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Eucalyptus geometry in agroforestry on waterlogged saline soils influences plant and soil traits in North-West India

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ABSTRACT

Impacts of agroforestry comprising wheat and rice crops in combination with *Eucalyptus tereticornis* trees having high transpiration rate were assessed for remediation of waterlogged saline soils. To find out optimum spacing of trees in strip plantation for higher water table draw down, wood production and crop yield, a study was carried on waterlogged fields by planting *E. tereticornis* (clone C-7) in paired rows on ridges (0.5-m height) made along the field boundaries in north-south direction at 1 m × 1 m, 1 m × 2 m and 1 m × 3 m spacing resulting in population of 300, 150 and 100 trees ha^{-1}. The results were also compared with the control (field without tree plantation) and block plantation. During sixth year of growth, *Eucalyptus* attained the maximum growth in 1 m × 3 m spacing followed by 1m × 2m, 1m × 1m; and minimum in block plantation. Due to higher number of trees per unit area, timber dry wood production was 33.5 Mg ha^{-1} in spacing of 1 m × 1 m; 19.1 Mg ha^{-1} in 1 m × 2 m and 13.5 Mg ha^{-1} in 1m × 3 m and sequestered 15.2, 8.9 and 6.4 Mg C ha^{-1}, respectively. Block plantations of *Eucalyptus* generated 141.7 Mg ha^{-1} timber wood biomass and sequestered 66.5 Mg C ha^{-1}. The transpiration rate of *Eucalyptus* in block plantation on an average was 40.0 L day^{-1} $tree^{-1}$ compared to 68.0, 71.5 and 73.8 L day^{-1} $tree^{-1}$ in 1 m × 1 m, 1m × 2 m and 1m × 3 m tree spacing, respectively in strip plantation. The corresponding total amount of water transpired per annum was 1825 mm in block plantation and 745, 391, 269 mm in 1 m × 1 m, 1 m × 2 m and 1m × 3 m tree spacing. Due to high transpiration rate of *Eucalyptus*, water table was lowered by 43.0 cm in 1 m × 1m; 38.5 cm in 1 m × 2 m and 31.5 cm in 1 m × 3 m spacing during the fourth year of plantation than in adjacent fields without plantation. Near the tree lines, grain yields of both wheat and rice were comparatively low. But lowering of water table resulted in improvement in soil properties which produced 1.7 and 1.3 folds higher grain yield of wheat and rice respectively compared to control. The results suggested that in a rotation of six years, 1 m × 1 m spacing for strip plantation of *Eucalyptus* in paired rows on farm acre line was the optimum for achieving higher water table draw down, wood biomass production, carbon sequestration and crop productivity on waterlogged fields.

1. Introduction

Canal irrigation introduced for increasing crop production in arid and semi-arid regions caused rise in the groundwater table leading to the problem of waterlogging and secondary salinization (Chhabra and Thakur, 1998; Singh, 2005). These problems are the result of a multitude of factors, including seepage from unlined canals, inadequate provision of surface and sub-surface drainage, over irrigation and use of poor-quality groundwater for irrigation. Waterlogged saline soils apart from environmental degradation result in poor crop yields reducing yields as high as 80% (Shabala, 2011) and finally in abandoning the land from cultivation. World over one-third of the irrigated area faces the threat of waterlogging and 11% of it is already salinized (FAO, 2012). In India, more than 5.6 M ha is waterlogged (NAAS, 2010). In North-West India where lies the study area, about 200 km long axis of arable land is underlain by saline ground water and forms an inland basin with no natural drainage. Efforts to remediate saline waterlogged land

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by installing sub-surface drainage had limited success particularly in land locked areas because of problems associated with disposal of drainage effluent (Ohlendorf and Santolo, 1994). Under these conditions, biodrainage from plantation of trees like *Eucalyptus,* which have high transpiration rate and go straight thus low shading effects, can be a viable alternative for management of waterlogged saline soils (Jeet-Ram et al., 2007; Kapoor, 2014; Minhas et al., 2015). In waterlogged areas, trees can be successfully grown by ridge or mound planting which in turn improve survival and growth of trees (Arya et al., 2006; Jeet-Ram et al., 2011). Reliance on capability of vegetation to reduce water table has been found promising both in India (Chhabra and Thakur, 1998; Jeet-Ram et al., 2011) and abroad (Bhutta and Choudhary, 2000; Heuperman et al., 2002). Moreover, compared to sub-surface drainage technology, biodrainage is more economical because it requires investment only on initial establishment; thereafter the system provides economic returns by means of fodder, wood or fibre. Restoring degraded ecosystems has an additional advantage of C sequestration (Lal, 2004). Afforestation is definitely expected to sequester C in aboveground, but the impacts of afforestation on soil organic carbon are very diverse ranging from no effect to enrichment or depletion (Fialho and Zinn, 2014; Jeet-Ram et al., 2011; Lima et al., 2006; Madeira et al., 2002; Yu and Jia, 2015). Small changes in the soil organic carbon stock could significantly affect atmospheric carbon dioxide (CO_2) concentrations, therefore; need to be investigated along with carbon locked in biomass (Conant and Paustian, 2002; Parras-Alcántara et al., 2015).

Compared to strip plantation, block plantation effectively lowers down water table and sequester high amount of carbon because of more number of trees per hectare. In developing countries farmers have small land holdings and usually show restraints to spare their lands for sole forestry plantation which

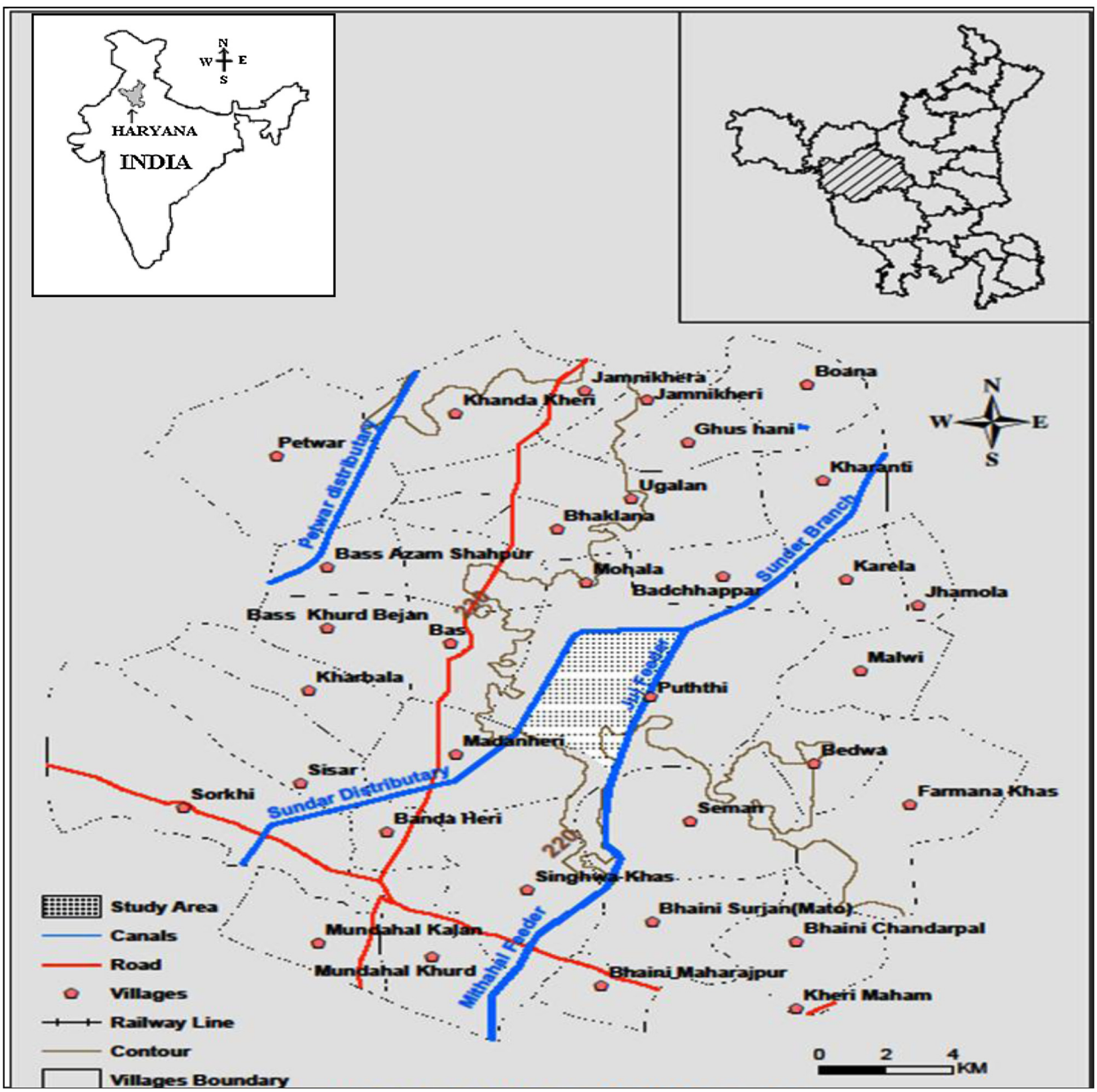

Fig. 1. Location of Research Plot at Puthi.

give returns after a gap of six years or more. Agroforestry comprising crops in combination with high transpiring trees would not only lower down water table but may also provide returns at regular interval therefore, may be preferred over sole forestry. Crop yields are reduced near the tree line therefore planting of trees on the common field boundary is a point of conflict. Planting of trees in paired rows, each row owned by a farmer on either side will solve such problems and also increase the plantation density and consequently higher biodrainage potential. The favourable effects of strip plantations of *Eucalyptus tereticornis* in paired rows with a spacing of 1 m × 1 m on reclamation of waterlogged areas were observed in our previous study (Jeet-Ram et al., 2011). Raising higher number of trees per unit area in agroforestry is expected to enhance biodrainage potential but may reduce girth and overall tree growth and yield of the associated crop because of increased competition for space, radiation and nutrients. It emphasizes to find the optimum spacing of trees for strip plantation to harness the maximum benefits. Therefore, impacts of comprising paired rows of clonal *E. tereticornis* raised on field boundary in north south direction at 1 m × 1 m, 1 m × 2 m and 1m × 3 m spacing in an agroforestry model for remediation of saline waterlogged soils were assessed for biomass production, crop yields, spatial and temporal variation in water tables and carbon sequestration.

2. Material and methods

2.1. Study site

The present study was carried out on canal-irrigated, waterlogged fields in village Puthi, Hisar District, Haryana, India (Fig. 1). The Puthi research plot (long. 76°14′E and lat. 29°04′N) is landlocked as it is surrounded by two parallel canals (Mitathal and Jui) in the east (1 km), Sunder canal branch in the north (3 km) and west (2 km), and Bass–Puthi road (0 km) in the south enclosing around 1000 ha area. The terrain is plain and faces sub-surface waterlogging (groundwater table within 1.0–3.0 m) throughout the year and surface waterlogging during monsoon (July–September). The climate of the area is semi-arid with average annual rainfall and mean open pan evaporation during the study period (2007–2013) at nearby observatory at Hisar were 595 ± 140 and 1748 ± 164 mm, respectively with the mean daily maximum and minimum temperatures of 31.30 ± 0.65 and 16.35 ± 1.05 °C, respectively. The annual rainfall ranged from 459 mm (during 2009) to 735 mm (during 2013).

2.2. Soil analysis

Physical and chemical properties of soil were determined by collecting samples from different depths in the beginning and at the end of the experiment. To overcome the spatial variability, soil samples from 0 to 15, 15–30 and 30–60 cm soil layers from four places were collected from each treatment acre plot and mixed thoroughly by quartering technique. Dry soil samples were processed and passed through a 2 mm sieve and analysed for pHs (pH of saturation paste), electrical conductivity (ECe) of saturated extract, different cations and anions following standard methods (Richards, 1954). Soil bulk density was determined by using core sampler. Soil organic carbon was determined by using the dichromate oxidation method (Walkley and Black, 1934).

The soils of the site are Inceptisols. These are alluvial sandy-loam having 10–12% clay, with sub-surface calcareous concretions. In the surface 0–15 cm layer, initial pH of the soil saturation paste (pHs) ranged from 8.1 to 9.0 with an average of 8.5, whereas electrical conductivity of the saturation extract (ECe) ranged from 2.3 to 10.1 with an average of 8.0 dS m^{-1}. In general, pHs was higher whereas the ECe values were lower in the sub-surface layers (15–120 cm) compared to the surface layer. The soils were also poor in organic carbon (OC). It was 0.3% in the upper 15 cm soil layer and decreased with depth. The steady state infiltration rate (of six locations) varied from 5.2 to 11.8 mm h^{-1}, with an average of 7.3 mm h^{-1}.

2.3. Plantations

Plantations of genetically superior clonal *E.tereticornis* (C-7) were raised in paired rows on ridges prepared along the farm acre boundaries (60 m × 66 m) in May 2007 in north–south direction at 1 m × 1 m, 1 m × 2 m and 1 m × 3 m spacing resulting in tree population of 300, 150 and 100 trees ha^{-1}. Two parallel ridges were constructed in north-south direction along the bunds of agricultural waterlogged fields. Ridge to ridge distance was about 60 m and each ridge was 2.5 m in basal width and 2.0 m in top width and 0.5 m in height. The plantations raised on ridges were named as bund plantations containing two rows of *E. tereticornis*. For each spacing three replications were planted. The area covered under bund plantations was only 4% and the rest was planted with arable crops (rice in summer and wheat in winter) thus making it an agroforestry model. To compare the effects on water table drawdown, wood biomass and carbon sequestration, block plantations of *Eucalyptus* were also raised. Block plantation

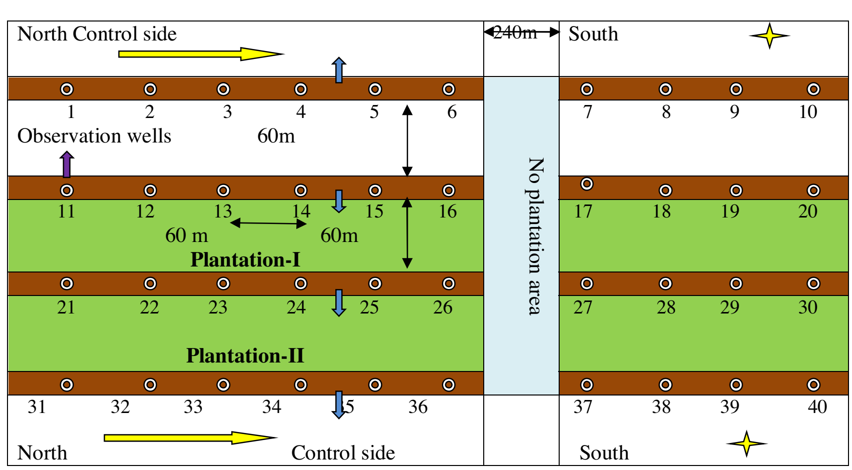

Fig. 2. Layout of observation wells.

consisted of 23 ridges with ridge to ridge distance of 4 m and tree distance of 2 m resulting 1250 trees per hectare.

2.4. Measurements of growth parameters of trees

Girth of the trees was measured at breast height with the help of measuring tape whereas the height was measured using altimeter. The wood volume was determined by calculating the bole volume (V) of individual tree using the equation: $V = 0.00352 + 0.0341G^2H$ (Chaturvedi, 2000); where V is volume (m^3); G is the girth (m) at breast height (1.37m); and H is height (m) of the tree. To find the biomass and carbon sequestration, 5 trees belonging to different girth class of different tree spacing (viz. 1 m × 1 m, 1 m × 2 m and 1 m × 3 m, respectively) were felled. Above ground fresh biomasses (shoot) were partitioned into timber, fuel wood and twig/leaves and weighed. For dry biomass the representative samples were kept in oven at 60 °C till weight became constant. Roots of 5 trees in each category were also excavated, washed and a representative sample was oven-dried and weighed.

2.5. Monitoring of ground water table

To measure the groundwater table, draw down, 40 observation wells were installed at a spacing of 60 m in four transects parallel to each other and perpendicular to the strip plantations. The set of observation wells numbering from 11 to 20 and 21–30 were under the plantation while the set of observation wells numbering from 1 to 10 and 31–40 out of plantation (control) (Fig. 2). The levels of groundwater table in the observation wells were measured twice in a month and averaged. A row of observation wells was also installed in block plantation for comparison. Each observation well was consisted of a GI pipe of 8.2 m in length and 6.4 cm in inner diameter. The lower end of the GI pipe was closed by fixing a cap. Perforations of 1 cm diameter were made in the lower 2.1 m length of the GI pipe. The perforated portion of the GI pipe was first wrapped with two layers of polyester cloth and then with one layer of synthetic mess to avoid passage of even fine soil particles into the GI pipe.

2.6. Carbon sequestration

For calculating carbon sequestration, oven dry timber, twigs and leaves, and roots samples were weighed and their carbon contents determined by CHNS analyser (Model Elementar Vario EL). Weight of carbon sequestered per hectare was determined by summing the products of dry weight of every component with its carbon content.

2.7. Transpiration

From each spacing, four trees of *E. tereticornis* were selected and measured their transpiration rates in May (pre-monsoon), July (monsoon), October (post-monsoon), January (winter) every year to cover all the seasons prevailing throughout the year using Dynamax Sensors (Flow 32) system. Since the whole tree transpiration rate and sap flow rate (Fs) are in close approximation, the transpiration was assumed to be equal to the sap flow rate. Sap flow rate (Fs) was calculated from the sap flow index (k) using the equation (Granier, 1987): $K = (dTM/dT)/dT$, where dT is difference in temperature between upper and lower needle and its value was monitored from differential voltage between these needles. The dTM was the value of dT when there was no sap flow, i.e. $dT = 0$. Average flow velocity (V in $cm\ s^{-1}$) and sap flow rate (Fs in $cm^3\ h^{-1}$) were determined from sap flow index by using equation (Granier, 1987): $V = 0.0119 \times k^{1.231}$ and $Fs = As \times V \times 3600$; where As is cross sectional area (cm^2) of sap conducting wood.

2.8. Crop yield

Crop yields of rice and wheat were recorded by harvesting the above ground biomass in 1m × 1 m quadrant both in research plots and four adjacent untreated fields (without *Eucalyptus* plantation). After threshing, grains were separated and weighed.

3. Results and discussion

3.1. Tree growth and biomass parameters

The growth (both height and girth) and biomass of *E. tereticornis* per tree increased with advancement in age both in strip and block plantation. When grown on bunds as strip plantation tree growth was higher in wider spacing (1 m × 3 m and 1m × 2m) compared to narrower spacing (1m × 1m) however; it was better than in the block plantation. In the initial two years of growth, spacing had no effect on tree height and girth but the effects were conspicuous after third year of age (Fig. 3).

The growth rates (height and girth) of *Eucalyptus* followed log pattern, the rate increasing initially with age thereafter decreasing during 4th and 6th year as also reported in irrigated *Eucalyptus* plantations by Minhas et al. (2015). The annual increase in volume per ha was the maximum during 4th year in all categories, particularly in block plantations and the rate gradually decreased in 5th and 6th year. It was obvious because volume is governed by the height and girth of trees. Though there was a significant increase in the volume of individual tree with the increase in tree spacing but the increment was not sufficient enough to compensate the increase in number of tree per hectare with the decrease in the tree spacing. Therefore, the tree volume and biomass on the hectare basis was higher in narrow spaced plantation. Increase in height and girth of *Eucalyptus* with increase in tree spacing was also observed in Hawaii by Walters (1980). Total biomass production per ha was obviously the highest in block plantations because of more number of trees. The timber volume of *Eucalyptus* at the age of six years was 65.4, 43.6 and 31.5 $m^3\ ha^{-1}$ in 1 m × 1 m, 1 m × 2 m, and 1 m × 3 m tree spacing in strip plantation, respectively whereas in block plantation it was 204.0 $m^3\ ha^{-1}$ (Table 1). Similar pattern was recorded in case of dry biomass of timber, twigs and leaves and root. The total dry biomass (including root biomass) on respective spacing was 49.5, 28.7 and 20.0 $Mg\ ha^{-1}$, respectively and 192.9 $Mg\ ha^{-1}$ in case of block plantation indicating a mean annual increment of 8.3, 4.8, 3.3 and 32.1 $Mg\ ha^{-1}$. Similar annual wood production rates (2.9 $Mg\ ha^{-1}\ y^{-1}$) in case of 100 trees of *E. globules* per hectare planted on field boundaries at the age of twelve years were also recorded in Ethiopia by Kidanu et al. (2005). Forrester et al. (2010) obtained 56 $Mg\ ha^{-1}$ aboveground biomass from five years old 1000 *Eucalyptus* trees in Victoria, Australia. Under similar conditions on waterlogged saline soils of Rajasthan, Soni et al. (2012) recorded 77.6 $Mg\ ha^{-1}$ above ground biomass of *Eucalyptus* with a stocking density of 1100 trees ha^{-1}. Zohar et al. (2008) found about 50 $Mg\ ha^{-1}$ biomass accumulations of the five-year-old *Eucalyptus* trees felled with a stocking density of 1280 trees ha^{-1} in waterlogged areas of Israel with a mean annual increment of 12.2 $Mg\ ha^{-1}$. Pereira et al. (1989) estimated an individual tree above ground biomass of 84.3 kg in a six-year old stand in Portugal. Similar to the present study, root and aboveground biomass as high as 44.1 and 157.4 $Mg\ ha^{-1}$ were obtained from six years old 1100 trees of *E. globules*, respectively in the fertilized and irrigated conditions (Soares and Tome, 2012). Comparisons among plantations in different parts of the world are difficult due to the

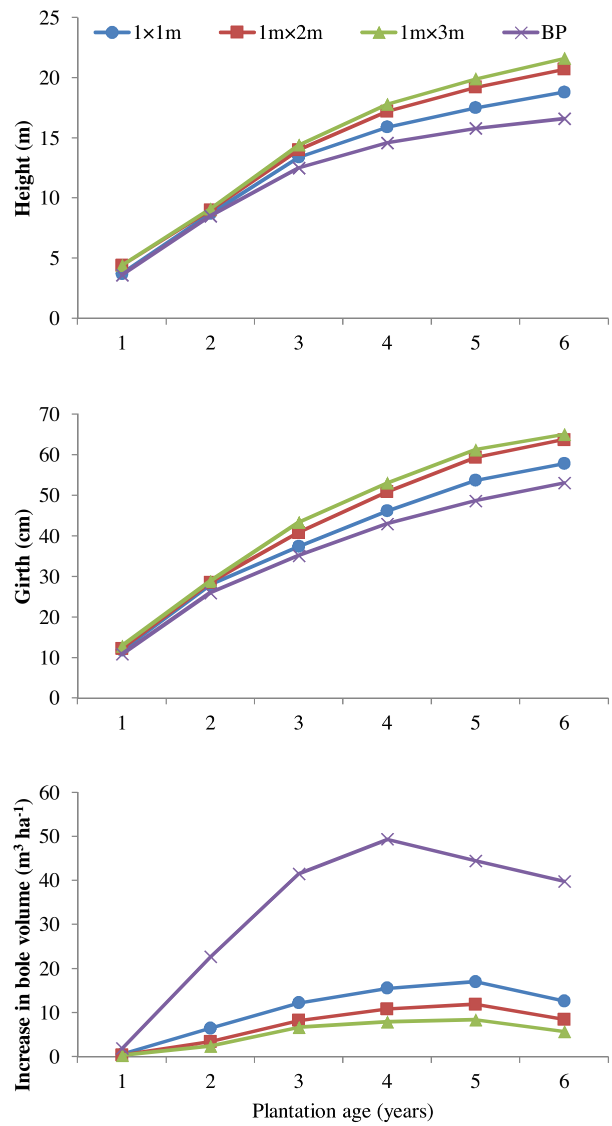

Fig. 3. Impact of spacing and block plantation on yearly height, girth and increase in volume of Eucalyptus.

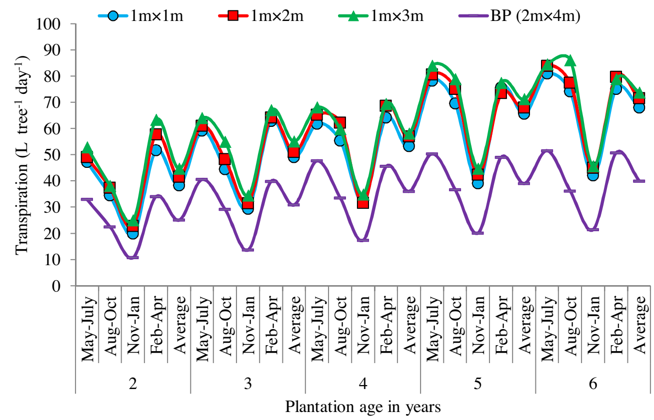

Fig. 4. Daily transpiration (L tree^{-1} day^{-1}) rate of Eucalyptus in different seasons during the growth period; BP: block plantation in 2 m × 4 m space.

differences in climate, soil properties, species, genetic improvement or management conditions. In the present study enhanced wood production per tree from *Eucalyptus* planted on boundaries can be attributed to genetically superior planting material (clone C-7), low competition for growth resources, space and light and access to nutrients applied to associated rice and wheat crops, as their fine roots extended laterally into adjacent cropped area (Kidanu et al., 2005). Planting of *Eucalyptus* along field boundaries will also assist in meeting the major demands for timber and wood products without inducing a major shift in ongoing land use.

The tree performance depends upon the coordination of growth between the aboveground components (stem, branches and leaves) and the belowground component. In bund plantation, most of the roots remained in bunds but were well distributed up to 1 m depth. The sinker roots travelled down up to 3.5 m along with water table. Root depth and the volume of the root system indicate how much of the soil and which of its components are explored for nutrients and water. Depending upon soil properties tree roots penetrate deep into soil in search of water but in waterlogged situations these were shallow and confined above the water table. Different workers found roots spread of *Eucalyptus* changes with the tree species, plantation age and prevailing soil conditions and goes as deep as 4.40 m (Dabralet al., 1987; Jeet-Ram et al., 2007; Karejahet al., 1994; Prasad et al., 1984). Root biomass of *E. tereticornis* was 13.4 Mg ha^{-1} in 1 m × 1 m; 8.0 Mg ha^{-1} in 1 m × 2 m and 5.4 Mg ha^{-1} in 1 m × 3 m tree spacing as strip plantations, respectively, whereas in block plantations it was 41.4 Mg ha^{-1} (Table 1). In a nine years old *Eucalyptus* block plantation in Spain the root biomass was 13.2 Mg ha^{-1} yr^{-1} for aboveground biomass productivity of 63.3 Mg ha^{-1} yr^{-1} thus 21% of the above ground biomass (Herrero et al., 2014). In the present study also the contribution of roots to the total wood biomass was about 28% in strip plantation and 22% in block plantation.

3.2. Transpiration rates

The trend in daily and annual transpiration rates by clonal *Eucalyptus* when grown in different spacing is shown in Figs. 4 and 5. The transpiration values during the sixth year of growth ranged from 42.1 to 45.6 L day^{-1} tree^{-1} from November to January (winter season) and were lower in comparison to other months because of

Table 1
Growth performance of six years old *Eucalyptus*.

Tree geometry	Height (m)	Girth (cm)	Total dry biomass (kg tree^{-1})	Timber volume (m^3 ha^{-1})	Timber dry biomass (Mg ha^{-1})	Twigs and leaves dry biomass (Mg ha^{-1})	Root biomass (Mg ha^{-1})	Total dry biomass (Mg ha^{-1})
1 m × 1 m[a]	18.8 ± 2.1	57.8 ± 7.6	164 ± 23	65.4 ± 8.4	33.5 ± 3.2	2.6 ± 0.4	13.4 ± 1.4	49.5 ± 5.1
1 m × 2m	20.7 ± 2.3	63.8 ± 9.1	191 ± 28	43.6 ± 6.2	19.1 ± 2.1	1.6 ± 0.2	8.0 ± 1.3	28.7 ± 3.5
1 m × 3m	21.6 ± 1.7	65.1 ± 7.9	200 ± 25	31.5 ± 2.7	13.5 ± 1.3	1.1 ± 0.2	5.4 ± 0.7	20.0 ± 2.1
Mean	20.4	62.2	185	46.8	22.0	1.8	8.9	32.7
Block	16.6 ± 1.9	53.1 ± 10.5	154 ± 18	204.0 ± 24.3	141.7 ± 16.2	9.8 ± 1.2	41.4 ± 5.8	192.9 ± 22.1
LSD $p \leq 0.05$	4.1	NS	NS	28.0	16.7	1.3	5.7	23.2

NS-not significant.
[a] 1 m × 1 m, 1 m × 2 m and 1 m × 3 m indicate tree spacing in strip plantations.

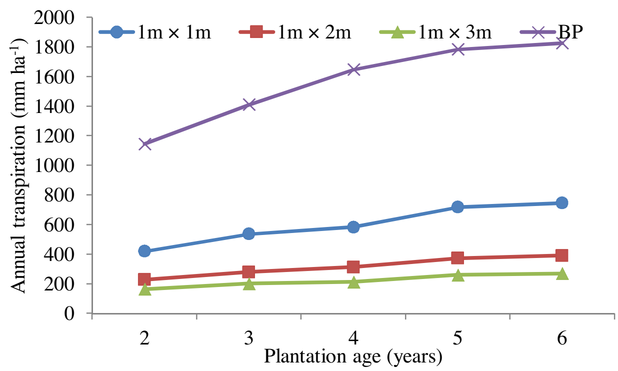

Fig. 5. Annual transpiration (mm ha^{-1}) of Eucalyptus when planted at different spacing.

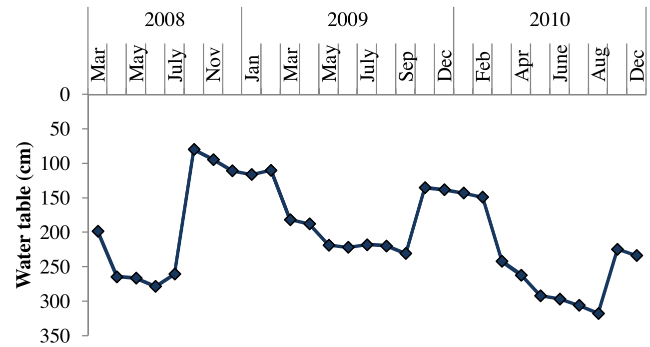

Fig. 6. Temporal changes in water table (cm) at the study site.

lower radiation, temperature and vapour pressure gradient and aerodynamic factor prevailing during winter season. With increased radiation, temperature and vapour pressure gradient during dry months (May–July), transpiration rates further increased up to 84.5 L day^{-1} tree^{-1}. The rate of transpiration per tree also increased both with plantation spacing and tree age. Averaged over the different seasons, transpiration rate per tree was found to be 38.3, 41.6, 44.7 and 25.1 L tree^{-1} day^{-1} in 1 m × 1 m, 1 m × 2 m, and 1 m × 3 m spacing and block plantation during second year, whereas the respective values in sixth year were 68.0, 71.5, 73.8 and 40.0 L tree^{-1} day^{-1}. The total amount of water transpired annually by *Eucalyptus* plantations per hectare was higher in closed spacing mainly because of higher number of trees per hectare which indicates that improved growth of widely spaced individual trees could not compensate water use of increased tree numbers in closer spacing. During the second year of growth, it was 419, 228 and 163 mm per hectare per annum in 1 m × 1 m, 1 m × 2 m, and 1 m × 3 m spacing, respectively in strip plantation on bunds. In block plantations (2 m × 4 m tree spacing, 1250 trees ha^{-1}) it was 1145 mm (Fig. 5). It gradually increased with age of trees and was 745, 391 and 269 mm in respective space of strip tree plantations and 1825 mm in block plantation at the age of 6 years. Minhas et al. (2015) in a long-term study in *E. tereticornis* found that transpiration rate stabilises at the age of 7 years and varies only when there is change in climate. *Eucalyptus* has been used the most for biodrainage purpose because of its luxurious and higher water consumption than native species of trees (Zahid et al., 2010). In arid and semi-arid regions receiving about 400 mm of rainfall, 745 and 1825 mm of water transpired by the six years old trees of clonal *E. Tereticornis* planted at 1 m × 1 m spacing as strip and 4 m × 2 m as block plantation, respectively will definitely contribute significantly in lowering of water table on waterlogged soils. In a study conducted in Southern India, Calder et al. (1997) also observed that water use of *Eucalyptus* exceeded rainfall received in that area.

In the similar work carried earlier, Jeet-Ram et al. (2011) found that the discharge of groundwater by the 3 year strip plantation of clonal *E. tereticornis* was 1.3 times more than the recharge by rainfall resulting in reclamation of waterlogged areas. At Karnal, India, total amount of water transpired in sewage irrigated block plantation of *E. tereticornis* ranged between 418 and 473, 1373–1417, and 1567–1628 mm during 7–10 years of planting having under 163, 517 and 1993 stems per ha, respectively (Minhas et al., 2015). In Israel, annual transpiration of three-year-old trees *E. camaldulensis* was found to be 1360 mm (Zohar et al., 2008). Greenwood et al. (1985) reported 1200–2300 mm year^{-1} of transpiration by tree plantation underlain by relatively shallow water tables. Forrester et al. (2010) found transpiration rate of 1.6–1.9 mm day^{-1} by a stand 1000 *Eucalyptus* trees aging between 5 and 7 years.

3.3. Effects of tree spacing on ground water table underneath plantation

Monthly groundwater table recorded during the initial three years showed wide temporal variations and ranged from 0.8 to 3.4 m (Fig. 6). The water table in general was the lowest during summer months (May–July) and highest in the months of October after the end of monsoon. The effects of *Eucalyptus* plantation on water table draw down started from the first year itself as indicated by the lower groundwater table observed in the fields with plantation than agricultural fields without plantation (Fig. 7). Observations could not be recorded in August and September being rainy months and in October it was within 0.7–0.8 m in agricultural fields and 0.85–0.95 m below trees. The net water table was lowered down by 41.0, 36.0 and 31.0 cm in September 2009 and 43.0, 38.5 and 31.5 cm in December 2010 in *Eucalyptus* strips plantation spacing of 1m × 1m, 1 m × 2 m, and 1 m × 3 m, respectively compared to fields without *Eucalyptus* plantation. During consecutive years also the trend was same except that excessive rain months deviated during August to October when rise in water table was more. Plantation spacing did not have much effects on water table draw down up to January 2009, thereafter the groundwater table in the fields having strip plantation of 1m × 3 m in general was higher comparative to 1 m × 1 m, 1 m × 2 m plantations. Over the period, difference in water table draw down recorded under 1 m × 1 m and 1 m × 2 m was from −3.5 to 8.5 cm with a mean value of 1.5 cm indicating that both plantation spacing had similar effects on water table draw down. In block plantations the water table was lower than the strip plantations throughout the study period showing the better efficiency of block plantations in lowering down the water table. Averaged over plantation

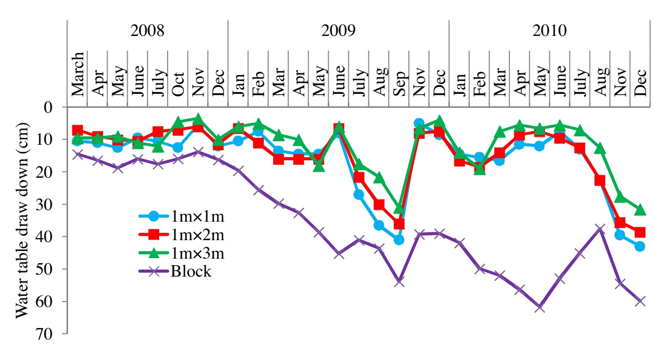

Fig. 7. Changes in water table drawdown (cm) with Eucalyptus plantation at different spacing compared to control (without Eucalyptus plantation).

spacing, net water table was lowered by 9.3, 15.6 and 17.2 cm in the fields with strip plantation of *Eucalyptus* at the age of two, three and four years, respectively compared to the field without tree plantation. The corresponding values of water table draw down in case of block plantation were 16.1, 37.0 and 51.1 cm. The higher water table draw down values in block plantation than the strip plantation could mainly be due to higher amount of water transpired and no irrigation water added in block plantation.

Deep root systems of trees intercept saturated zone or unsaturated capillary fringe above water table and restrict upward movement of water under shallow water table conditions. Under ideal conditions, a tree canopy may lower water tables by 1–2 m over a time period of 3–5 years (Heuperman et al., 2002; Kapoor, 2001). In waterlogged areas of Indian desert, *Eucalyptus rudis* raised on raised bunds lowered the groundwater table from 25 cm to 145 cm (Bala et al., 2014). On abandoned waterlogged degraded land in Haryana, India Tokyet al. (2011) also recorded an overall 20 cm decline in water table during the 5th year growth compared to control (without plantation) and classified *Eucalyptus* as a fast bio-drainer tree. Jeet-Ram et al. (2011) reported that the strip plantations (1 m × 1 m) as a whole could lower down 0.84 m water table at the age of 3 years and the lowering-down influence was up to 33 m in agricultural fields. The observations could not be taken beyond four years as some of the observation wells were disturbed and trees were removed by some of the farmers. However, it was clear from these studies that clonal *Eucalyptus* could efficiently lower down the water table when planted on ridges as strip plantations. Roy-Chowdhury et al. (2011) also reported lowering down of water table by *E. Camaldulensis* and *Casuarina equisetifolia* plantations on bunds of agricultural fields. Block plantation of 18 years old *E. tereticornis* (2.6 ha with 300 trees) lowered the ground water table up to a distance of 730 m in agricultural fields from the edge of the plantations (Jeet-Ram et al., 2007).

3.4. Carbon sequestration

Carbon content in various tree components of *Eucalyptus* ranged from 45.7 to 47.4% in stem (bole); 43.8–45.5% in twigs and branches and 45.3–48.5% in roots. Six years old clonal (C-7) *E. tereticornis* sequestered 22.8, 13.5 and 9.5Mg ha^{-1} carbon (both above and below ground) in strip plantations planted in 1 m × 1 m, 1 m × 2 m, and 1 m × 3 m, respectively while 90.6 Mg ha^{-1} when planted in block of 2 m × 4 m space along canal (Fig. 8). Amongst various tree parts, tree bole contributed 66.6–73.5% of the total C absorbed (including below ground) by *Eucalyptus*; whereas contribution of below ground biomass varied from 22.0 to 28.9% of the total C stock. Small branches, leaves and twigs contributed only about 5% towards total C removal by *Eucalyptus* plantations.

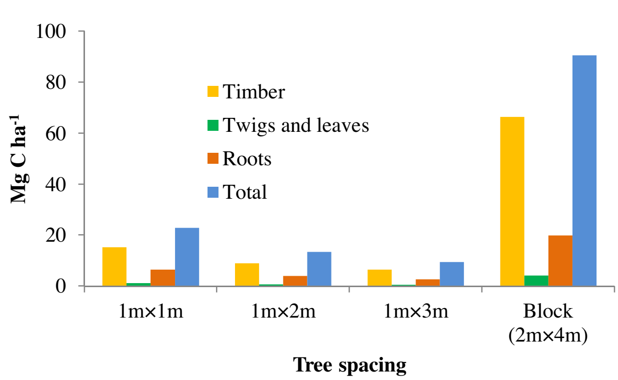

Fig. 8. Carbon sequestration (Mg ha^{-1}) by different tree components of six year old Eucalyptus.

In villages and small towns of developing countries like India, bole of *Eucalyptus* is not brunt for fuel or charcoal making but usually used as shuttering for construction purposes, therefore locks carbon for longer duration. Wood products can also play a potential role in the mitigation of greenhouse gas emissions by substituting more energy-intensive construction materials (e.g. concrete, steel) and fossil fuels (Burschelet al., 1993; Schlamadinger and Marland, 1996). Total C removed per hectare by 6 years old *Eucalyptus* planted at 1 m × 1 m spacing was 1.7 and 2.4 times more than recorded in 1 m × 2 m and 1 m × 3 m spacing which was less than the respective times increase in number of trees per hectare. In general, there was better growth of trees when planted in wider spacing due to reduced competition for radiation, root spread and essential plant nutrients thus higher C absorption per tree. Studies carried by other researchers also found lower carbon storage rates associated with higher plantation densities (Hubbard et al., 2010; Pérez-Cruzado and Rodríguez-Soalleiro, 2011). However, number of trees per hectare had a larger effect on carbon storage because the mean annual increment in growth vis a vis C removal in wider spaced plantation was not in proportion to increase in number of stem ha^{-1} in case of narrow spacing. While increasing tree density increases carbon storage, raising densities too high may reduce net absorption due to suppressed tree growth (Naidu et al., 1998). Earlier, Jeet-Ram et al. (2011) also observed 15.5 Mg ha^{-1} carbon in strip plantation of 5 years and 4 months old plantations. Minhas et al. (2015) reported carbon sequestration of 34.6, 114.0, 151.9, and 144.3 Mg C ha^{-1} in ten years old *E. tereticornis* planted at a density of 163, 517, 1993 and 6530 stems ha^{-1}, respectively. This shows that besides lowering of water table *Eucalyptus* has quite high potential of carbon sequestration.

3.5. Crop productivity of paddy and wheat in association with plantations

Wheat and paddy grains yield declined significantly near the tree line. With increase in the distance from tree line crop yields also increased (Table 2). In four to six year-old stands the reduction in wheat and rice yields associated with distance from the tree row was significant within the first 10 m in 1 m × 1 m and 1 m × 2 m spacing and within 5 m in 1 m × 3 m spacing (Table 2). During *rabi* (winter), grain yield of wheat declined by 6–25% within first 5 m and up to 13% in 5–10 m and beyond 10 m no reduction in yield was recorded. During *kharif* (rainy) season, the rice grain yield also declined by 17–21% within 5 m from the bunds of tree line; 7–9% in 5–10 m and beyond 10 m the decline in yield was not significant as compared to rest of the field (20–33 m) (Table 2). Average grain and straw yields during last three years were 3.3 and 4.2 Mg ha^{-1} in wheat and 4.2 and 5.5 Mg ha^{-1} in rice, respectively. Overall, wheat and rice grain yield obtained in fields having strip plantation at different spacing were similar indicating no impact of plantation spacing on crop yields. Accounting even the adverse effects of tree shade on crop yields near the tree lines, wheat grain yields in fields with plantations were 1.7 times higher due to lowering of water table than those without plantations. With plantations rice yields over the years got improved by 27%, which could mainly be due to reduced salt content in surface soil with lowering of water table as rice grows well in saturated conditions but is less tolerant to salinity than wheat. Increase in soil organic carbon with plantation could have also contributed towards achieving higher crop yields (Musinguzi et al., 2015).

The decline in crop yields near the tree lines could be due to the shade and strong root system of *Eucalyptus* both horizontally and vertically competing aggressively with the crops for moisture and nutrients particularly in early crop establishment stages (Toky and Bisht, 1992). In agroforestry system, near the tree line a significant amount of photosynthetically active light is intercepted and

Table 2
Impacts of strip plantation of *Eucalyptus* raised on bunds with different spacing on average wheat and rice grain yield (Mg ha^{-1}).

Distance from tree line (m)	Wheat				Rice			
	1 m × 1 m[a]	1 m × 2 m	1 m × 3 m	Control (without tree plantation)	1 m × 1 m	1 m × 2 m	1 m × 3 m	Control (without tree plantation)
0–5	2.7	2.8	3.0	2.3	3.3	3.6	3.7	3.6
5–10	3.1	3.3	3.3	2.0	3.9	4.0	4.2	3.1
10–15	3.7	3.5	3.4	1.8	4.4	4.4	4.4	3.4
15–20	3.8	3.6	3.4	1.8	4.4	4.6	4.6	3.3
20–33	3.6	3.6	3.3	2.0	4.2	4.4	4.5	3.2
Overall	3.4	3.4	3.2	2.0	4.1	4.2	4.3	3.3
LSD ($p \le 0.05$)	Distance (D) = 0.4; Spacing (S) = NS; D × S = NS				Distance = 0.4; Spacing = NS; D × S = NS			

[a] 1 m × 1 m, 1 m × 2 m and 1 m × 3 m indicate tree spacing in strip plantations. NS- not significant.

transmitted by tree canopy before it reaches the under storey crop, thereby the diffused radiation is the main source of radiation for under storey crop (Ong et al., 1996). Dhillon et al. (1982) also studied the effect of *Eucalyptus* trees grown along the field boundaries on grain yield of wheat, barley, paddy and potato crops and recorded higher yield reduction near the tree line. Significant depression of tef (*Eagrostistef*) and wheat yields up to 12 m from the tree line of *Eucalyptus* planted on field boundary, equivalent to yield losses of 4.4–26% and 4.5–10% per hectare, respectively was also observed in Ethiopia by Kidanu et al. (2005). Ahmed (1989) observed that *E. tereticornis* grown on all sides of field bunds at a spacing of 1.8 m (222 tree ha^{-1}) had negligible negative effect on associated agricultural crops during the first two years (due to smaller height and girth of trees) followed by 8.2% loss during 3rd and 4th years and 13.6% loss during 5th and 6th years. In the present study, the losses in wheat grain yield due to *E. tereticornis* were higher which might be due to combined effects of tree shade and shallow water table.

3.6. Soil characteristics

At the end of the study, soil pHs and ECe varied with depth and ranged from 8.1 to 8.8 and 2.3 to 5.8 d Sm^{-1} indicating that the soil is moderately saline to alkali in nature (Table 3). The soil organic carbon content varied from 0.21 to 0.45% with depth and spacing of tree plantations compared to 0.32–0.58% in block plantation indicating beneficial effects of sole forestry over agroforestry. Similarly, soil bulk density was reduced under forestry plantations due to added organic matter. Compared to its initial values and control (fields without plantation) there was a decrease in soil pH, electric conductivity and bulk density and increase in organic carbon with plantation but not affected by tree spacing.

Addition of organic matter by plantation through leaf fall, root biomass in the soil and acid released by trees were mainly responsible for increase in organic matter and reduction in soil pH and bulk density, whereas electrical conductivity values were reduced due to lowering of water tables by tree plantation. Reforestation has a great potential to sequester C belowground and the forest soils were found to have more soil organic carbon than the cultivated soils (Holeplass et al., 2004; Saha et al., 2014; Silver et al., 2000; Wei et al., 2010). *Eucalyptus* plantation established on degraded pastures in Brazil also resulted in significant increase in soil organic carbon (Lima et al., 2006). Land use is an important factor controlling soil organic carbon storage in soils because it affects the amount and quality of litter input, the litter decomposition rate and processes of organic matter stabilization in soils (Sahaet al., 2014; Schwendenmann and Pendall, 2006). Köchy et al. (2015) also predicted that agroforestry producing sufficient C input or wetland cropping (paddy) may be ways to conserve soil organic carbon and extract food at the same time. However, other workers observed that changing native vegetation and natural forest trees with fast growing *Eucalyptus* plantations in average had no net effect on soil organic carbon stocks and exhausted soil nutrients (Araújo et al., 2010; Fialho and Zinn, 2014; Zhang et al., 2015). But in the present study *Eucalyptus* plantations were made extra on farm boundaries in combination with crops rather than replacing existing native forest trees, therefore, improved organic carbon in soil.

Table 3
Soil properties as affected by spacing of *Eucalyptus*in strip plantation raised on bunds.

Tree spacing	Soil depth (cm)	pHs	ECe (dSm^{-1})	OC (%)	Bulk density (g cm^{-3})
Initial	0–15	8.5	8.0	0.30	1.49
	15–30	9.0	7.1	0.20	1.55
	30–60	8.6	5.3	0.15	1.61
Control	0–15	8.4	6.4	0.38	1.49
	15–30	8.8	5.5	0.25	1.54
	30–60	8.5	4.8	0.23	1.58
1 m × 1 m[*]	0–15	8.2	4.8	0.45	1.41
	15–30	8.7	3.5	0.38	1.44
	30–60	8.5	2.3	0.23	1.49
1 m × 2 m	0–15	8.3	5.5	0.42	1.38
	15–30	8.8	4.1	0.37	1.46
	30–60	8.5	2.3	0.21	1.49
1 m × 3 m	0–15	8.5	5.8	0.39	1.39
	015–30	8.7	5.0	0.32	1.44
	30–60	8.6	3.8	0.22	1.48
Block	0–15	8.2	4.5	0.58	1.32
	15–30	8.1	4.0	0.46	1.35
	30–60	8.4	2.9	0.32	1.38
LSD ($p \le 0.05$)		0.4	1.4	0.1	0.20

[*] 1 m × 1 m, 1 m × 2 m and 1 m × 3 m indicate tree spacing in strip plantation.

4. Conclusions

Two parallel strip-plantation (spaced at 60 m and each having two rows of trees) of clonal *E. tereticornis* grown at spacing of 1 m × 1 m, 1 m × 2 m and 1 m × 3 m raised on bunds for six years in agroforestry lowered the groundwater table in canal-irrigated waterlogged fields in a semi-arid region by 31.5–43.0 cm during their four years of growth compared to control (fields without strip plantation). Impacts of strip plantation on water table draw down were more conspicuous in narrower tree spacing because of higher amounts of water transpired per hectare. There was concomitant generation of invaluable biomass that has both environmental benefits (C-sequestration) and economic returns as timber and fuel wood obtained from the harvest of six years old *Eucalyptus* trees. Lowering of water table and associated soil improvement by *Eucalyptus* plantations increased grain yield of wheat and rice by 1.7 and 1.3 times, respectively. Among different densities, 1 m × 1 m proved better over 1 m × 2 m and 1 m × 3 m resulting in higher wood biomass, carbon sequestration and water table draw down but crop yields were not affected by tree spacing in strip plantation. The study also indicated that block plantation lowered down water table more effectively and produced substantial biomass and sequestered carbon both in wood and roots but provides economic returns only after a gap of 6 years, therefore may not be preferred by poor farmers.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.08.025.

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