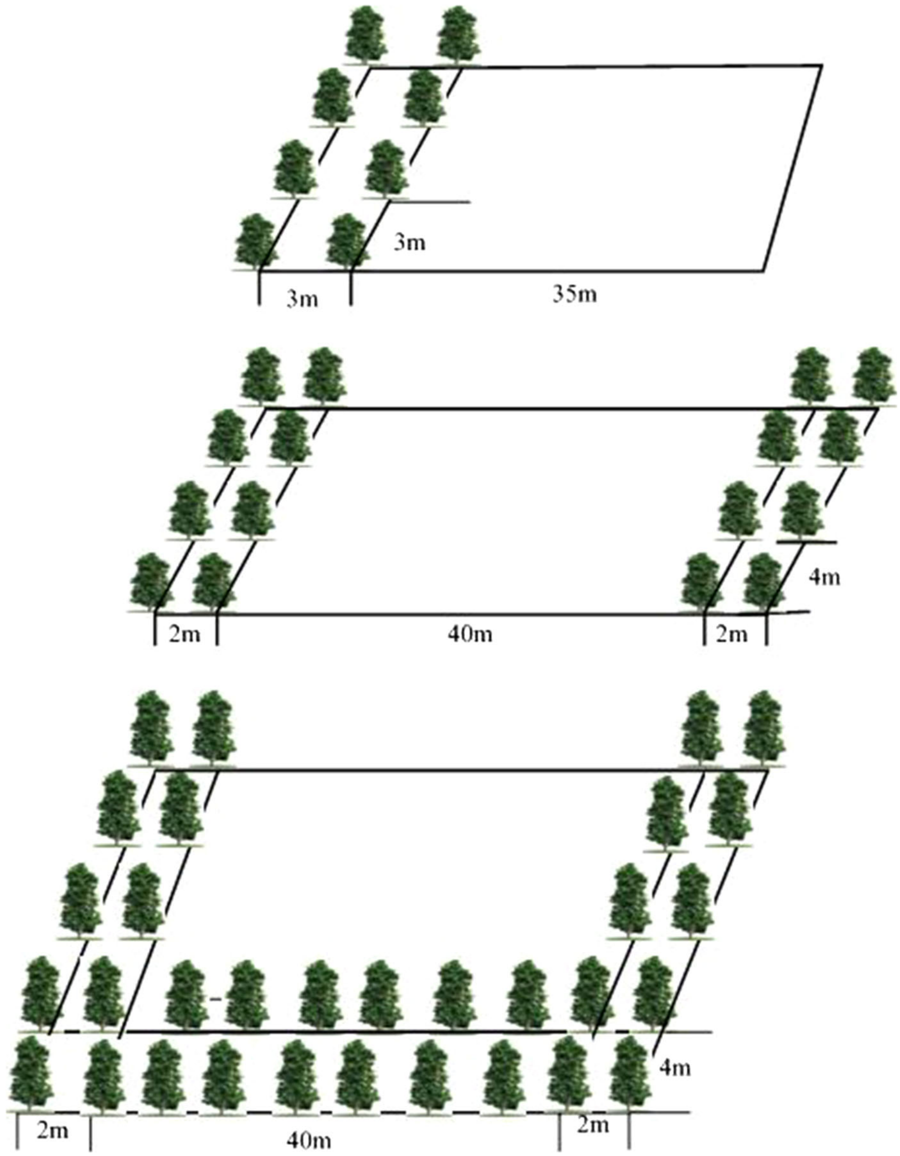

Fig. 1 Schematic showing of three poplar intercropping patterns in the temperate desert region of Northwest China. Configuration A: 177 trees ha^{-1}; Configuration B: 231 trees ha^{-1} and Configuration C: 269 trees ha^{-1}

$$B_{stembark} = 0.0186 \times (D^2H)^{0.7326} \quad (4)$$

$$B_{root} = 0.0093 \times (D^2H)^{0.8943} \quad (5)$$

where B is biomass, D is diameter at breast height and H is tree height.

Crop carbon stock

Maize biomass was measured by placing a quadrate of four in the field at full maturity, and six quadrats were placed at each poplar–maize intercropping system pattern according to the "S" type from east to west. Total biomass of maize was measured by cutting, excavating, drying and weighing all the plant material within the square. Aboveground biomass of maize was divided into four (leaf, stalk, grain and cob) components. Root excavation extended downwards to 50–60 cm, until no additional roots were visible. Fresh weights of all components for each 4 m^2 quadrat were determined in the field, and then subsamples of each component were collected for carbon analysis. Based on the biomass sampling measurement, crop biomass was scaled by area to the field as a whole.

All plant materials were oven dried at 70 °C followed by grinding with a Wiley mill, and stored in airtight bags for chemical analysis. Carbon concentrations of plant samples were analyzed by wet combustion with potassium dichromate (Bao 2000). The mass of carbon stored in individual crop compartments was estimated by multiplying their measured mass by the carbon concentrations. The carbon stocks in crops were then expanded to an area basis.

Measurements of soil carbon stocks

In the three intercropping systems, soil samples were collected in the same quadrat that was used to measure the crop biomass. Five sampling points in each quadrat following a diagonal line were collected from six depths at each point (0–10, 10–20, 20–30, 30–40, 40–60 and 80–100 cm) then mixed to obtain a composite sample for each depth. The soil sample was air-dried and passed through a 2 mm sieve, and then transported to the laboratory and analyzed by wet combustion with potassium dichromate (Bao 2000). Bulk density was determined separately for each depth using a 100 cm^3 stainless steel cylinder. The total soil carbon stock (t ha^{-1}) for the full 100 cm measured depth was determined using the formula:

$$S = \sum (C_i \times d_i \times D_i \times 0.1)$$

where S is the total soil carbon stock in 100 cm depth (t ha^{-1}), C_i is the soil carbon content in the i soil layer, d_i is the soil bulk density measured in 2013 (g cm^{-3}), and D_i is the thickness of soil layer i (cm).

Statistical analysis

The experimental data were analyzed using the one-way analysis of variance procedures of the SPSS 10.0 statistical software program (SPSS Inc., Chicago, IL, USA). Multiple comparisons were conducted for significant effects using the least significant difference test. All graphical constructions were completed using the Origin 8.0 software package.

Results

Poplar biomass carbon stock

Table 1 shows that there was some difference between the DBH and height of poplar trees in the three different configurations, but this difference was not significant ($P > 0.05$). Based on the biomass production and carbon fraction, the carbon stocks of aboveground and belowground biomass in poplar trees were significantly different between the three configurations ($P < 0.05$) (Fig. 2). Total carbon stock in poplar trees was in the order of configuration C > configuration B > configuration A. The total carbon stock of poplar trees in configuration C (36.46 t ha^{-1}) was 15.12 % and 51.41 % higher than that in configurations A and B, respectively.

Table 1 The DBH and height of poplar trees in different agroforestry systems in the temperate desert region of northwest China

	DBH (cm)	Height (m)
Configuration A	28.34 (2.09)	17.24 (1.54)
Configuration B	27.76 (2.68)	17.52 (2.31)
Configuration C	28.24 (2.02)	17.66 (1.45)

Numbers in parentheses are standard deviations

Crop biomass carbon stock

The highest aboveground biomass of maize (12.8 t ha^{-1}) was achieved in configuration C, and it was 1.83 % higher than configuration B and 15.9 % higher than configuration A. However, the difference was not statistically significant ($P > 0.05$) (Fig. 3). The grain yield of maize (2.48 t ha^{-1}) was highest in configuration A, and it was 6.04 % higher than configuration B and 14.3 % higher than configuration C. However, there was also no significant difference between the three configurations for grain yield ($P > 0.05$). The highest belowground biomass of maize (2.26 t ha^{-1}) was achieved in configuration B, but also showed no significant difference with configurations A and B ($P > 0.05$).

The carbon concentrations in the maize leaf, stalk and cob were not significantly different between the three configurations ($P > 0.05$) (Table 2). For the root, the carbon concentration in configuration B was significantly lower than that in configurations A and C ($P < 0.05$); it was 7.93 % higher in configuration A and 7.88 % higher in configuration C compared with configuration B. The carbon concentration for grain in configuration B was significantly higher than those of configurations A and C ($P < 0.05$); it was 1.61 %

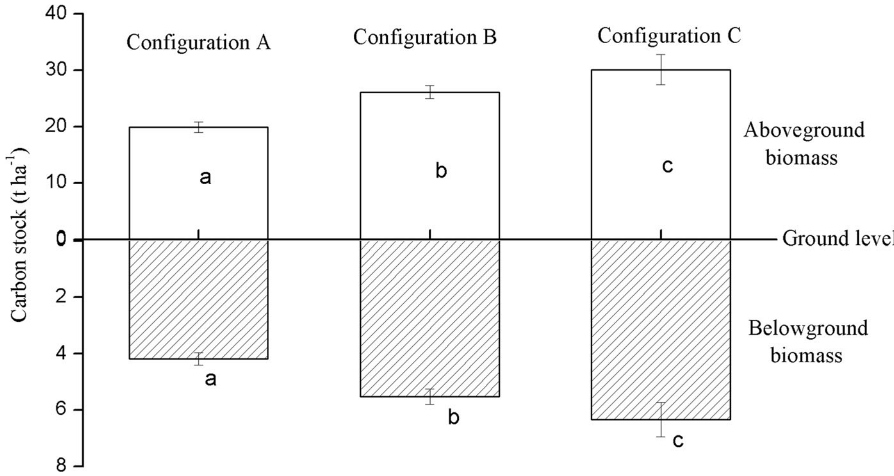

Fig. 2 Aboveground and belowground carbon stock of poplar trees in different agroforestry systems in the temperate desert region of Northwest China. Means with the different lowercase letter across agroforestry systems are significantly different at $P < 0.05$

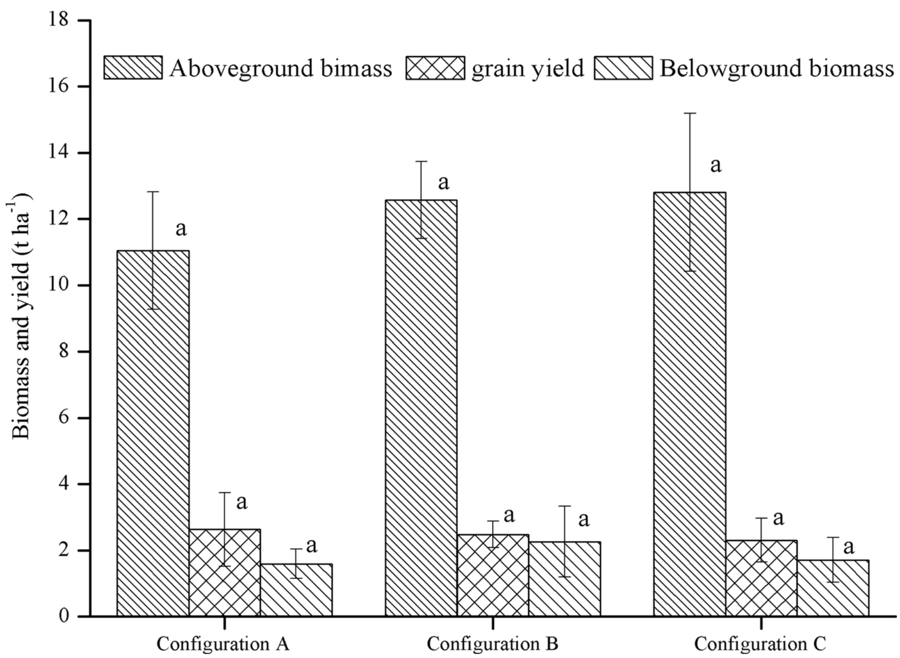

Fig. 3 The biomass production and economical yield of maize in different agroforestry systems in the temperate desert region of Northwest China. Means with the same lowercase letter across agroforestry systems are not significantly different at $P < 0.05$

lower in configuration A and 2.11 % lower in configuration C relative to configuration B.

The total carbon stock of maize in configuration A was significantly different from configurations B and C ($P < 0.05$), but there was no significant difference between configurations B and C ($P > 0.05$) (Table 2). The highest total carbon stock of maize was achieved in configuration B. Compared with configuration B, total carbon stock in configuration A and configuration C was lower by 9.56 and 0.6 % respectively.

Soil carbon stock

Figure 4 showed that there was some difference in carbon concentration in the same soil layer between the different intercropping configurations. There was a significant difference in the carbon concentrations in the 0–10 cm soil layer of the three configurations, with higher carbon concentrations in configuration B (12.97 t ha^{-1}) and lowest in configuration A (11.7 t ha^{-1}) ($P < 0.05$). In the 10–20 cm soil layers, the C

Table 2 Carbon concentration and carbon stock of maize in different agroforestry systems in the temperate desert region of northwest China

Component	Configuration A	Configuration B	Configuration C
Carbon concentration (g kg^{-1})			
Leaf	409.72 ± 5.15a	408.77 ± 2.37a	412.72 ± 5.31a
Stalk	433.16 ± 2.44a	435.90 ± 1.93a	436.02 ± 4.31a
Root	424.31 ± 13.22a	393.14 ± 10.67b	424.11 ± 18.91a
Cob	431.39 ± 3.52a	432.15 ± 4.13a	432.28 ± 3.64a
Grain	441.04 ± 3.43a	448.13 ± 3.13b	438.67 ± 2.31a
Carbon stock (t ha^{-1})			
Leaf	1.22 ± 0.27a	1.44 ± 0.14b	1.41 ± 0.3b
Stalk	2.02 ± 0.30a	2.22 ± 0.35b	2.41 ± 0.78b
Root	0.67 ± 0.10a	0.92 ± 0.12b	0.71 ± 0.15a
Cob	1.46 ± 0.27a	1.55 ± 0.16ab	1.65 ± 0.18b
Grain	1.16 ± 0.21a	1.08 ± 0.18ab	1.00 ± 0.08b
Total	6.53 ± 0.1.02a	7.22 ± 0.87b	7.18 ± 1.11b

Means with the different lowercase letter in the same line indicates significant difference at $P < 0.05$

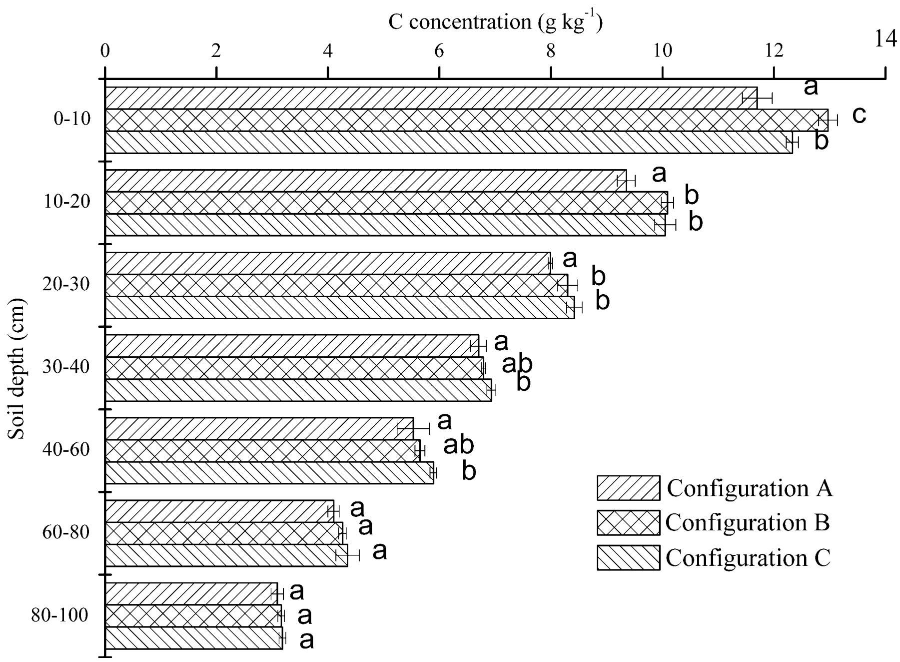

Fig. 4 The carbon concentration of soil in different agroforestry systems in the temperate desert region of Northwest China. Means with the different lowercase letter across agroforestry systems are significantly different at $P < 0.05$

concentration in configuration B (10.09 g kg^{-1}) and configuration C (10.05 g kg^{-1}) were significantly higher than that in configuration A (9.35 g kg^{-1}) ($P < 0.05$). In the 20–30 cm soil layers, the C concentration in configuration B (8.30 g kg^{-1} and configuration C (8.42 g kg^{-1}) were also significantly higher than that in configuration A (7.99 g kg^{-1}) ($P < 0.05$). In the 40–60 cm soil layer, the carbon concentration in configuration C was significantly higher than that in configuration A ($P < 0.05$). There was no significant difference in carbon concentration in the 60–80 and 80–100 cm soil layers between the three configurations ($P > 0.05$).

The soil bulk density did not differ significantly between the three configurations at any soil depth (Table 3). In the surface soil layers (0–10 and 10–20 cm), the carbon stocks were significantly higher in configuration B (20.01 t ha^{-1} for 0–10 cm and 15.41 t ha^{-1} for 10–20 cm) and configuration C (19.19 t ha^{-1} for 0–10 cm and 15.38 t ha^{-1} for 10–20 cm) than in configuration A (18.06 t ha^{-1} for 0–10 cm and 14.36 t ha^{-1} for 10–20 cm) ($P < 0.05$).

Table 3 Soil bulk density and carbon stock in different agroforestry systems in the temperate desert region of northwest China

Soil depth (cm)	Bulk density ($g\ cm^{-3}$)			Carbon stock ($t\ ha^{-1}$)		
	Configuration A	Configuration B	Configuration C	Configuration A	Configuration B	Configuration C
0–10	1.54 ± 0.02a	1.54 ± 0.06a	1.56 ± 0.03a	18.06 ± 0.41a	20.01 ± 0.58b	19.19 ± 0.22b
10–20	1.54 ± 0.04a	1.53 ± 0.02a	1.53 ± 0.04a	14.36 ± 0.33a	15.41 ± 0.34b	15.38 ± 0.28b
20–30	1.51 ± 0.03a	1.52 ± 0.03a	1.53 ± 0.02a	12.07 ± 0.29a	12.61 ± 0.49ab	12.86 ± 0.27b
30–40	1.52 ± 0.03a	1.49 ± 0.02a	1.48 ± 0.03a	10.21 ± 0.18a	10.09 ± 0.21a	10.24 ± 0.24a
40–60	1.51 ± 0.03a	1.49 ± 0.01a	1.50 ± 0.03a	8.36 ± 0.13a	8.40 ± 0.11a	8.82 ± 0.19a
60–80	1.46 ± 0.02a	1.47 ± 0.03a	1.45 ± 0.03a	5.98 ± 0.21a	6.25 ± 0.12a	6.29 ± 0.31a
80–100	1.45 ± 0.04a	1.45 ± 0.01a	1.44 ± 0.03a	4.49 ± 0.15a	4.57 ± 0.11a	4.58 ± 0.12a
0–100	–	–	–	73.53 ± 3.42a	77.34 ± 2.14b	77.37 ± 3.56b

Means with the different lowercase letter in the same line indicates significant difference at $P < 0.05$

In the 20–30 cm soil layer, the carbon stock was highest in configuration C and was significantly higher than configuration A ($P < 0.05$), but showed no significant difference from configuration B ($P > 0.05$). There was no significant difference in carbon stock had no significant difference between the three configurations in other soil layers ($P > 0.05$). Overall, in the 0–100 cm soil layer, the total carbon stock was significantly higher in configuration B (77.34 t ha^{-1}) and configuration C (77.37 t ha^{-1}) than in configuration A (73.53 t ha^{-1}) ($P < 0.05$).

Total carbon stock

Total carbon stock (biomass carbon + soil carbon) of each configuration was calculated and compared in the three different soil depth ranges. There was a significant difference in the total carbon stock between the three configurations ($P < 0.05$) (Table 4). Overall, configuration C had the highest total carbon stock, and was significantly different from the other two configurations, irrespective of the soil depths considered (0–20, 0–40, or 0–100 cm) ($P < 0.05$). The lowest total carbon stock was found in configuration A and was significantly lower than configurations B and C ($P < 0.05$).

Discussion

Plant carbon sequestration in agroforestry systems

Estimates of carbon sequestration potential in agroforestry systems are highly variable, ranging from 0.29 to 15.21 t C ha^{-1} y^{-1} (Nair et al. 2009), depending on a number of factors including the site characteristics, land-use types, species involved, stand age, and management practices. Takimoto et al. (2008) found that traditional agroforestry systems store more carbon than improved agroforestry systems or abandoned land, mainly because the improved agroforestry systems are relatively young. In the current study, the carbon stock in the 20 year-old poplar trees ranged from 24.1 to 36.5 t C ha^{-1}, which is much higher than the results of other studies. For example, Peichl et al. (2006) showed that the total mean carbon stock in 13 year-old poplar was 15.1 t C ha^{-1} at 111 stems ha^{-1}. In addition, Fang et al. (2010) found that the carbon stock in poplar trees was 7.8 t C ha^{-1} in 5 year-old trees at 250 stems ha^{-1}. We showed that of the three configurations, the poplar carbon stock was highest in configuration C because of the higher tree density. In agroforestry systems, the crops also influence the overall carbon stock in the system as well as the soil organic carbon. Fang et al. (2010) reported the carbon storage in a wheat–corn double cropping system was 1.42 times than that in a wheat–soybean double cropping system. In our study, the commercial seed maize was planted in the three configurations, and the total carbon stock of maize was 6.53–7.22 t C ha^{-1}. The carbon stock in maize in configurations B and C were significantly higher than configuration A. Oelbermann et al. (2006) indicated that aboveground crop components contributed the greatest carbon input (86 % for maize, 89 % for soybeans, and 88 % for wheat), and the remainder was derived from crop roots. In this study, the carbon stock

Table 4 Total carbon stock (biomass C + soil C at different depths) of three different agroforestry systems in the temperate desert region of northwest China

	Total C stock (t ha^{-1})		
	More C← 1	2	→ Less C 3
Biomass + 0–20 cm soil C	CC 71.74A	CB 68.01B	CA 57.17C
Biomass + 0–40 cm soil C	CC 94.84A	CB 90.72B	CA 79.45C
Biomass + 0–100 cm soil C	CC 114.54A	CB 109.93B	CA 98.28C

Means with the different uppercase letter in the same line indicates significant difference at $P < 0.01$

CC configuration C, *CB* configuration B, *CA* configuration A

in aboveground components of maize accounted for 87–90 % of total carbon stock in the maize plant. However, the aboveground biomass of maize was removed from our research area, and the input of organic matter was only through the remaining root biomass. Therefore, the carbon stock in the aboveground biomass of maize was not calculated in the total carbon stock within the three agroforestry systems.

Soil carbon sequestration in agroforestry system

As an important subsystem, soil has an important function for decreasing CO_2 in the atmosphere in the agroforestry system. A general trend of soil carbon sequestration in agroforestry systems compared with other land-use practices (with the exception of forests) can be ranked in terms of their SOC content in the order: forests > agroforests > tree plantations > arable crops (Nair et al. 2009). Some studies in Africa have shown that planting trees for carbon sequestration will not immediately retain soil carbon equal to the baseline level nor increase it in the short term (Kaya and Nair 2001; Walker and Desanker 2004). Peichl et al. (2006) found within a poplar intercropping system, total soil carbon increased compared with the crop only system in southern Ontario, Canada. In our study, we found some significant differences in the soil carbon stock (0–100 cm) between the three configuration systems; the carbon stock in configuration C was significantly highest compared to configuration A, the reason may be that the amount of litter input provided by the poplar trees is greater in configuration C because of the higher density of poplar trees, resulting in a much higher carbon input to soil (Alegre et al. 2004).

Total carbon sequestration and select an optimum poplar intercropping system

Many consider promotion of agroforestry as a major opportunity to deal with problems related to land-use and CO_2-induced global warming. In the temperate North America, the total amount of carbon stored (biomass and soil) was 5.8 and 8.2 t C ha^{-1} greater in Douglas fir (*Pseudotsuga menziesii*)–(*Lolium perenne*)/(*Trifolium subterraneum*) silvopasture than in pasture or Douglas fir plantation (Udawatta and Jose 2012). In the Huanghuaihai Plain, Li (2008) reported the total carbon stock in a 13 year-old poplar–crop intercropping system was two times higher than the crop only system. In our study, we found the total carbon stock (biomass carbon + 0–100 cm soil carbon) in the poplar–maize intercropping systems ranged from 104.14 to 121.01 t ha^{-1}. However, selecting a suitable agroforestry configuration for a certain area should be based on the tradeoffs between higher yields and higher carbon stock. Fang et al. (2010) suggested the optimum poplar intercropping system in Jiangsu province of China is the narrow-wide spacing pattern ($4 \times 4 \times 16$ m^3) that had the highest biomass production (40.15 t ha^{-1}) and the largest carbon stock (18.9 t C ha^{-1}) in this intercropping system. In our research, configuration C ($2 \times 4 \times 40$ m^3) had the highest total carbon stock in the system; however, there was no significant difference in maize yield between configurations. We therefore suggest that configuration C is the optimum poplar–maize intercropping system of those studied.

We suggest that application of this configuration may have both economic and carbon sequestration benefits and can be applied to the desert oasis agricultural area in the northwestern China.

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