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Original Article

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Root Carbon Sequestration and Its Efficacy in Forestry and Agroforestry Systems: A Case of *Populus euramericana* I-214 Cultivated in Mediterranean condition

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Abstract

Poplar is one of the most popular species of forestry and agroforestry land-use worldwide. It is currently assuming a growing importance for timber, bioenergy production and Carbon sequestration. Soil Carbon accumulation is associated with root litter, whereas available studies are disproportionate on root system in this species. Therefore, the study aimed at finding how much root Carbon, a hybrid poplar species (*Populus euramericana* I-214) sequestered in Forest System (FRS) and Agroforest System (AFS) by using soil excavation and root coring methods. A suitable conversion factor was used to get sequestered Carbon estimated from biomass. Carbon was distributed in maximum length, breadth and depth through different root components of both the systems, AFS occupied more rooting volume. Total belowground sequestered Carbon was higher in AFS (59.2 kg tree^{-1}) than FRS (54.7 kg tree^{-1}). The pattern was similar in other components like fine roots, medium roots, coarse roots and stump roots. However, on hectare basis, FRS accumulated (11.1 Mg ha^{-1}) more Carbon than AFS (8.2 Mg ha^{-1}). Although FRS stored higher belowground Carbon (without grain production), AFS was more efficient on account of Carbon land equivalent ratio. Thus the two available management systems have their own advantages in terms of Carbon storage and grain production.

Keywords: carbon distribution; carbon LER; hybrid poplar; Mediterranean region; sequestered Carbon

Introduction

Poplar is one of the most popular species of plantation and agroforestry worldwide as evident by its coverage of 8.6 million ha (1.5 m ha in agroforestry systems) (Kutsokon *et al.*, 2015) and its prediction of further expansion in the future on marginal agricultural land to meet the demand of bioenergy and lumber in different countries (Christersson, 2010; FAO, 2012; Nielsen *et al.*, 2014). Poplar and its hybrids have displayed the capacity for rapid biomass accretion (Anderson *et al.*, 1983; Pallardy *et al.*, 2003). They can be raised to create economic benefit as well as to improve environment quality. Adopting this species in agri-silvicultural system has the added advantage of offsetting Carbon emission by agriculture (Kort and Turnock, 1988; Oelbermann *et al.*, 2004; Peichl *et al.*, 2006).

Today's urgent need for substantive CO_2 emission reduction could be met more cheaply through available sequestration technology, such as expansion of forests, by planting unforested or other available land. Other option is to allow the forest to enhance or accumulate higher biomass (Lackner, 2003; Fang *et al.*, 2007). Due to faster growth and better silvicultural practices and management, plantation forestry has an edge over natural forests as regards the terrestrial Carbon stock enhancement (Updegraff *et al.*, 2004; Arora *et al.*, 2014). Afforestation of arable land is regarded as one of the major potential Carbon sinks in Europe (Powlson *et al.*, 1998). The potential advantages of agroforestry in temperate and Mediterranean climatic zones are multifaceted. Agroforestry diversifies the agriculture trade and market and reduces overproduction of agricultural commodities (Reisner *et al.*, 2007). Conversion of arable land to forest also implies a shift from a shorter to a longer residence time of Carbon by replacing annual crops with longer living, perennial, woody species (Rytter, 2012).

Aboveground Carbon has a low locking period, especially in a short rotation forestry crop like poplar on account of massive use of wood and wood products; however, belowground Carbon remains locked for a much longer period, serving the real purpose of Carbon sink. Although the belowground parts are crucial for woody biomass production and Carbon sequestration in the soil, there are insufficient studies on these tree peculiarities (Berhongaray *et al.*, 2015), especially in Mediterranean region.

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The objective of the present study was to find out belowground Carbon sequestration and its distribution in different root components by hybrid poplar in forestry (monocrop) and agroforestry model in Mediterranean climate, with fluvisol soil, at particular age. It also aimed at comparing the two systems as sink and examining the advantage, if any, of adopting one system over the other.

Materials and Methods

Study sites

Two plantations of *Populus euramericana* I-214 along with I-4551 clone were established side by side in 1996 in the vicinity of Vezenobres township (Longitude 4°9' E, Latitude 44°2' N, elevation 138 m a.s.l.) in the Mediterranean region of France (Fig. 1).

They were raised differently till the harvesting for the present study in 2009. The one having 7 m x 7 m spacing was not given any treatment other than pruning at 6 m and 10 m height. This plantation grew like a forestry system (FRS) without any treatment like weeding, hoeing etc. The other plantation having 16 m x 4.5 m spacing was used to grow Durum wheat, secondary crop in the alley, as agroforestry system (AFS). This was also pruned at 6 m and 10 m height. The soil was sandy alluvial fluvisol with 8% clay, 42% silt and 50% sand. The climate was sub-humid with an average temperature of 14.8 °C and an average annual rainfall of 1172 mm. Water table fluctuation was also common in the area (Mulia and Dupraz, 2006; Jha, 2017).

Tree selection and root harvesting

For root Carbon estimation, biomass conversion to sequestered Carbon using a Carbon factor was done. Root biomass was estimated by tree harvesting and dry matter estimation method. Instead of multiple tree, single tree harvesting (Fang *et al*., 1999) was done in both AFS and FRS following some parameters, like (i) Representative tree having average diameter at breast height (dbh), was chosen from inner area of the plantation, (ii) Its neighbouring trees had normal form and vigour and (iii) both trees, AFS and FRS, were I-214 clone and 6 m pruned. Selected FRS tree being thicker than the average tree was normalized by a factor (square of the ratio of average tree and harvested tree) 0.93 in this case (Jha, 2017).

Root harvesting

Soil excavation method was used for harvesting of roots to capture lateral root variability in larger volume of soil (Berhongaray *et al*., 2015; Addo-Danso *et al*., 2016). One quarter of the rooting zone of a single tree from both the plantations was selected randomly for excavation. Harvestable quarter volume of the soil (3.5 m x 3.5 m x 3 m in FRS and 8 m x 2.25 m x 3 m in AFS) was divided into 2D voxels (Jha, 2017). Different components of roots recognised in the present study were fine roots (< 2 mm), medium size roots (2 mm to 10 mm) and coarse roots (> 10 mm), although they were categorized and named differently in literature (Lodhiyal *et al*., 1995; Laclau, 2003; Tufekcioglu *et al*., 2003; Das and Chaturvedi, 2005; Fortier *et al*., 2015a). All the components were harvested in voxels of X and Y axes and their diagonals (Fig. 2). A detail protocol in this regard is available (Jha, 2017). The stump root was excavated along with all the proximal roots around it from first voxel column.

Root biomass estimation

Harvested roots were cleaned, weighed and their samples were dried at 90 °C temperature in oven till constant weight was achieved. Fresh and dry weight ratio was used to calculate the biomass for harvested voxels. For remaining voxels highly significant exponential decrease regression equations, developed from voxel data of X and Y axes, were used. Root biomass of one quarter rooting zone was extrapolated arithmetically four times to get total root biomass of the tree (Jha, 2017).

Increasing the accuracy of root biomass estimates is important for a better understanding of Carbon cycling (Fortier *et al*., 2015b). Therefore, soil coring method was also used for getting another set of data of fine root biomass (Mulia and Dupraz, 2006; Levillain *et al.,* 2011) in addition to excavation method as it is reported to underestimate fine roots due to its loss during excavation (Friend *et al*., 1991). The well spread soil cores from Nine and six points in the alley of AFS and FRS trees, respectively, were analysed for

Fig. 1. Location of study site (yellow pin), Vezenobre in Southern France as in 2015. Aerial photo next to google map, taken in 2011 shows two plantations studied (lower block on the right side): wider rows on the left side of the block is AFS and narrower rows on the right to AFS is FRS (Map and photo courtesy: INRA, Montpellier and Google Earth)

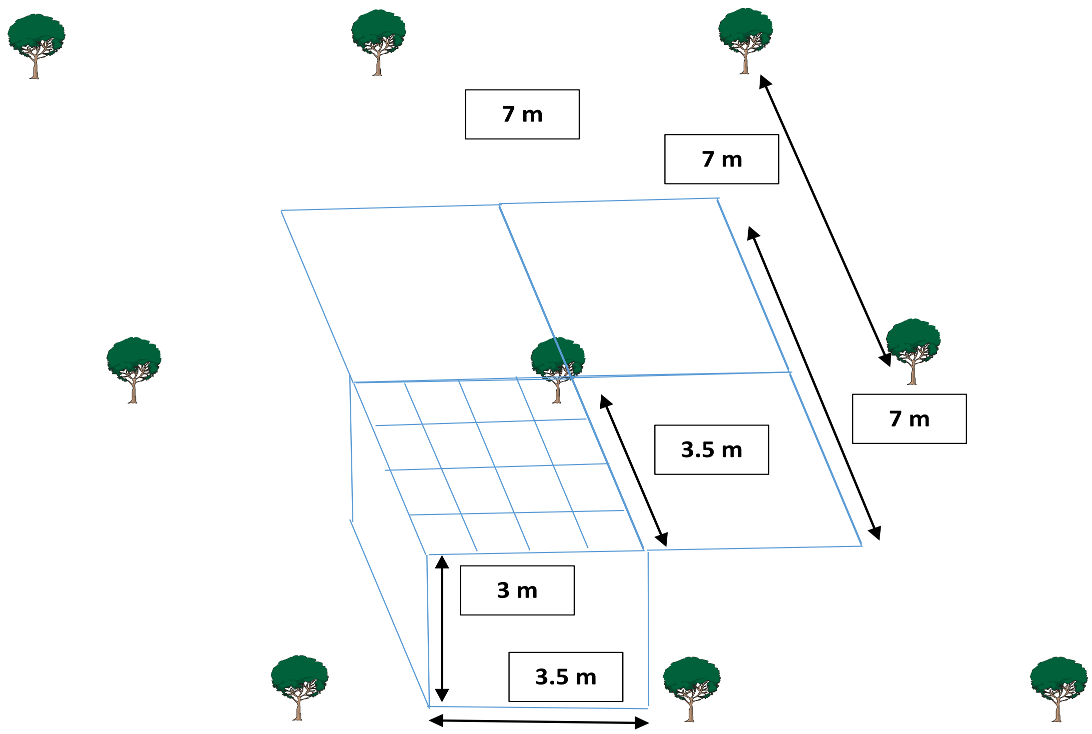

Fig. 2. Drawing depicting 'quarter rooting space harvest design' of biomass assessment along with spacing of plantation (FRS). Figure is not to the scale. Checkered quarter was selected for cubic removal of soil and collection of roots. The numbers mentioned above in meters will vary in Agroforestry System (AFS) accordingly as there is spacing difference from FRS

finding out root numbers to be used in the following formula. Root density constant (143.55) and specific root length (17.86 m g^{-1}) were adopted from Mulia (2005).

$$\text{Root biomass} = \frac{\text{Average root number x Rooted volume x Density constant}}{\text{Specific root length}}$$

Carbon stock estimation

Estimation of biomass is essential for estimating sequestered Carbon in roots and other parts (Cooper, 1983; Chambers *et al.,* 2001; Specht and West, 2003). Carbon stock estimation was done using biomass estimated above and Carbon conversion factor (Gower *et al.,* 2001; Nowak and Crane, 2002; Terakunpisut *et al.*, 2007; Jha, 2015). Half biomass (0.5) proposed by IPCC is the most commonly used factor (Fonseca *et al.*, 2011). However, there are studies which suggest Carbon content in dry biomass between 45-50% (Chan, 1982; Schlesinger, 1991). Further, Magnussen and Reed (2004) have proposed to take 0.475 as a fraction of biomass to estimate Carbon in any vegetation. Nevertheless, instead of taking empirical factor, it is always good to take species and site specific factor (Jha, 2015) to have accurate estimation since universal factor is prone to over-estimation or under-estimation in the specific case. Since there was no factor available for the study area and concentration varied in different plant parts (Table 1), an average Carbon concentration value (45.56%) of roots of poplar plantations growing in different climates was used as conversion factor in this study.

Table 1. Carbon content in poplar biomass from tropical and temperate zones

Species	Country	Carbon content (%)				Reference
		Trunk	Branch	Leaf	Root	
Populus deltoides	India	51.66	45.33	41.66	--	Arora *et al.* (2014)
Populus deltoides	India	45.67	46.56	45.50	47.82	Chauhan *et al.* (2012)
Populus deltoides	India	46.20	46.20	--	--	Pingale *et al.* (2014)
Populus deltoides	India	45.6	45.2	44.2	--	Kanime *et al.* (2013)
Populus deltoides	China	50.12	47.87	42.94	47.63	Fang *et al.* (2007)
Populus simonii	China	45.60	44.50	44.00	43.80	Gao *et al.* (2014)
Hybrid poplar	Canada	--	--	--	43.00	Guy and Benowicz, (1998) in McKenney *et al.* (2004)
Hybrid poplar	Canada	46.00	47.20	--	--	Zabek and Prescott (2006)
	Average	47.41	46.12	43.66	45.56	45.72 (Tree)

Results

Biometric measurements like tree height and tree girth of *Populus euramericana* I-214 at the age of 13 years in AFS and FRS trees were 30.7 m and 1.39 m, and 30.7 m and 1.41 m, respectively (Jha, 2017). Their corresponding plantation density and root length were 139 tree ha^{-1} and 204 tree ha^{-1}; and 137 km and 113 km, respectively. Estimated values of sequestered Carbon are recorded in Table 2.

Carbon sequestration

Total sequestered root Carbon accumulation estimated by excavation method was higher in FRS (11.1 Mg ha^{-1}) than AFS (8.2 Mg ha^{-1}) on hectare basis. However, this was higher in AFS tree (59.2 kg C $tree^{-1}$) than FRS tree (54.7 kg C $tree^{-1}$). The pattern was similar in different root components. Excluding stump root, coarse root, medium root and fine root sequestered 26.7 kg C $tree^{-1}$, 5.6 kg C $tree^{-1}$ and 2.5 kg C $tree^{-1}$ (total 34.8 kg), respectively in AFS, while 24.7 kg C $tree^{-1}$, 4.9 kg C $tree^{-1}$ and 2.1 kg C $tree^{-1}$ (total 31.7 kg) in FRS. Although the total quantity of roots differed by 3.1 kg $tree^{-1}$, the contribution of different components in AFS and FRS were almost similar, for example, just 1% difference in coarse (77%-78%) and medium (15%-16%) roots and remained same in fine root (7%). Total 34.8 kg and 31.7 kg Carbon was distributed in 344 m^3 and 147 m^3 rooting soil volume, respectively. It was observed that roots were highly concentrated under the tree but 3 m^3 of tree voxel represented only 12% of total roots of the tree in AFS (12.1%) and FRS (11.9%) tree. The quantity of fine root Carbon varied in the two different methods of assessment. Coring method (3.5 kg $tree^{-1}$, AFS; 2.7 kg $tree^{-1}$, FRS) assessed higher Carbon quantity than excavation (2.5 kg $tree^{-1}$, AFS; 2.1 kg $tree^{-1}$, FRS) in both trees.

Carbon distribution

Sequestered Carbon was distributed all along the horizontal breadth and vertical depth in rooting space in the form of different categories of roots. The arrangement of proximal coarse roots on stump root showed that they were projected in all directions but resource distribution in AFS was distinctly in two tiers while there was no such distinction in FRS tree. The coarse roots grew farther from the tree base and turned into medium roots. The medium roots grew farther and culminated into fine roots which occupied farthest available distance from the tree beyond 7m in AFS and 3m in FRS. As regards the vertical distribution AFS stored root Carbon down to 2.8 m soil depth while in FRS storage depth was restricted to 2.4 m.

Fine root Carbon storage in AFS varied from 0.44 kg (0-20 cm) to 0.02 kg (260-280 cm) while in FRS it varied from 0.49 kg (0-20 cm) to 0.07 kg (200-220 cm). However, generalization showed that there was maximum fine root Carbon storage in first meter (48% in AFS and 45% in FRS) of rooting space followed by second meter (27% in AFS and 40% in FRS) and then third meter (26% in AFS and 15% in FRS). This did not predict any relationship with total roots of stump voxel column as they quantified differently in first meter (59% in AFS and 61% in FRS), second meter (38% in AFS and 35% in FRS) and third meter (3% in AFS and 4% in FRS).

Keeping in view varied microbial activity at different depth and assumed similar proportion of roots in other voxels vertical analysis of Carbon storage was done along first 0.5 m, next 1.5 m and the rest at 1.0 m depth. It was found that coarse root Carbon (medium and coarse combined) in first layer of tree voxel column was 37% and 18% in AFS and FRS, respectively. Corresponding figures for second layer and third layer were 60% and 77%, and 3% and 5% respectively.

Discussion

Sequestered Carbon variation

Two plantations faced different resource competition from tree density and received different growth enhancing treatments in the present study. The FRS trees with lower spacing were subjected only to pruning while AFS trees, in addition to pruning, were provided environment manipulation like irrigation, fertilizer application etc. Such a varied management regime could be assigned as the reason for higher Carbon sequestration in AFS than FRS as suggested by Jha and Gupta (1991) and Banerjee *et al.* (2009). They hypothesized that growing auxiliary crops with poplar and bamboo, respectively, and providing agriculture operations during the early age of intercropping enhanced the tree growth. On account of such growth, the trees accumulated more biomass and sequestered more

Table 2. Estimated sequestered Carbon in Agroforestry (AFS) and Forestry (FRS) plantations

Tree parameters	Unit	Plantation systems	
		AFS	FRS*
Fine roots (excavation)	kg	2.5	2.1
Fine roots (coring)	kg	3.5	2.7
Medium roots	kg	5.6	4.9
Coarse roots	kg	26.7	24.7
Stump root	kg	24.2	22.9
Below ground $tree^{-1}$ (coring)	kg	60.1	55.1
Below ground $tree^{-1}$ (excavation)	kg	59.2	54.7
Below ground ha^{-1} (coring)	Mg	8.4	11.2
Below ground ha^{-1} (excavation)	Mg	8.2	11.1

FRS * is factorized value (0.93) for average tree (refer method section)

Carbon (Singh and Sharma, 2007). Other corroborating reports of enhanced biomass, in turn Carbon, accumulation are (i) agrisilviculture having an edge over natural plantation (Pingale *et al*., 2014), (ii) higher fine root biomass and turnover in fruit trees due to annual addition of manure, fertilizer and watering (Raizada *et al*., 2013), (iii) standing crop of live roots increase with fertilizer treatment in young *Populus deltoides* plantation (Kern *et al*., 2004), and (iv) significantly increased root biomass due to Phosphorus application in *Acacia mangium* (Danial *et al*., 1997). Differences in Carbon quantity in both cases, with similar decreasing pattern in different root components (coarse root > medium root > fine root) could be due to the biomass produced for structural requirement which ultimately depends on the diameter and length. McCormack *et al.* (2012) also hypothesized that increasing root diameter and root tissue density traits represent greater Carbon investment in root tissue per unit of surface area.

Carbon distribution and storage

Agroforestry poplar roots grew very deep (Mulia and Dupraz, 2006) in the present case also down to approximately 3.0 m to avoid the competition from the agriculture crop. Thus, in the long run soil Carbon storage seemed feasible in deeper layer of poplar based agroforestry system. Block *et al.* (2006) have reported that fine roots in deeper layer (within the 0.3-0.6 m depth) lived significantly longer than those at upper layer (0-0.3 m depth). Moreover, fluctuating water table in the study region (Vezenobres) gave another dimension to Carbon storage. Submergence of fine roots in uprising water table created anoxia, resulting in earlier mortality and quick release of Carbon in soil. Although fine roots represent only a small fraction of total roots, their frequent turnover becomes relevant as they contribute up to 40% of the Carbon in the carbon pool. Their role in the soil of an ecosystem has been compared with leaves in the aerial environment (Tjoelker *et al*., 2005) like the litter. The coarse roots persist long after harvest of above ground parts (Johnsen *et al*., 2001; Ludovici *et al*., 2002), therefore, provide a longer term Carbon storage mechanism than that provided by fine roots (Wang *et al*., 2012). Hu *et al.* (2016) also concluded most recently that root drives soil Carbon sequestration, rather than leaf litter input, in the subsurface of marginal soil, and planting deep rooted trees with large belowground biomass production could be used to increase soil organic Carbon sequestration in marginal croplands. Therefore, in most ecosystems, belowground parts represent major sink of Carbon (Al Afas *et al*., 2008).

Intensive management of *Populus* has the potential to sequester considerable amount of soil Carbon, through repeated fine root turnover and longer term accumulation and decomposition of larger roots and stumps (Pregitzer and Friend, 1996; Rytter, 1999; Coleman *et al.*, 2000; Zan *et al.*, 2001; Block, 2004). It is widely accepted that fine roots have a longevity of 1 year or sometime less (Guo *et al*., 2008). Poplar fine roots in general have a life span of 30 to 365 days; *Populus tremuloides, Populus* × *canadensis* and other hybrid poplars, in particular, have a span of 95 to 153 days, 33 to 95 days and 36 to 100 days, respectively (Black *et al.*, 1998; Block *et al.*, 2006; McCormack *et al.*, 2012). However, assuming three carbon injection cycle in a year AFS and FRS (hybrid poplar) have the potential of three times Carbon generation annually as against one summer assessment in the study. Since fine root longevity in the present study site has not been done, further study will give better insight to accuracy of fine root turnover and in turn Carbon injection in soil. Therefore, complete information on fine root biomass and its production is critical since it plays an important role in the cycling of Carbon in a system (Chen *et al*., 2004; Graefe *et al*., 2008). However, extrapolated value (1 Mg ha^{-1} yr^{-1} to 1.6 Mg ha^{-1} yr^{-1}) or predicted value (0.85 Mg ha^{-1} yr^{-1}, unpublished data from modelling) of fine root production, fell in or matched with the range of 0.2 Mg ha^{-1} yr^{-1} - 1.6 Mg ha^{-1} yr^{-1} recorded from various studies (Block *et al.*, 2006).

Mediterranean vis a vis other regimes

In order to compare Carbon sequestration in Mediterranean condition with other regimes like temperate and tropical condition, earlier reports of carbon sequestration in poplar species was reviewed and is presented in Table 3. A close perusal of the data revealed lot of variation and indicated its dependency on spacing and age of the stand (Fang *et al*., 2007; Jha *et al*., 1991). However, below ground Carbon storage in the present study (8.2 Mg ha^{-1}-11.1 Mg ha^{-1}) fell in the reported range of temperate (0.17 Mg ha^{-1}-18.95 Mg ha^{-1}) and tropical (0.48 Mg ha^{-1}-21.5 Mg ha^{-1}) countries. Although precise comparison is not possible due to many variants involved in earlier reports and the present study, a tentative conclusion could be drawn. Rate of root biomass Carbon production in Mediterranean condition (present study: AFS, 13 years, 109 trees ha^{-1}, 8.2 Mg ha^{-1} C), for example, (i) is lower than Tropical condition of India {(Ajit *et al*., 2011): AFS, 9 years, 500 trees ha^{-1}, 15.51 Mg ha^{-1} C}, and (ii) is higher than Temperate China {(Gao *et al*., 2014): FRS, 40 years, 1420 trees ha^{-1}, 18.95 Mg ha^{-1} C} and USA {(Koerper and Richardson, 1980): FRS, 52 years, 16.41 Mg ha^{-1} C} etc.

Forest versus Agroforest systems

The root structure of two differently nurtured trees were different, consequently the carbon distribution in the rooting space was also different. AFS had tiered and deeper distribution of Carbon in contrast to less deep and non-tiered distribution in FRS. Such variation got support from Mulia and Dupraz (2006) who hypothesized that in Mediterranean climate agroforestry trees develop a different rooting pattern than forestry ones. The reason for such variation was mainly due to physical and agronomic factors (Bishopp, 2009; Fukaki and Tasaka, 2009) and the genetic makeup (Kell, 2012). Wullschleger *et al.* (2005) further explained this through genotype and age. The present results differed from those of Wullschleger *et al.* (2005) and Kell (2012) since both the AFS and FRS trees were of the same clone and age. However, irrespective of the controlling reasons, different pattern of Carbon investment in AFS is advantageous since tiered growth is an adaptation against adverse condition like drought and ploughing damage to roots (Perry, 1989; Gary, 2000).

Albuquerque *et al*. (2015) hypothesized that the concentration of root biomass (or carbon) under the stem base is much higher than in the area between the trees. This was found true in the present estimation in both the trees

Table 3. Belowground Carbon in different species at different age and density in different climate regimes

Location	Species	Age (years)	Density (ha^{-1})	Root: shoot ratio (%)	**Below ground C (Mg ha^{-1})	Authors
USA	*Populus tremuloides*	8	12,670	58	6.28	Rurak and Bokheim (1988)
	Populus tremuloides	14	6,600	38	6.97	
	Populus tremuloides	18	6,495	34	7.15	
	Populus tremuloides	32	1,575	21	9.74	
	Populus tremuloides	63	890	18	10.61	
USA	*Populus granidentata* (good site)	52±2	-	21*	16.41	Koerper and Richardson (1980)
	Populus granidentata (intermediate site)	52±2	-	21*	12.31	
	Populus granidentata (poor site)	60±2	-	21*	3.68	
USA	*Populus deltoides*	8	-	21*	8.58	Shelton *et al.* (1982)
	Populus deltoides	16	-	21*	16.26	
USA	*Populus deltoides* 26C6R51	5	10,000	22.4	5.45	Dowell *et al.* (2009)
	Populus deltoides 2059	5	10,000	21.1	5.55	
	Populus deltoides 1112	5	10,000	23.8	5.78	
	P. deltoides × *P. nigra* 145/41	5	10,000	20.1	2.80	
	P. deltoides × *P. nigra* Eugeneii	5	10,000	19.2	2.89	
Canada	*Populus trichocarpa* × *P. deltoides*	12	1,111	21*	10.75-15.89	Zabek and Prescott (2006)
Canada	Hybrid Poplar	6	2,222	21*	1.35-10.92	Fortier *et al.* (2010b)
Canada	*Populus nigra* × *P. maximowiczii* 3230	6	2,222	21*	4.59	Fortier *et al.* (2010a)
	P. deltoides × *P. nigra* 3570	6	2,222	43.5	7.19	
	P. canadensis × *P. maximowiczii* 915508	6	2,222	17.5	4.01	
	P. nigra × *P. maximowiczii* 3729	6	2,222	21*	6.99	
	P. maximowiczii × *P. balsamifera* 915311	6	2,222	24.5	7.00	
Canada	Hybrid Poplar (*P. deltoides* × *P. nigra* 3570, *P. canadensis* × *P. maximowiczii* 915508, *P. maximowiczii* × *P. balsamifera* 915311)	9	2,222	21*	5.01-13.2	Fortier *et al.* (2013)
Canada	*P. deltoides* × *P. nigra* 3570	13	833	27-54	2.0-9.1	Fortier *et al.* (2015b)
	P. canadensis × *P. maximowiczii* 915508	13	833	5-25	5.6-8.8	
	P. maximowiczii × *P. balsamifera* 915311	13	833	20-34	4.7-6.6	
Germany	Hybrid Poplar clones (Muhle Larson, Rap, Beaupre, Max1, Max 3, Max 4, Androscoggin, Hybride 275)	8	8,333	21*	2.29-4.68	Bungart and Huttl (2004)
Germany	*P. trichocarpa*, Mhule Larsen (First rotation)	5	-	21*	2.2-3.7	Hofmann- Schiell *et al.* (1999)
	P. trichocarpa, Mhule Larsen (Second rotation)	5	-	21*	5.9-6.5	
Sweden	*P. balsamifera, P. trichocarpa* and Hybrid poplar	4-73	4,690	21*	13.58	Johansson and Karacic (2011)
Sweden	*P. trichocarpa* × *P. deltoides,* Beaupre	6	5,000	21*	4.38	Teleniusa (1999)
	P. trichocarpa × *P. deltoides,* Boelare	6	5,000	21*	4.18	
France	*Populus* × *euramericana* I-214 (AFS)	10	139	12.5	6.77	Arraiolos (2006)
France	*P. trichocarpa* × *P. deltoides,* Boelare	8	1,900	21*	5.78	Brahim *et al.* (2000b)
	P. trichocarpa × *P. deltoides,* Beaupre	8	1,900	21*	5.38	
	P. trichocarpa × *P. deltoides,* Raspalje	8	1,900	21*	5.39	

France	*P. trichocarpa* × *P. deltoides*, Beaupre	9	4,000	21*	10.56	Brahim *et al.* (2000a)
		9	2,000	21*	5.10	
		7	2,000	21*	7.63	
France	*Populus euramericana* I-214 (AFS)	13	139	11.8	8.2	Present study
France	*Populus euramericana* I-214 (FRS)	13	204	13.2	11.1	Present study
China	*P. deltoides* I-63 and I-69, *P. euramaricana* I-72	10	1,111	15	9.4	Fang *et al.* (2007)
		8	1,111	18	9.6	
		6	1,111	22	8.8	
		4	1,111	25	6.0	
China	*P. deltoides* × *P. nigra* Zhonglinmeihe	3	1,111	37	0.20	Fang *et al.* (2008)
		2	1111	87	0.17	
China	*Populus simonii*	40	1,420	28.5	18.95	Gao *et al.* (2014)
India	*Populus deltoides* D121 clone	5	400	19.2	7.31	Lodhiyal *et al.* (1995)
		6	400	20.0	9.00	
		7	400	20.6	12.90	
		8	400	21.0	16.02	
India	*Populus deltoides* (AFS/FRS)	4	666	16	7.45	Lodhiyal and Lodhiyal (1997a)
India	*Populus deltoides*	9	400	25	21.5	Lodhiyal and Lodhiyal (1997b)
India	*P. deltoides* (FRS)	8	500	27.19	20.51	Singh and Lodhiyal (2009)
India	*Populus deltoides* (AFS)	3	500	12.2	1.00	Das and Chaturvedi (2005)
	Populus deltoides (AFS)	9	500	20.08	7.10	
India	*Populus deltoides* (AFS)	1	500	28.76	0.48	Ajit *et al.* (2011)
	Populus deltoides (AFS)	9	500	21.5	15.51	
India	*Populus deltoides* (AFS, Wheat)	9	500	22.36	5.83	Yadava (2010)
	Populus deltoids (AFS, Lemon grass)	9	500	21.55	5.48	
	Populus deltoides (AFS, Wheat)	9	130	17.4	1.53	
India	*P. deltoides* (AFS) 65/27 clone	6	500	19.4	5.51	Swamy *et al.* (2006)
	D121 clone	6	500	16.8	4.55	
	G48 clone	6	500	20.9	5.51	
	G3 clone	6	500	16.77	4.28	
	S7C1 clone	6	500	13.8	3.05	
India	*P. deltoides* G-48 (AFS)	4	493	21*	4.30	Chauhan *et al.* (2011)
		5	493	21*	7.24	
		6	493	21*	7.83	
India	*Populus deltoides*	5	493	9.03	2.80	Chauhan *et al.* (2012)
India	*Populus* sp.	6	740	21*	12.0	Chauhan *et al.* (2015)

**Carbon content in roots has been quoted from the studies or derived using total or aboveground biomass, root: shoot ratio and Carbon factor (45.56%), *21% root: shoot ratio is the calculated average (Jha, 2009) which falls in the reported range 18-30% (Cairns *et al.*, 1997). Use of this average ratio may not give exact estimation but approximate amount of Carbon sequestered in that condition.

but the quantum of Carbon storage (12% of the total Carbon) did not match at all, obviously, due to high difference in rooting space under and between the tree, plant species and their growing regime.

Most of the studies have concluded that majority of coarse and fine roots of poplar in plantation and agroforestry system are located near soil surface, therefore, the Carbon storage (Puri *et al.*, 1994; Tufekcioglu *et al.*, 1999; Al Afas *et al.*, 2008; Douglas *et al.*, 2010; Fortier *et al.*, 2013) and effective rooting or Carbon storage depth could be 1.0 m (Callesen *et al.*, 2016). But in the present case both the systems had deeper and wider roots or carbon storage as a result of maximum nutrient exploitation strategy (Allen *et al.*, 2004; Dougherty *et al.*, 2009) adopted by the plant. On this account AFS is more useful than FRS since it has its roots, comparatively, in deeper and wider region possibly due to ploughing and damage of upper layer roots as well as presence of crop roots (Yocum, 1937; Gary, 2000; Mulia and Dupraz, 2006).

Coarse roots accumulate largest amount of belowground Carbon (Fonseca *et al.*, 2011) and play major role in Carbon storage in the soil. In fact, large roots have particularly slow decay rates and they can contribute to the belowground biomass Carbon pool over a century after harvest (Liski *et al.*, 2014) possibly due to a very high density of microorganisms in top 25 cm with substantial change within 50 cm and inactive presence in the next 150 cm (Fierer *et al.*, 2003; Senga *et al.*, 2015). Also the fine root turnover represents one of the major Carbon sources in the soil and thus play a significant role in ecosystem Carbon cycling (Gill and Jackson, 2000). From these viewpoints, FRS system should be more useful for the given results since this system sequestered higher Carbon content on per hectare basis as compared to AFS (on account of higher tree density in the case of former) and also due to higher proportion of storage of Carbon beyond 50 cm (82% FRS, 63% AFS; per tree basis).

Similar results of higher Carbon sequestration was found by Winans *et al.* (2015) in the case of hybrid poplar FRS and hay-corn poplar AFS, though the spacing, growth regime and harvest age varied from the present study. However, total Carbon storage could be enhanced in AFS provided the tree density is increased optimally with some compromise in grain production. This hypothetical assumption has the following foundations (i) successful wheat based poplar agroforestry in tropical region at lower tree spacing (Singh and Singh, 2016) or less rooting space (ii) lower tree spacing enhances coarse root production in poplar (Puri *et al*., 1994) and (iii) at later stage tree density could be reduced by canopy opening to provide sufficient light in the alley.

Land equivalent ratio (LER) is a measure of the overall effectiveness of the mixed system (Chaudhry, 2003). The productivity of an agroforestry system can be compared to monoculture system using LER (Mead and Willey, 1980). Similarly, Carbon LER (CLER) could be used in understanding the superiority of the system in terms of Carbon sequestration if the ratio is more than one (Jha, 2009). CLER of the studied agroforestry system is 1.3 (unpublished data) which clearly indicated the AFS efficiency over FRS.

Conclusions

Both systems have good potential of belowground Carbon sequestration. However, allocation of Carbon per tree was higher in different root components – fine, medium and coarse roots in AFS. Even so, on hectare basis, sequestered Carbon was more in FRS, mainly due to higher tree density. Nevertheless, AFS was found more efficient on CLER account. Therefore, it is apparent that FRS is more useful for total Carbon sequestration purpose, but grain production is compromised in this system. It is likely that Carbon storage may be enhanced by opting for researched optimum AFS tree density. The difference in fine root biomass assessment by two different methods - excavation and coring - was also confirmed, under estimation in the former case which could be due to root loss during the process. AFS stored Carbon in much deeper layer having an advantage of longer storage. Nonetheless, the results available in the present study provided two land-use management options with different advantages.

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