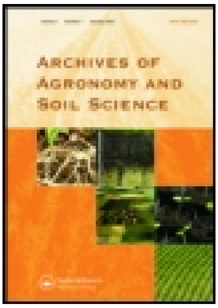

Archives of Agronomy and Soil Science
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gags20

Tree biomass, resource use and crop productivity in agri-horti-silvicultural systems in the dry region of Rajasthan, India

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Accepted author version posted online: 12 Nov 2013.Published online: 09 Dec 2013.

Archives of Agronomy and Soil Science, 2013
http://dx.doi.org/10.1080/03650340.2013.864386

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(*Received 24 June 2013; accepted 17 October 2013*)

A combination of silvicultural species [*Prosopis cineraria* (L.), *Ailanthus excelsa* Roxb. and *Colophospermum mopane* (J. Kirk ex Benth.)] were planted with horticultural species [*Ziziphus mauritiana* (L.), *Cordia myxa* (Forster), and *Emblica officinalis* (Gaertn)] and intercropped with wheat (*Triticum aestivum*). *Z. mauritiana +P. cineraria* combination produced greater fruit, fodder and fuel wood and was less competitive to wheat crop. Crop yield reduced by 5% to 23% in the agroforestry systems than the yield in sole crop plot. Lowest yield was in *C.* mopane + *C. myxa* combination. Fodder yield was 0.53, 0.20 and 0.07 t ha^{-1} from *C. mopane (cursive)*, *P. cineraria* and *A. excelsa*, respectively, whereas utilizable biomass was 2.63 t ha^{-1} from *C. myxa (cursive)* + *P. cineraria*, 2.21 t ha^{-1} from *C. myxa (cursive)* + *C. mopane* and 2.18 t ha^{-1} from *Z. mauritiana* + *P. cineraria* combinations. Soil organic carbon and NH_4–N increased (by 7% and 8%, respectively), whereas NO_3–N and PO_4–P decreased in agroforestry compared to the sole tree plots. Primary root attributes of *P. cineraria*, *A. excelsa* and *C. mopane* were higher in agroforestry and mostly concentrated in the top 0–25 cm of the soil layer. *Z. mauritiana* + *P. cineraria* were the best combination with minimum yield reduction and were found to be beneficial in enhancing soil fertility.

Keywords: crop yield; dry region; irrigation; horti–silvi species; organic carbon; soil nutrients

Introduction

Adversities of climatic factors in arid and semi-arid regions accelerate soil moisture deficit and chance of crop failure throughout the world (Lawless et al. 2008; Cai et al. 2009). Increasing human population is placing unprecedented demand for food and natural resources. It has been estimated that an increasing population and changing dietary intake will lead to about 80–120% increase in global food requirement by 2050 (Tilman et al. 2001; FAO 2006; Foley et al. 2012). This large amount of food production cannot be achieved by the agricultural sector only, rather through a combination of technological improvements and involvement of other natural ecosystems (Licker et al. 2010). Traditional tree-integrated farming systems are adopted since time immemorial for security of food, fodder and fuel wood in drought-prone arid region (Harsh et al. 1992; Leakey & Simons 1998; Ndayambaje & Mohren 2011; FAO 2013), but are unable to meet the requirement of the ever increasing population. There is a need of intensification of such tree-integrated system too to improve total land productivity as it provides greater carbon offset opportunities than any other climate mitigation practices in agriculture (FAO 2004; Udawatta & Jose 2012; Murthy et al. 2013).

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Tree-integrated system is one of the options with multifunctional value among numerous issues involved with livelihood improvement in dry areas (Gathumbi et al. 2002; Pandey 2007; Fukushima et al. 2010). The most important benefit of agroforestry systems is the enhancement in total production by improving soil fertility (Stahl et al. 2002; Singh 2010), mitigation of soil carbon loss by erosion control, replenishment of nutrients removed through biomass harvest (Nair et al. 1999; Ilany et al. 2010), improvement in microbial population (Belsky et al. 1989; Yadav et al. 2008; Vallejo et al. 2012), economic benefits (Gajja et al. 1999; Jianbo 2006; Fadl & Sheikh 2010), and nutrient and water-use efficiency (Anderson et al. 2009; Pinho et al. 2011). Below-ground resources are more limiting than the above-ground resources in an arid environment that influences the growth and productivity of tree and crop both. There is a tacit assumption that the shallow-rooted trees compete with companion crops through their root system and this lead to yield depression and contributes to the economic failure of land-use system (Ong & Black 1994; Schroth et al. 1996). Understanding the spatial distribution of tree roots (horizontal and vertical distribution) and biomass yield may be useful in managing this system for better productivity. Because of access to deeper nutrient pools than the crop, tree absorbs nutrient from deeper root zone and returns nutrients through litter fall and root turnover to the subsurface, thus helping in accumulating nutrients and improving soil physical properties (Puri et al. 1995; Singh & Rathod 2006) and nutrient-use efficiency in the system (Lehmann et al. 1999; Buresh et al. 2004).

Farmers maintain and promote randomly and widely growing sparse trees on their farmlands throughout the dry regions of the world. For example, *Prosopis cineraria* (L.), *Tecomella undulata* (L.), *Acacia nilotica (*Linn), *Salvadora oleoids* (L.), *S. persica* (L.) and *Zizyphus nummularia* (L.) are maintained on cultivated fields for the production of fodder, fuel, nutrition and to support income in the arid region of India (Tewari et al. 2007). Other plant systems exist: Oil palm, kola, coffee, *Sarcophrynium brachystachys*, *Megaphrynium macrostachyum*, *Tetracarpidium conophorum*, *Aframomum melegueta* in Nigeria (Oladokun 1990), *Faidherbia albida*, *Acacia karroo, Acacia erioloba, Acacia tortilis, Colophospermum mopane, Dichrostachys cineria, Olea europaea* and *Ziziphus mucronata* in the savannah region of South Africa (Esterhuyse 1989) and *Adansonia digitata*, *Tamarindus indica*, *Zizyphus mauritiana*, *Sclerocarya birrea* and *Mangifera indica* in the sub-Saharan and the Sahel region of Africa (Jama et al. 2007). However, in most of the regions, people are reluctant to adopt agroforestry because of lesser short-term benefits from silvicultural species. Integrating horticultural species with silvicultural species will ensure income/productivity to the farmers much earlier. Irrigation to the system, where water is available, will provide added income to the farmers. While tree component in agri-horti-silvicultural system maintains higher productivity, enhances economy of the farmers, improves farmers livelihood on sustainable basis and provides carbon sequestration benefits, wheat (*Triticum aestivum*) as staple food grown under irrigation (wherever water is available) could provide additional benefits of improved productivity of all components, i.e. tree, horticultural species and agriculture crop because of irrigation.

The present study intended to assess the growth and biomass of trees and their effects on wheat productivity when intercropped under irrigation-now under adaptation in some parts of the Indian arid zone. Further, the effects of this system on soil fertility and thus controlling land degradation were investigated.

Material and methods

Site description

The experiment was conducted for six consecutive years (2006–2012) on a farmers' land near Bilara, Jodhpur, (26º 45′ N, 72º 03′ E) district of Rajasthan, India. The climate of the site is tropical and characterized by hot and dry summer, hot rainy season, warm autumn and cool winter. The period from mid-July to September is the monsoon season, which receives most of the rainfall. Annual rainfall received was 455, 417, 384, 129, 339 and 476 mm in 2006, 2007, 2008, 2009, 2010 and 2011, respectively, with an average annual rainfall of 367 mm. Maximum temperature rises to as high as 48°C in the summer and the minimum drops to 0°C in winter. Wind velocity in the summer months is 20–30 km h^{-1}. Soil of the experimental site is Aridisol 'coarse loamy, mixed, hyperthermic of Typic Haplocambids' as per the USDA classification. The soil contained 82% of sand, 17.67% of silt and 0.33% of clay in the 0–25 cm soil layer, with low available nitrogen and phosphorus. Soil was saline in nature with a pH of 8.87, electrical conductivity (EC) of 0.99 dS m^{-1} and soil organic carbon (SOC) of 0.26% in the 0–25 cm soil layer. Potential evapotranspiration fluctuated between 2.47 mm day^{-1} in December to 8.54 mm day^{-1} in May showing high water deficit in the region (Rao et al. 1971).

Experimental design

The trial was laid in a randomized block design in three replicates. The planted horticultural species were *Ziziphus mauritiana* (L.) (grafted Ber, variety – Gola) (ZM), *Cordia myxa* (Forster) (COM) and *Emblica officinalis* (Gaertn) (grafted Aonla variety – NA and Krishna) (EO) and the silvicultural species were *Prosopis cineraria* (L.) (PC), *Ailanthus excelsa* Roxb. (AE) and *Colophospermum mopane* (J. Kirk ex Benth.) (CM). Horti- and silvicultural species were planted alternate to each other in nine possible combinations in August 2006 at a spacing of 6 × 6 m. Totally, 25 seedlings of horti- and silvicultural species were planted in each plot. In addition, there was a sole plot of horti- and silvicultural species as well as agricultural crop as the control.

Basal doses of 10 kg farmyard manures, 150 g diammonium phosphate (DAP), 450 g single super phosphate (SSP) and 25 g forate (anti-termite insecticide) were applied at the time of plantation. The plantation was maintained through different silvicultural practices viz. irrigation, soil working, weeding, protection, anti-termite treatment, pruning etc. which were common to all plots. *Sesbania aculeata* (Dhaincha) was intercropped from 2009 for green manuring in kharif (mansoon season of July to October) to ameliorate the soil condition and sustain crop production and growth of the planted species. Wheat (*Triticum aestivum* linn.) variety – C 306 was cultivated as the intercrop in rabi (winter season of November to March) season in all the years in both the tree-integrated and the sole agricultural plot. DAP fertilizer was applied at 60 kg per ha at the time of sowing of wheat crop in November each year. Grafted ber was lopped for better fruiting in the first week of May each year. *Z. mauritiana* started fruiting after 2007, (except in 2009 and 2010). Irrigation was provided to the plantation at 10 days interval in summer and 15 days interval in winter season through drip irrigation, whereas flood irrigation was provided to the wheat crop. The water used for irrigation had a pH of 7.27 and EC of 10.7 dS m^{-1}.

Data recording

Height, collar diameter (10 cm above from the ground level) and crown diameter of the plants were recorded at 6 months interval. One tree of each species with average growth parameters in both tree-integrated and control plots was felled for biomass recording and root distribution study. The above-ground part of felled trees was separated into stem, branches and leaf in March 2012. Roots of the felled trees were excavated by manual digging and up to a diameter of 0.5 cm. Roots-spread were anchored to retain their normal positions throughout the process of digging away the soil and exposing the roots. An area of about 12.57 m^2 (2 m radius) was excavated as deep as the roots penetrated. The remainder of the individual root beyond 2 m was excavated completely. The length and diameter of all primary and secondary roots were measured. For the estimation of biomass, the fresh weight of the stem, branches, leaves and roots was recorded immediately after harvesting of the tree and separating it into different components. Samples were collected from stem, branches, leaves and roots, and dry biomass was recorded after oven drying of the sample at 80°C. Fodder yield (leaf biomass) was recorded for *P. cineraria*, *A. excelsa* and *C. mopane*.

Harvesting and yield recording of wheat crop was done in three quadrates (one each near the silvicultural or horticultural trees and in between both types of species) of 2×1 m^2 size in each plot as well as the sole crop plots. Crop was harvested in March each year from the above mentioned quadrates and threshed. Straw and the grain of wheat were separated by winnowing and their yield were recorded in megagram (Mg) per ha.

Soil sampling and soil nutrient analysis

Soil samples were collected from each plot in August 2006 and March 2012 to a depth of upto 0–50 cm (divided into 0–25 and 25–50 cm soil layers). These soil samples were homogenized to form a composite sample of each treatment and soil layer in three replicates. The soil samples were air dried, ground and passed through a 2-mm mesh sieve before analysis. Soil pH, EC and SOC were determined using standard procedures (Walkley & Black 1934; Jackson 1973). Available nitrogen (NH_4–N and NO_3–N) was determined using UV spectrophotometer (Model Shimadzu-1650PC, Shimadzu Corporation, Japan) after 0.5 M K_2SO_4 extraction. Extractable phosphorus was determined by the Olson's extraction method (Jackson 1973) using the above-mentioned UV spectrophotometer.

Data calculation and analysis

Canopy volume was calculated considering the canopy of these trees as hemisphere using Equation (1):

$$\text{Canopy volume} = 2/3\pi r^3, \qquad (1)$$

where r is radius of the canopy.

Basal area of each tree species in each plot was calculated using Equation (2):

$$\text{Basal area of the tree} = \pi \ \text{CD}^2/4 \times n, \qquad (2)$$

where CD is the collar diameter, n is the number of tree.

Data collected were statistically analysed using the SPSS statistical package. Height, collar diameter, crown diameter, basal area, canopy volume of the tree species and crop yield were analysed using a one-way ANOVA. Paired *t*-test was used to observe changes in physico-chemical parameters and the nutrients of soil between the years. Available soil NH_4–N, NO_3–N and PO_4–P were also analysed. Duncan's multiple range test (DMRT) was applied to get homogenous subsets of the treatments (i.e. silvi–horti combinations). The least significant difference test was used to compare treatments at the $P < 0.05$ levels. For obtaining relationships between different plant growth variables, soil properties and crop yield, a Pearson correlation was calculated.

Results

Growth of tree plantation

Five and a half years after planting, plants height and collar (15 cm above soil surface) diameter varied ($P < 0.05$) between the treatments. *C. mopane*, *A. excelsa*, *P. cineraria* and *C. myxa* trees were taller ($P < 0.05$) by 51%, 109%, 17% and 37%, respectively, than the respective species in the alone tree plots (Table 1). Among the tree species, *A. excelsa* attained the greatest height. The shortest height was recorded in *Z. mauritiana* (184 cm). Collar diameter of *A. excelsa*, *C. mopane* and *P. cineraria* was greater by 61%, 63% and 32%, respectively in tree-integrated than in the alone tree plots. The collar diameter was the greatest for *A. excelsa* (Table 1). The crown diameter was also greater in the tree-integrated than in the alone tree plots. *C. mopane* attained the highest crown diameter, whereas crown diameter was lowest for *Z. mauritiana* plants (Table 1).

Basal area and canopy volume

Basal area and canopy volume of all horticultural, silvicultural and there combinations differed significantly ($P < 0.001$) between different agroforestry systems (Table 2). Among horticultural species, *Z. mauritiana* had greater ($P < 0.05$) basal area as compared to *C. myxa*, whereas canopy volume was in reverse order. *P. cineraria* and *A. excelsa* indicated ($P < 0.05$) highest and lowest basal area, whereas canopy volume was the highest ($P < 0.05$) for *C. mopane* among the silvicultural species. Among the combinations, ZM + PC system indicated the highest ($P < 0.05$) basal area whereas EO + CM system showed the lowest basal area. Canopy volume was the highest ($P < 0.001$) in COM + CM system, whereas EO + AE system showed the lowest canopy volume.

Root growth and structure

Primary and secondary roots showed a wide range of variation (Table 3). The number of primary roots was the highest in the tree-integrated plots than in the alone tree plots. Number of roots was the highest in *P. cineraria* among the trees species. Number of secondary roots was greater in the alone tree plots for *C. mopane* and *Z. mauritiana*, whereas *A. excelsa* and *C. myxa* showed a reverse trend. Primary roots were longer in tree-integrated plots, except for *C. mopane*, which showed greater primary root length in the alone tree plots. Average primary root diameter was greater in tree-integrated plots compared to the alone tree plots. Average secondary root length and root diameter was greater in tree-integrated plots except for *P. cineraria* which showed a 30% greater root length in alone tree plots compared to the tree-integrated plots.

Table 1. Height, collar and crown diameter of horti- and silvicultural tree species in agroforestry systems in the Indian arid zone. Values are means ± standard deviation of three replicate plots.

	Height (cm)			Collar diameter (cm)			Crown diameter (cm)		
	Sept 06	March 12		Sept 06	March 12		Sept 06	March 12	
Species	Initial	Combined tree	Sole tree	Initial	Combined tree	Sole tree	Initial	Combined tree	Sole tree
A. excelsa	46 ± 3	341 ± 143*	163 ± 21	0.55 ± 0.11	11.43 ± 5.3*	7.10 ± 0.4	33 ± 2	205 ± 101*	67 ± 20
C. mopane	30 ± 3	307 ± 62*	204 ± 45	0.38 ± 0.08	7.60 ± 1.7*	4.66 ± 1.1	27 ± 2	272 ± 64*	178 ± 69
P. cineraria	33 ± 3	264 ± 87*	226 ± 78	0.3 ± 0.08	6.90 ± 2.8*	5.21 ± 1.7	21 ± 2	168 ± 67*	131 ± 52
C. myxa	36 ± 3	262 ± 83*	191 ± 33	0.81 ± 0.14	8.53 ± 2.7	7.59 ± 1.3	31 ± 3	219 ± 82*	127 ± 20
E. officinalis	66 ± 4	–	–	0.90 ± 0.18	–	–	26 ± 2	–	–
Z. mauritiana	32 ± 3	186 ± 45	175 ± 25	0.31 ± 0.04	3.74 ± 1.3	3.24 ± 0.7	3 ± 2	124 ± 44*	91 ± 22

Note: * Significant at $P < 0.05$ as compared to respective species control value.

Table 2. Basal area and canopy volume of horti- and silvicultural tree species in agroforestry systems in the Indian arid zone. Values are mean ± standard deviation of three replicate plots.

	Basal area ($cm^2\ ha^{-1}$)			Canopy volume ($m^3\ ha^{-1}$)		
Species combination	Horticultural	Silvicultural	Total	Horticultural	Silvicultural	Total
ZM + PC	1554 ± 11.28	9011 ± 5.11	10565 ± 6.18	31.37 ± 0.48	114.70 ± 0.64	146.06 ± 1.11
ZM + AE	1458 ± 19.21	8503 ± 24.90	9960 ± 42.87	29.64 ± 0.52	77.77 ± 0.23	107.40 ± 0.75
ZM + CM	1507 ± 12.22	8196 ± 12.53	9202 ± 13.14	30.63 ± 0.36	452.88 ± 0.64	483.50 ± 0.29
COM + PC	1371 ± 10.67	8914 ± 17.87	10286 ± 18.97	153.90 ± 0.37	113.47 ± 0.25	267.36 ± 0.13
COM + AE	1348 ± 9.20	7887 ± 9.43	9234 ± 12.11	151.15 ± 0.23	72.14 ± 0.25	223.29 ± 0.48
COM + CM	1299 ± 8.02	8625 ± 7.70	9923 ± 11.98	145.64 ± 0.34	476.57 ± 0.65	622.21 ± 0.70
EO + PC	–	8865 ± 8.07	8865 ± 8.07	–	112.84 ± 0.41	112.84 ± 0.41
EO + AE	–	8749 ± 5.82	8749 ± 5.82	–	80.05 ± 0.35	80.05 ± 0.35
EO + CM	–	8291 ± 4.41	8291 + 4.41	–	458.16 ± 0.56	458.16 ± 0.56
	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$	$P < 0.01$

Note: Significant at $P < 0.01$, *Z. mauritiana* (ZM), *Cordia myxa* (COM), *E. officinalis* (EO) , *P. cineraria* (PC), *A. excelsa* (AE), *C. mopane* (CM).

Table 3. Root growth parameters of horti- and silvicultural tree species in agroforestry systems in the Indian arid zone.

Species	Primary root						Secondary root					
	Number		Length (cm)		Diameter (cm)		Number		Length (cm)		Diameter (cm)	
	Combined tree	Sole tree	Combined tree	Sole tree	Combined tree	Sole tree	Combined tree	Sole tree	Combined tree	Sole tree	Combined tree	Sole tree
A. excelsa	3	2	142 ± 23*	51 ± 2	4.13 ± 0.75*	2.10 ± 0.36	14	6	89 ± 73	52 ± 23	1.48 ± 0.78	1.28 ± 0.46
C. mopane	3	2	92 ± 17	98 ± 18	2.22 ± 0.28	1.95 ± 0.07	17	23	129 ± 39	108 ± 59	1.09 ± 0.20*	0.55 ± 0.34
P. cineraria	4	4	169 ± 21*	138 ± 12	2.43 ± 0.50	2.23 ± 0.90	8	7	60 ± 25	78 ± 20	0.78 ± 0.44	0.70 ± 0.31
Cordia myxa	2	3	153 ± 32	112 ± 18	4.40 ± 0.14*	2.17 ± 0.97	11	9	201 ± 50*	130 ± 65	1.56 ± 0.53	1.46 ± 0.64
Z. mauritiana	2	4	210 ± 28*	132 ± 8	2.15 ± 0.08*	1.40 ± 0.42	11	23	117 ± 37	101 ± 42	1.04 ± 0.42	0.78 ± 0.31

Note: * Significant at $P < 0.05$ as compared to respective species control value.

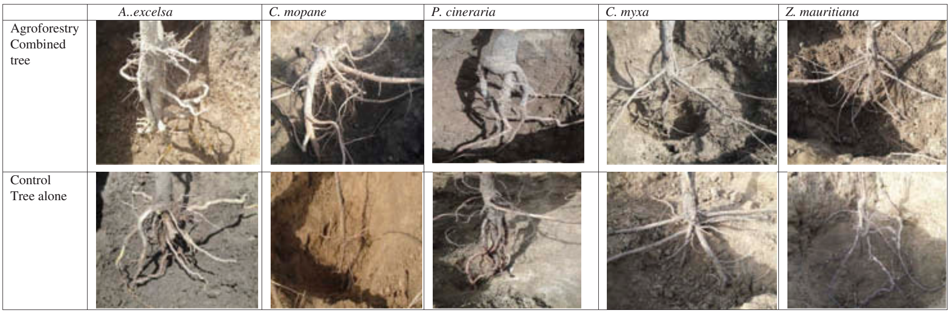

Figure 1. (colour online) Distribution of roots of different horti- and silvicultural tree species integrated into farming systems in the Indian arid zone. Combination of horti- and silvicultural species were *Z.* mauritiana + *P. cineraria*, *Z.* mauritiana + *A. excelsa*, *Z.* mauritiana + *C. mopane*, *C.* myxa + *P. cineraria*, *C.* myxa + *A. excelsa*, *C.* myxa + *C. mopane*, *E.* officinalis + *P. cineraria*, *E.* officinalis + *A. excels* and *E.* officinalis + *C. mopane*.

Roots of *C. mopane* and *C. myxa* were concentrated in the top 40 cm of soil profile and indicated a fan-shaped appearance around the root stock (Figure 1). The roots of these species spread nearly parallel to the ground surface. Primary roots were thick and further branched into several thin and long or small roots. The roots of *P. cineraria* and *A. excelsa* were concentrated in the top 90 cm, whereas *Z. mauritiana* roots were concentrated in the top 60-cm of the soil profile. The roots of *P. cineraria* and *A. excelsa* showed vertical distribution of roots in a typical bale-shaped structure and penetrated deeper into the soil. The roots of *Z. mauritiana* appeared as umbrella shape, and penetrated down into the sub-soil layers. The spread of secondary roots was found symmetrical in the tree-integrated system.

Plant biomass

P. cineraria showed the highest total dry biomass in both the tree-integrated as well as in the *P. cineraria* alone tree plots (Table 4). Lowest biomass was recorded for *Z. mauritiana*. The dry biomass in tree-integrated plots was greater by 11.0-fold in *A. excelsa*, 4.5-fold in *C. mopane*, 2.0-fold in *P. cineraria*, 2.7-fold in *C. myxa* and 2.0-fold in *Z. mauritiana* as compared to their respective biomass in the alone tree plots. Utilizable biomass (stem + branches for fuel wood) was also greater in the tree-integrated plots as compared to the alone tree plots (Table 4) for all species. Dry leaves

Table 4. Dry biomass in different components of horti- and silvicultural tree species in agroforestry systems in the Indian arid zone.

	Dry biomass (kg per tree)									
	Combined tree					Sole tree				
Species	Leaf	Branch	Stem	Root	Total	Leaf	Branch	Stem	Root	Total
A. excelsa	1.038	2.064	5.586	2.691	11.378	0.016	–	0.541	0.449	1.006
C. mopane	3.046	3.228	3.128	3.875	13.277	0.517	0.687	0.746	1.029	2.979
P. cineraria	1.077	6.737	3.408	2.796	14.018	0.307	2.564	1.705	2.367	6.944
Cordia myxa	0.638	2.372	3.003	1.101	7.114	0.015	–	0.987	1.616	2.618
Z. mauritiana	0.265	–	0.845	0.957	2.067	0.077	–	0.186	0.719	0.983

production was highest in *C. mopane* which was greater in tree-integrated plots as compared to the alone tree plots (Table 4). Fodder production was less by 83% in *C. mopane* and 72% in *P. cineraria* in the alone tree plots as compared to tree-integrated plots. Root biomass was highest for *C. mopane* trees. In general, root biomass was greater in tree-integrated plots as compared to the alone tree plots for all species. Allocation of dry biomass in different components of tree species (Supplementary Figure 1 a, b, c, d and e) showed greater allocation to leaf and branch in tree-integrated plots as compared to the alone tree plots. Dry biomass allocation to stem was higher in *Z. mauritiana* and *C. myxa* in tree-integrated plots and for rest of the species in the alone tree plots. Dry biomass allocation to root was higher in alone tree as compared to tree-integrated plots in all species.

Fruit production

Fruiting in *Z. mauritiana* plants started in 2008, when fruit production was only 0.036 kg $plant^{-1}$. Fruit production was 0.918 kg $plant^{-1}$ in 2011 and 1.130 kg $plant^{-1}$ in 2012. The fruit production was not influenced by horti–silvi combinations in different years. Because of drought and soil water stress *Z. mauritiana* did not yield fruits in 2009 and 2010. Plants of *C. myxa* started flowering in 2012.

Wheat production

Total biomass (straw + grain) as well as grain yield of wheat did not differ ($P < 0.05$) among different combinations during 2007 to 2010. The highest wheat yield (4.57 Mg ha^{-1} total and 1.61 Mg ha^{-1} grain) was in the sole wheat plot. However, there were reductions in both total biomass and grain yields from 2007 to 2011 particularly in 2010 and 2011 (Table 5). In 2011, the highest total biomass was in the sole wheat plots. Among the horti–silvi combinations, ZM + PC showed the highest grain yield, whereas total biomass was lowest ($P < 0.05$) in the COM + CM combination. The reduction in total biomass was 26.0% in COM + CM and 14% in ZM + PC combinations compared to the sole wheat plots.

Though, grain yield was higher ($P < 0.05$) in sole wheat plot, it reduced by 23% in COM + CM combination and by 5% in ZM + PC combination in March 2011 (Table 5). There were no significant differences ($P < 0.05$) in grain yield between different horti–silvi combination plots. The lowest (5%) yield reduction was in ZM + PC combination, which did not differ with yield in EO + PC combination as well as yield in sole wheat plots (1.61 Mg ha^{-1}) in March 2011.

Soil properties

There was a decrease in soil pH in both soil layers in March 2011 as compared to the initial value in 2006, but the decrease in soil pH in the tree-integrated plots was greater ($P < 0.05$) as compared to the sole wheat plots (Table 6). EC increased in the 25–50 cm of the soil layer in the tree-integrated plots than the control plots. SOC was also greater ($P < 0.05$) in the tree-integrated than the sole wheat and alone tree plots. SOC was higher in the 0–25 cm soil layer and decreased in the 25–50 cm soil layer. SOC increased by 73% in the COM + AE and ZM + PC combination. The increase was by 67% in *A. excelsa* and 63% in *C. mopane* combinations in 2012 compared to 2006.

Table 5. Total yield (straw + grain) and grain yield of wheat in agroforestry systems in the Indian arid zone. Values are means ± standard deviation of three replicate plots.

	Total yield (Mg ha^{-1})					Grain yield (Mg ha^{-1})				
Species combination	March 07	March 08	March 09	March 10	March 11	March 07	March 08	March 09	March 10	March 11
ZM + PC	5.33 ± 0.82	4.55 ± 0.84	4.69 ± 0.50	3.52 ± 0.59	3.91 ± 0.53	2.37 ± 0.32	2.13 ± 0.29	2.08 ± 0.33	1.41 ± 0.09	1.53 ± 0.31
ZM + AE	5.72 ± 0.75	4.36 ± 1.01	4.28 ± 0.46	3.55 ± 0.19	3.74 ± 0.34	2.47 ± 0.21	1.75 ± 0.48	1.78 ± 0.32	1.35 ± 0.18	1.39 ± 0.13
ZM + CM	4.12 ± 0.67	4.41 ± 0.31	4.93 ± 0.13	3.33 ± 0.23	3.51 ± 0.16	1.83 ± 0.35	1.75 ± 0.08	2.02 ± 0.13	1.36 ± 0.13	1.33 ± 0.13
COM + PC	4.8 ± 0.76	4.32 ± 0.47	4.78 ± 0.39	3.49 ± 0.22	3.74 ± 0.41	2.13 ± 0.42	1.97 ± 0.30	1.85 ± 0.18	1.37 ± 0.10	1.41 ± 0.13
COM + AE	5.02 ± 0.82	4.07 ± 0.70	4.53 ± 0.27	3.58 ± 0.29	3.61 ± 0.40	2.13 ± 0.27	1.75 ± 0.28	1.81 ± 0.19	1.33 ± 0.09	1.28 ± 0.09
COM + CM	5.68 ± 0.64	4.54 ± 0.59	4.60 ± 0.37	3.30 ± 0.17	3.40 ± 0.34	2.43 ± 0.21	1.68 ± 0.18	1.78 ± 0.08	1.32 ± 0.11	1.24 ± 0.20*
EO + PC	4.74 ± 1.22	4.24 ± 0.46	5.20 ± 0.62	3.41 ± 0.17	3.75 ± 0.10	2.31 ± 0.44	1.77 ± 0.24	2.08 ± 0.36	1.42 ± 0.13	1.53 ± 0.27
EO + AE	5.10 ± 0.86	4.37 ± 0.51	4.57 ± 0.49	3.47 ± 0.21	3.70 ± 0.22	2.21 ± 0.20	1.92 ± 0.37	1.97 ± 0.26	1.36 ± 0.14	1.39 ± 0.12
EO + CM	5.47 ± 0.39	4.44 ± 0.85	4.99 ± 0.35	3.22 ± 0.16	3.51 ± 0.24	2.30 ± 0.28	1.72 ± 0.08	1.99 ± 0.32	1.33 ± 0.13	1.33 ± 0.23
Sole wheat	5.23 ± 0.74	4.65 ± 0.56	5.14 ± 0.47	3.43 ± 0.27	4.57 ± 0.30*	2.27 ± 0.31	2.15 ± 0.45	2.18 ± 0.38	1.43 ± 0.16	1.61 ± 0.24
	NS	NS	NS	NS	*$P < 0.05$	NS	NS	NS	NS	$P < 0.05$

Note: * Significant at $P < 0.05$, NS- Non significant. *Z. mauritiana* (ZM), *Cordia myxa* (COM), *E. officinalis* (EO), *P. cineraria* (PC), *A. excelsa* (AE), *C. mopane* (CM).

Table 6. Soil physio-chemical properties and nutrient contents of different soil layers influenced by different combinations of horti- and silvicultural tree species in agroforestry systems in the Indian arid zone. Values are means ± standard deviation of three replicate plots.

		pH		Ec (dS m^{-1})		OC (%)		NH_4–N (mg kg^{-1})		NO_3–N (mg kg^{-1})		PO_4–P (mg kg^{-1})	
Treatment	Soil Depth (cm)	2006	2012	2006	2012	2006	2012	2006	2012	2006	2012	2006	2012
ZM + PC	0–25	8.93	8.81^{cd}	0.99	0.86^{c}	0.25	0.42^{de}	11.46	24.67^{d}	6.33	12.97^{ab}	24.49	22.36^{ab}
	25–50	8.53	8.74^{a}	0.84	1.32^{bcd}	0.18	0.28^{f}	7.34	9.32^{ab}	3.28	9.88^{d}	29.37	19.43^{ab}
ZM + AE	0–25	9.14	8.57^{b}	0.94	0.80^{bc}	0.23	0.41^{cd}	8.00	21.31^{bcd}	7.77	10.36^{a}	26.91	24.36^{ab}
	25–50	8.57	8.91^{bc}	0.98	1.33^{bcd}	0.15	0.26^{bcdef}	7.18	11.98^{bcde}	6.24	8.75^{cd}	26.16	18.74^{a}
ZM + CM	0–25	8.86	8.75^{bc}	1.06	0.74^{bc}	0.26	0.41^{bcd}	8.57	18.11^{abc}	8.18	9.59^{a}	30.77	22.97^{ab}
	25–50	8.66	8.93^{bcde}	1.01	1.39^{cd}	0.17	0.27^{ef}	8.54	12.87^{cde}	6.69	6.94^{abc}	28.85	18.86^{a}
COM + PC	0–25	9.19	8.29^{a}	0.90	0.53^{a}	0.23	0.43^{e}	7.42	19.05^{abc}	10.15	10.61^{a}	29.26	23.19^{ab}
	25–50	8.77	8.91^{bcd}	0.89	1.26^{abc}	0.17	0.27^{ef}	6.51	10.16^{abc}	7.12	7.13^{abc}	23.07	19.10^{ab}
COM + AE	0–25	8.97	8.87^{cd}	1.09	0.53^{a}	0.28	0.42^{cde}	8.26	22.52^{cd}	6.21	10.83^{a}	25.16	24.54^{ab}
	25–50	8.62	8.95^{cde}	1.10	1.12^{ab}	0.19	0.26^{bcdef}	7.79	13.84^{de}	7.83	7.17^{abc}	29.97	19.28^{ab}
COM + CM	0–25	8.93	8.84^{cd}	1.16	0.69^{abc}	0.22	0.41^{bcd}	8.20	19.11^{abc}	10.09	11.34^{a}	30.66	21.84a^{ab}
	25–50	8.71	8.99^{de}	1.06	1.28^{abc}	0.15	0.26^{bcdef}	6.63	8.97^{ab}	3.91	5.36^{a}	29.88	20.55^{ab}
EO + PC	0–25	9.04	8.80^{cd}	1.04	0.65^{abc}	0.25	0.41^{bcd}	8.16	17.13^{ab}	8.01	9.41^{a}	26.50	22.48^{ab}
	25–50	8.79	8.94^{bcde}	0.93	1.49^{d}	0.16	0.27^{ef}	7.42	8.49^{a}	4.95	8.07^{bcd}	37.33	19.75^{ab}
EO + AE	0–25	8.88	8.78^{cd}	1.15	0.80^{bc}	0.23	0.40^{abc}	8.29	19.76^{abc}	10.47	11.17^{a}	35.51	26.03^{b}
	25–50	8.70	8.91^{bcd}	0.94	1.36^{bcd}	0.17	0.25^{abcd}	6.35	13.21^{cde}	6.11	6.44^{ab}	25.50	19.32^{ab}
EO + CM	0–25	9.01	8.79^{cd}	1.07	0.58^{ab}	0.26	0.39^{ab}	12.11	18.65^{ab}	10.55	11.42^{a}	30.77	25.45^{ab}
	25–50	8.87	8.85^{abc}	0.99	1.38^{cd}	0.16	0.24^{abc}	9.08	12.48^{cde}	4.01	7.44^{bc}	35.75	21.12^{ab}
Sole crop	0–25	8.81	8.97^{d}	0.88	0.72^{abc}	0.26	0.38^{a}	11.65	17.49^{abc}	6.93	15.58^{b}	24.60	24.99^{ab}
	25–50	9.13	9.05^{e}	0.86	0.97^{a}	0.18	0.23^{a}	7.62	10.99^{abcd}	4.55	8.96^{d}	22.07	19.76^{ab}
Sole tree	0–25	8.93	8.89^{cd}	0.93	0.64^{abc}	0.27	0.39^{a}	9.72	15.68^{a}	7.93	12.19^{ab}	30.53	24.81^{ab}
	25–50	9.08	8.99^{de}	1.08	1.04^{ab}	0.17	0.24^{abc}	6.73	13.28^{e}	5.33	7.39^{bc}	34.53	21.78^{b}

Notes: Values with different alphabets (superscript) in a column indicate significant ($P < 0.05$) difference. *Z. mauritiana* (ZM), *Cordia myxa* (COM), *E. officinalis* (EO), *P. cineraria* (PC), *A. excelsa* (AE), *C. mopane* (CM).

Availability of NH_4–N, NO_3–N and PO_4–P in 2012 differed due to treatments ($P < 0.05$) and soil layer ($P < 0.05$) (Table 6). NH_4–N and PO_4–P were higher in 0–25 cm as compared to 25–50 cm of the soil layer, whereas NO_3–N was higher in 25–50 cm of the soil layer. DMRT indicated higher values of NH_4–N and NO_3–N in the ZM + PC plots, whereas PO_4–P was the highest in the EO + AE plot. When compared between tree-integrated and alone tree plots, NH_4–N and PO_4–P were greater in concentration in tree-integrated plots, whereas NO_3–N was greater in the alone tree plots as compared to the other plots.

Correlations between plant growth, crop yield and soil properties

Average plant height and average collar diameter were positively correlated ($r = 0.717$, $P < 0.01$), whereas former variable was negatively correlated ($r = -0.452$, $P < 0.05$) to crop yield. Total basal area showed positive correlations to SOC in 0–25 cm (r = 0. 762, $P < 0.01$) and 25–50 cm ($r = 0.690$, $P < 0.01$) of the soil layers, whereas negative correlation to soil available phosphorus ($r = -0.465$, $P < 0.05$) in the 0–25 cm soil layer. Soil EC in the 0–25 cm soil layer indicated negative correlation ($r = -0.803$, $P < 0.01$) to canopy volume of horticultural species. Grain ($r = 0.386$, $P < 0.05$) and straw ($r = 0.428$, $P < 0.05$, $n = 27$) yield showed positive correlation with total basal area (silvi + horti species). Total biomass of wheat was negatively correlated ($r = -0.492$, $P < 0.05$) to soil pH in the 25–50 cm soil layer. However, we did not observe any correlation between crop yield and canopy volume.

Discussion

Plant growth and biomass

Interaction between tree and wheat crop influenced crop yield and tree growth, depending upon availability of soil resources (Belsky et al. 1989; Siriri et al. 2010). Significantly ($P < 0.05$) greater height of *A. excelsa* and *C. mopane* in tree-integrated plots than in the alone tree plots (Table 1) was because of greater availability of soil water added through flood irrigation to wheat crop. Greater primary and secondary root length in tree-integrated plots and consequently the effect of root surface area to utilize soil resources favoured plant growth similar to the observation of Meena et al. (2005). Variations in height and collar diameter, height increment in *C. mopane* and collar diameter in *P. cineraria* was due to the genetic character (Yadav et al. 2005), though Singh and Rathod (2012) observed that greater height, collar diameter and crown diameter of *C. mopane* trees in agroforestry was due to greater soil water use. Patterns of tree growth depend on unit light interception and relate linearly to growth per unit of leaf area and canopy volume, where higher crown leaf area and canopy volume in *C. mopane* was a function of resource (light, water, nutrients) acquisition (Binkley 2013). However, lowest canopy volume in EO + AE combination appeared to be due to their sensitiveness towards soil salinity as indicated by negative correlation between horticultural species and EC ($r = -0.803$, $P < 0.01$). Species with deep primary roots and more spreading secondary roots take up nutrient and water more efficiently from deeper soil layers and over a wider area, and provide firm anchorage to the tree in soil and cause less competition with the associated crop as observed in the case of *P. cineraria*, *A. excelsa* and *Z. mauritiana* in the present study. Deep primary roots and moderate secondary root length of trees are less competitive with the companion crops (Odhiambo et al. 2001; Das & Chaturvedi 2008;

Makumba et al. 2009). Dense secondary roots of *C. mopane* and *C. myxa* distributed in the top soil layer acquire soil resources from the root zone of wheat crop and were found to be more competitive as compared to *P. cineraria*, *A. excelsa* and *Z. mauritiana* trees similar to the observations of Odhiambo et al. (1999). Low soil moisture availability in the tree alone plots influenced length of the secondary roots and biomass allocation to roots in all species. Yavitt and Wright (2001) observed a reduction in fine root growth in tropical forests under reduced soil moisture availability, but long-term decrease in moisture availability resulted in greater biomass allocation to roots as compared to other components of the plant.

C. mopane and *C. myxa* plants exhibited spreading primary and secondary roots parallel to the soil surface that provided higher absorptive surface to exploit water and nutrients and increased below-ground competition reducing wheat yield as observed in other studies (Dhyani et al. 1990; Toky & Bisht 1992; Akinnifesi et al. 2004). Lower nutrient availability affected growth and biomass of tree roots in the alone tree plots. However, low soil fertility have also been observed to increase biomass allocation in plants to root (Kozlowski & Pallardy 2002; Giardina et al. 2004). Relatively greater availability of soil water and nutrients facilitated growth and biomass production of all species in tree-integrated plots than in the sole tree plots similar to the observation of Singh et al. (2012), where biomass allocations was relatively greater of stem, branch and foliage (Singh & Singh 2003).

Wheat production

Yield of an agriculture crop in an agroforestry system depends upon a balance in positive and negative interactions between tree and the crop (Casper & Jackson 1997; Newaj et al. 2005). The highest reduction in total as well as grain yield of wheat in COM + CM combination indicated a competitive use of soil resources by the tree species. Increased plant growth and corresponding canopy volume under competitive utilization of soil resources and decreased light intensity under dense canopy affected crop yield. Semwal et al. (2002) observed greater canopy volume of unlopped trees that reduced photosynthetically active radiation and affected yields of winter crops under agroforestry. Fadl and Sheikh (2010) also observed competitive interaction in *A. senegal* agroforestry system, where yield of groundnut, sesame and roselle reduced when compared to the sole cropping system. *C. mopane* reported to use more soil water, making it not available for crop use and affected crop yield negatively (Singh & Rathod 2012). Whereas tree growth in EO + AE combination was greater but had lesser effect on crop yield and it was because of greater space available for *A. excelsa* resulting from the mortality of *E. officinalis* plants. All combination of horti–silvi species reduced wheat yield, but the reduction in both total and grain yield of wheat crop was relatively less in ZM + PC combination indicating that this combination was better than other systems. Greater crop yields under *P. cineraria* tree canopy, because of improved soil fertility ($r = 0.726$, $P < 0.01$ between total basal area and SOC) have also been reported in other studies (Aggarwal et al. 1993; Yadav et al. 2005; Singh 2009). It was due to ameliorative influence of shade and less competition for soil water by the trees (Bonkoungou 1992; Verma et al. 2002). Kaushik and Kumar (2003) also observed positive effects of khejri (*P. cineraria*) based agri–silvi system on crop growth and grain yield in both the kharif and rabi seasons.

Soil properties

Tree integration enhanced ($P < 0.05$) SOC and ameliorated soil pH through a combined effect of tree species and green manuring with dhaincha (Jha et al. 2010). This indicates that multipurpose tree species (MPTs) based agroforestry system has the potential to maintain SOC (carbon sequestration) and enhance soil fertility (Yadav et al. 2008; Githae et al. 2011; Seddaiu et al. 2013). A positive correlation between the total basal area of the tree and SOC ($r = 0.726$, $P < 0.01$) substantiate the inference. The reduction in soil pH in 2012 than in 2006 in both the soil layers was due to increased organic carbon and the ameliorative effects of dhaincha as the green manure (Egodawatta et al. 2011). However, leaching of accumulated salt under irrigation enhanced EC in 25–50 cm of the soil layer in the agroforestry plots, but increase in sodicity/EC in deeper soil layer was also due to irrigation, with water having residual alkalinity (Mishra et al. 2004). Soil property changes under agroforestry system are generally species-specific and site-conditions dependent (Rao et al. 1998). *P. cineraria*- and *T. undulata*-based systems exhibited higher organic carbon and available N, P and K (Singh 2009) as compared to *A. excelsa* (Patel et al. 2009).

Increased availability of NH_4–N under *P. cineraria* combination plots was the effect of nitrogenous litter and biological nitrogen fixation by dhaincha (Vanlauwe et al. 2005; Makumba et al. 2009). Singh et al. (2000) reported that *Vigna radiata* crop with *Hardwickia binata* tree enhanced NH_4–N pool as compared to *C. mopane* and *E. officinalis*. Less number of plants in EO + AE plot (due to mortality of *E. officinalis*) were responsible for greater PO_4–P availability, but efficient use of PO_4–P caused a significant reduction in PO_4–P availability in COM + CM plot, where horizontal dense root spread and higher root biomass in a confined volume of soil facilitated uptake of PO_4–P (Lambers et al. 2006). Such type of variations in nutrient availability had also been observed in the *Vigna radiata* crop associated with *E. officinalis, H. binata* and *C. mopane* tree (Singh et al. 2000), though lower availability of PO_4–P under N_2-fixing species has also been reported because of PO_4–P use by nitrogen fixing bacteria (Muniafu & Kinyamario 2007; Makumba et al. 2009). Fixation of PO_4–P in the soil also affected available P in both soil layers in 2012 as compared to 2006 despite applied Diammonium phosphate (Ilany et al. 2010; Singh & Singh 2011). This might be due to interactive effects of Fe and Al, which renders PO_4–P essentially unavailable (Richardson et al. 2004).

Conclusion

This study suggests that the increased availability of soil water and nutrients facilitated plant roots to confine mostly in the top soil layer. For example, root configuration of *P. cineraria* and *A. excelsa* varied considerably with regard to rooting depth, fine root abundance in deeper soil layer as well as the form of structurallly symmetric primary and secondary roots. *C. myxa* and *C. mopane* had shallow roots, which are mostly concentrated in the top soil layer and competed for soil water and nutrients with companion wheat crop and reduced crop yield. Total biomass as well as grain yield of wheat was negatively affected under tree integration, but the magnitude of reduction varied with the nature of silvi- and horticultural tree species and was less in *Z. mauritiana* +*P. cineraria* plot. This showed that the best combination of horti- and silvicultural tree species have the potential in improving soil, sequestering carbon and enhancing food production. *Z. mauritiana* +*P. cineraria* were the best combination because of less competition of these tree species with wheat crop. In addition, this system provided fruit, fodder and fuel wood and helped farmers to get greater benefits as well as to control land degradation. The results emphasized on selecting suitable combination of horti- and silvicultural species based on scientific knowledge of its potential in soil fertility improvement and structural root architecture and the adoption of management strategies to increase overall production on sustained basis.

Acknowledgement

The authors thank the Director, AFRI, Jodhpur for guiding and providing critical suggestions during the course of this study.

Supplementary material

Supplemental data for this article can be accessed here http://doi:10.1080/03650340.2013.864386.

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