Biodrainage to combat waterlogging, increase farm productivity and sequester carbon in canal command areas of northwest India

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Rise in groundwater table followed by waterlogging and secondary soil salinization is a serious problem in canal-irrigated areas of arid and semi-arid regions. To combat the problem, an agroforestry model for biodrainage was tested in waterlogged fields of Haryana (northwest India), where 10% area (0.44 m ha) is waterlogged resulting in reduced crop yields and abandonment of agricultural lands. In this model, four parallel strip-plantations of clonal *Eucalyptus tereticornis* (Mysure gum) were raised in December 2002 on four ridges constructed in the north–south direction in 4.8 ha canal-irrigated waterlogged fields of farmers. The strip-plantations were spaced at 66 m and each strip-plantation contained two rows of trees at a spacing of 1 m × 1 m, resulting in a density of 300 plants ha^{-1}. Levels of groundwater table were measured over 3 years (April 2005–April 2008) in 22 observation wells installed in two transects across the strip-plantations. The groundwater table underneath the strip-plantations remained lower than that in the adjacent fields and the drawdown in groundwater table was 0.85 m in 3 years. The annual rate of transpiration by 240 surviving trees per ha was 268 mm annum^{-1} against the mean annual rainfall of 212 mm. The strip-plantations sequestered 15.5 t ha^{-1} carbon during the first rotation of 5 years and 4 months. Benefit–cost ratio of the first rotation of strip-plantations was 3.5 : 1 and it would be many folds for next 3 to 4 rotations due to negligible cost of coppiced *Eucalyptus*. Wheat yield (April 2008) in the interspace of strip-plantations was 3.4 times that in adjacent waterlogged areas without plantation. It was mainly because of lowering of the water table and improvement in soil properties.

Keywords: Agroforestry, biodrainage, carbon sequestration, *Eucalyptus tereticornis*, waterlogging.

CANAL irrigation introduced for increasing crop production in arid and semi-arid regions also caused a rise in the groundwater table followed by waterlogging and secondary soil salinization. For the reclamation of waterlogged saline soils, the conventional technique is sub-surface drainage which is relatively expensive and generates harmful drainage effluents. A viable alternative of the above technique could be biodrainage, which is 'pumping of excess soil water by deep-rooted plants using bioenergy'. Biodrainage is economical because it requires only initial investment for planting the vegetation, and when established, the system provides economic returns by means of fodder, wood or fibre harvested and additionally sequesters carbon in the timber.

Cloned *Eucalyptus tereticornis* (Mysure gum) is fast-growing, goes straight and thus has low shading effect and has luxurious water consumption where excess soil moisture conditions exist. It grows well under a wide range of climatic conditions. In waterlogged areas, it can be successfully grown by ridge planting. The world's *Eucalyptus* plantation area has increased to 19 m ha because of its fast growth rate, favourable wood properties and carbon sequestration, and thus seems to be a good option for biodrainage[1].

The impact of block plantations of *E. tereticornis* on reclamation of waterlogged areas has already been tested and found effective at the Indira Gandhi Nahar Project (IGNP) site in Rajasthan, India and Dhob-Bhali research plot in Haryana, India[2,3]. In developing countries like India, farmers have small holdings and cannot afford to put the land under tree plantations which yield after a gap of five to six years. Under such situations, agroforestry can be a viable and remunerative option, which provides regular income.

In the shade under trees, crop yields may be reduced. Planting of trees on the common field boundary shared by two farmers may become a point of conflict. In these conditions, planting of trees in paired rows, each row owned by a farmer will solve such problems and also increase the plantation density and consequently higher biodrainage potential. The main objective of the present

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study was to evaluate the impact of parallel strip-plantations of paired rows of clonal *E. tereticornis* on waterlogging, farm productivity and carbon sequestration in waterlogged areas of Haryana, where 10% area (0.44 m ha) is suffering from waterlogging resulting in reduced crop yields and abandonment of agriculture lands[4].

Study area

The present study was carried out on canal-irrigated, waterlogged fields in village Puthi, Hisar District, Haryana, northwest India. The Puthi research plot (long. 76°14′E and lat. 29°04′N) is land-locked 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 (Figure 1). The terrain is plain and faces sub-surface waterlogging (groundwater table within 3 m) throughout the year and surface waterlogging during monsoon (July–September). The main causes of waterlogging are seepage from canals, low withdrawal of brackish groundwater, flood irrigation with canal water and absence of natural drainage. The climate of the area is semi-arid with average annual rainfall of 212 mm during 2000–2007, with a minimum of 115 mm during 2006 and a maximum of 350 mm during 2001. In Hisar, groundwater table rose at an average rate of 35 cm annum^{-1} for the last 30 years (1974–2004). It was 15.5 m in June 1974 and rose to 6.4 m in June 2004. The fluctuations in groundwater table during 1974–2004 are shown in Figure 2.

The soils of the site were alluvial sandy-loam (72% sand, 16% silt and 12% clay), with subsurface calcareous concretions. In the surface 0–15 cm layer, initial pH of the soil saturation paste (pH_s) ranged from 8.11 to 9.33 with an average of 8.42, whereas electrical conductivity of the saturation extract (EC_e) ranged from 1.64 to 7.90 with an average of 3.02 dS m^{-1}. In general, pH_s was higher whereas the EC_e values were lower in the subsurface layers (15–120 cm) compared to the surface layer. The soils were also poor in organic carbon (OC). It was 0.38% 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}. Depth-wise initial properties of the soil are given in Table 1.

Methods

Plantations

Four parallel ridges (nos I, II, III and IV) were constructed in the north–south direction along the bund of agricultural waterlogged fields (Figure 3). Ridge-to-ridge distance was 66 m. Each ridge was 0.5 m high, 2.6 m wide at the base and 2.0 m wide at the top. Plantations of *E. tereticornis* (clone C-7) were raised on the ridges in December 2002. The plantations raised on ridges I–IV were named as strip-plantations I–IV respectively. Every strip-plantation contained two rows of plants. The row-to-row and plant-to-plant distance was 1 m, resulting in a total of 1440 plants in 4.8 ha with a density of 300 plants ha^{-1}. The area under strip-plantations was about 4% and the rest 96% was available for raising agricultural crops, thereby making it an agroforestry model for biodrainage.

Measurement of groundwater table

To measure the groundwater table, 22 observation wells were installed in two transects (Figure 3). Out of these, a

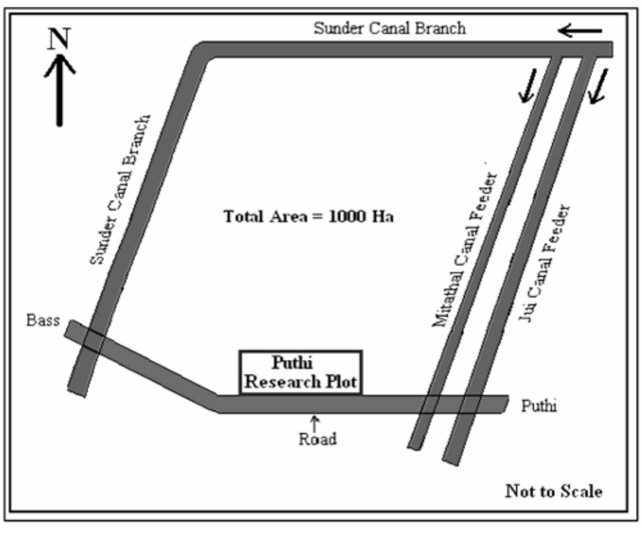

Figure 1. Land-locked area of Puthi research plot.

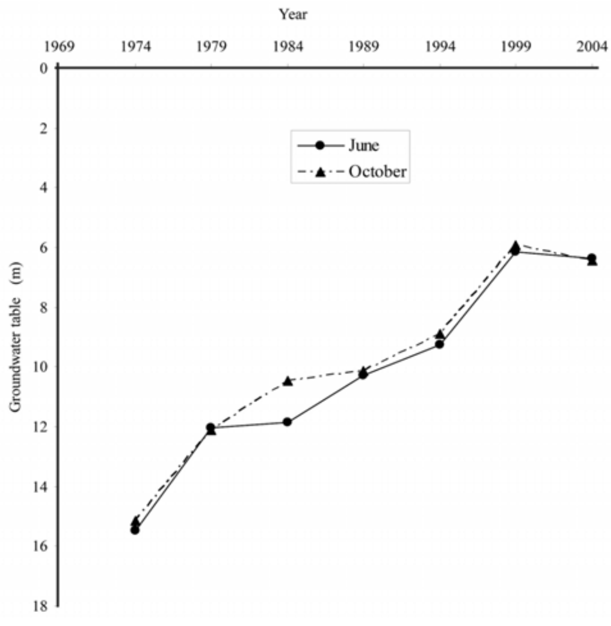

Figure 2. Groundwater table fluctuation during 1974–2004 in Hisar.

set of 11 observation wells (nos 1–11) was installed at equal spacing of 33 m in a straight line over a distance of 330 m in transect I. Similarly, another set of the remaining 11 observation wells was installed in transect II. Both transects were parallel to each other and perpendicular to the strip-plantations. Distance between the two transects was 60 m. Each observation well consisted of 6 m long galvanized iron pipe with inner diameter of 6.35 cm. The method of installation of observation wells was the same as described in a previous study[3]. The observation wells nos 1 and 11 of both transects, located in the adjacent fields without plantation, were taken as control.

The levels of groundwater table were measured thrice a day in April 2005, 2006, 2007 and 2008 in all the 22 observation wells with the help of a water-level recorder. During April, the fields are not irrigated, thus resulting in minimum interference to the groundwater table.

Biomass production

Girth of all *E. tereticornis* trees was measured at the breast height (1.37 m above the surface) with the help of a measuring tape during April 2008. The surviving 240 trees ha^{-1} were divided into four girth classes (30–39, 40–49, 50–59 and above 60 cm), finding 65, 55, 87 and 33 trees in the respective classes. The proportionate 22 representative trees (6, 5, 8 and 3 trees from girth classes 30–39, 40–49, 50–59 and above 60 cm class respectively) were felled during May 2008 and their height measured. Above-ground fresh biomass (shoot) was converted into timber, fuel wood and twigs/leaves and weighed.

Table 1. Initial soil characteristics of Puthi research plot

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH 1 : 2	EC_e (dSm^{-1})	OC (%)
0–15	72.2	16.0	11.8	8.64	3.0	0.38
15–30	71.3	16.7	12.0	8.81	2.3	0.30
30–60	70.9	17.0	12.0	8.85	1.9	0.20
60–90	69.6	18.0	12.4	8.83	1.6	0.12
90–120	68.9	18.1	13.0	8.80	1.7	0.08

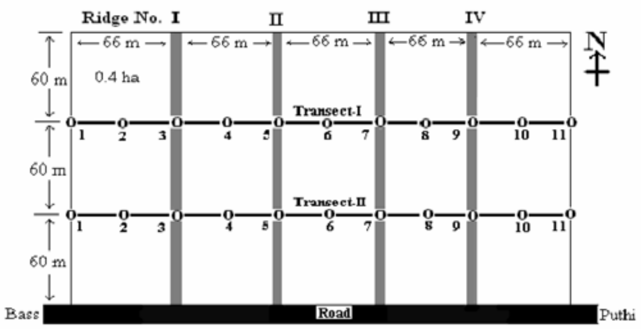

Figure 3. Layout of Puthi research plot. O, Observation well.

Roots of three representative *E. tereticornis* trees were also dug out and their biomass recorded. The fresh shoot and root biomass ha^{-1} was determined by multiplying the respective average biomass per tree with 240. These were added to determine the total fresh biomass ha^{-1}.

An open well of 2 m diameter was dug in June 2008 to verify whether the roots of trees had reached near the groundwater table or not.

Carbon sequestration

Oven dry timber, fuel wood, twigs/leaves and roots samples of felled trees were weighed and their carbon contents determined by dichromate oxidation method[5]. Weight of carbon sequestered ha^{-1} was determined by summing the products of dry weight of every component with its carbon content.

Rate of transpiration

Four trees of clonal *E. tereticornis*, from different representative girth classes were selected and their transpiration rate measured for 5 days in May (pre-monsoon), July (monsoon), October (post-monsoon), January (winter) 2007–08 to cover all the seasons prevailing throughout the year. The average transpiration per day per tree was multiplied by 365 to find the annual rate of transpiration per tree. Total amount of water transpired ha^{-1} was calculated by summing the products of annual rate of transpiration per tree of a particular girth class with the number of trees falling in that class.

The transpiration rate was measured using thermal dissipation probes (Dynamax, USA-make). The probe consisting of two needles (a heated needle above and a reference needle below) 4 cm apart was implanted in the stem sapwood at tree breast height. Sap flow rate in litres per day was calculated from sap flow index and velocity according to the methods defined by Granier[6,7].

Grain yield

Wheat was sown in the research plot and four adjacent untreated fields (without *Eucalyptus* plantation) during November 2007 depending upon the field conditions. Sowing in untreated plot was delayed by one to two weeks because of higher soil moisture. The grain yield of wheat was estimated at the time of harvesting (April 2008) by quadrant (1 m × 1 m) method.

Benefit–cost ratio

The benefit–cost ratio of parallel strip-plantations of clonal *E. tereticornis* was calculated by discounting the

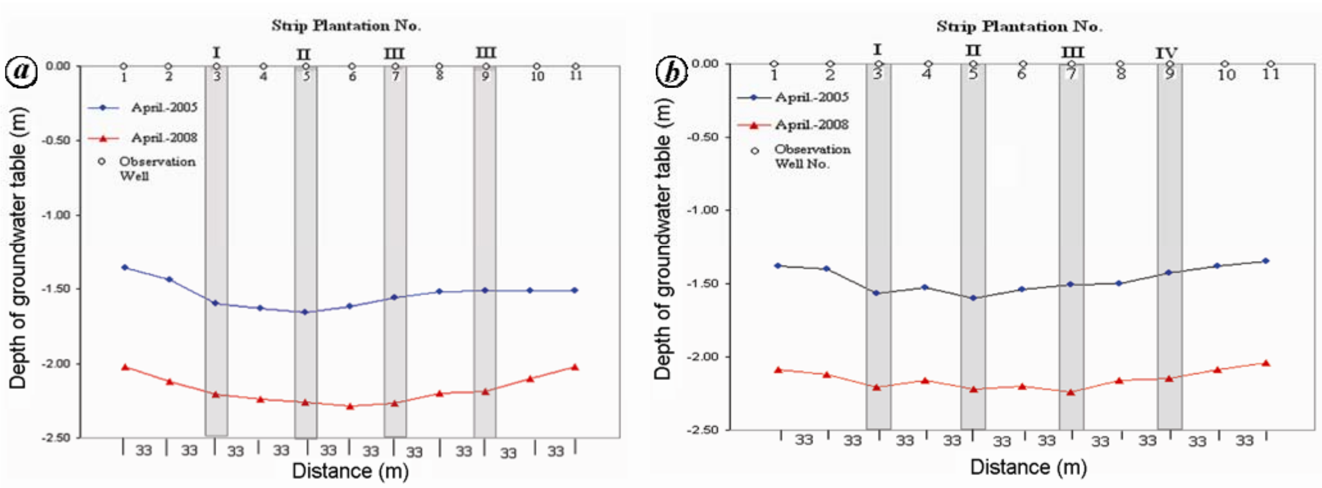

Figure 4. Trend of groundwater table levels in (***a***) transect I and (***b***) transect II at Puthi research plot during April 2005 and 2008.

benefit (revenue earned during April 2008 from the sale of trees) and the cost (expenditure incurred during December 2002 to April 2008 in raising and maintenance of plantations) at 12% rate of interest.

Results and discussion

Trend of groundwater table levels in transects I and II

In both the transects I and II, observations recorded during April 2005 clearly indicated that the mean level of groundwater table underneath all the strip-plantations except IV in transect I was lower than that in the adjacent fields (Figure 4). Groundwater table under strip-plantation IV in transect I was higher due to the presence of other trees near the observation well no. 11. These trees were felled in May 2005. Thereafter, the groundwater table underneath all the strip-plantations was lower than that in the adjacent fields. During April 2006, 2007 and 2008 also, the groundwater table under all the strip-plantations remained lower in both transects than in the adjacent fields.

In transect I, during April 2005, the mean groundwater table was 1.43 m in the control (in observation well nos 1 and 11) and 1.61 m underneath the central strip-plantations II and III (in observation well nos 5 and 7), resulting in a drawdown of 0.18 m by 2-yr-old plantations. Similar trend was observed during April 2006, 2007 and 2008, and the total drawdown of groundwater table during 3 years (April 2005–April 2008) was 0.84 m. In transect II also, the total drawdown of groundwater table in that period was 0.86 m. Thus, the average drawdown of groundwater table during 3 years was 0.85 m.

Water table drawdown could mainly be due to the luxurious water use by *Eucalyptus*. In IGNP also tree plantations established along the canal lowered the groundwater table by 14 m in 6 years[2]. The main reasons for the difference in drawdown of groundwater table at the two sites (IGNP and Puthi research plot) were the design and density of plantations and the sources of recharge of groundwater. IGNP had block plantation of 160 m width with the density of 1000 plants ha^{-1} and the sources of recharge of groundwater were only rainwater and seepage from one canal. Whereas Puthi had strip-plantations of 1 m width with a density of only 300 plants ha^{-1} and the sources of recharge of groundwater were rainwater, seepage from three canals and irrigation applied to agricultural crops between the strip-plantations. Therefore, at the Puthi research plot, the relatively higher recharge of groundwater from many sources and the relatively lower discharge of groundwater due to less number of trees ha^{-1} resulted in less drawdown of the groundwater table.

Bio-pumping

The shapes of drawdown curves of groundwater table in both transects (Figure 4) were similar to the combined cone of depression of four pumping wells working simultaneously for a long period. It indicated that four strip-plantations of clonal *E. tereticornis* were also working as bio-pumps. In previous studies also, trees were found to work as bio-pumps and drawdown curve of groundwater table due to *E. tereticornis* was similar to the cone of depression of a pumping well[3,8].

An open well dug in June 2008 showed that roots of *E. tereticornis* penetrated in the soil profile up to a depth of 3.30 m below the top level of 0.50 m high ridge or 2.80 m below the field surface. At this depth the soil was totally wet, which indicated that the roots have reached the zone of capillary fringe located above the groundwater table for water absorption.

Table 2. Fresh shoot biomass of 22 5-yr and 4-month-old trees of clonal *Eucalyptus tereticornis*

				Biomass (kg)			
Girth class (cm)	Tree no.	Girth (cm)	Height (m)	Timber	Fuel wood	Leaves	Total
30–39	1	32	12.5	76.5	2.5	3.5	82.5
	2	34	14.8	78.3	5.0	6.0	89.3
	3	35	11.4	76.5	2.5	5.0	84.0
	4	36	14.9	85.0	5.0	7.5	97.5
	5	38	12.5	92.5	2.5	7.0	102.0
	6	39	15.0	88.5	4.0	9.0	101.5
40-49	1	42	13.3	123.0	7.0	4.0	134.0
	2	44	16.1	143.5	4.0	7.0	154.5
	3	47	15.0	142.0	4.3	6.4	152.7
	4	48	18.9	145.2	5.0	6.5	156.7
	5	49	18.0	146.0	4.6	6.1	156.7
50-59	1	50	18.6	148.1	4.5	6.3	158.9
	2	51	16.8	150.5	4.8	6.7	162.0
	3	52	20.0	151.4	5.0	6.4	162.8
	4	53	18.0	152.0	5.1	6.3	163.4
	5	54	18.6	152.5	4.5	7.5	164.5
	6	55	18.0	153.1	4.8	6.5	164.4
	7	57	18.6	155.7	4.9	6.5	167.1
	8	58	19.5	157.2	5.0	7.0	169.2
Above 60	1	60	18.6	158.3	5.4	6.9	170.6
	2	62	20.4	159.7	5.7	6.3	171.7
	3	63	21.0	160.2	5.8	6.4	172.4
Total	22	1059	370.4	2895.7	101.9	140.8	3138.4
Average		48.14	16.8	131.6	4.6	6.4	142.7
Percentage				92.3	3.3	4.5	100.0

Table 3. Biomass and carbon sequestered by 5-yr and 4-month-old clonal *E. tereticornis*

	Fresh biomass		Dry biomass			
Tree component	kg tree^{-1}	t ha^{-1}	kg tree^{-1}	t ha^{-1}	C (%)	C sequestered ha^{-1}
Timber	131.6	31.6	92.1	22.1	47.0	10.4
Fuel wood	4.6	1.1	3.3	0.8	43.5	0.3
Twigs and leaves	6.4	1.5	4.5	1.1	43.9	0.5
Total shoot biomass	142.7	34.2	99.9	24.0		
Roots	51.4	12.3	37.0	8.9	48.0	4.3
Grand total	194.1	46.5	136.9	32.9	182.4	15.5

Biomass production

During May 2008, the average fresh shoot biomass of 5-yr and 4-month-old trees was 142.7 kg tree^{-1}, of which 131.6 kg (92.3%) was of timber (poles), 4.6 kg (3.3%) of fuel wood and 6.4 kg (4.5%) of twigs and leaves (Table 2), resulting in a total of 34.2 t ha^{-1} from 240 surviving trees ha^{-1} (Table 3). Similarly, the average and total root biomass was found to be 51.4 kg tree^{-1} and 12.3 t ha^{-1} respectively, from 240 surviving trees (Table 3). Therefore, total fresh biomass of both root and shoot worked out was 45.5 t ha^{-1}, with an annual increment of 8.0 m^3 ha^{-1} yr^{-1}.

Upon drying at 70°C, the fresh biomass of shoot and root was reduced to 99.9 and 37.0 kg per tree respectively. The oven-dried shoot and root biomass obtained from 240 surviving trees computed was 24.0 and 8.9 t ha^{-1} respectively, making a total of 32.9 t ha^{-1}. The moisture percentage recorded was 30.0 in timber, 29.4 in fuel wood, 30.1 in twigs and leaves, and 28.0 in the roots.

Many workers have recommended rehabilitation of salt-affected, waterlogged lands through tree plantations. Besides lowering the water table, *Eucalyptus* fetches high price and provides fuel wood. Biomass accumulation of the 5-yr-old *Eucalyptus* trees at a stocking density of 1280 trees ha^{-1} from block plantations was found to be 50 t ha^{-1} in waterlogged areas of Israel[9]. Prabhakar[10] also recorded 8 m^3 ha^{-1} as the mean annual growth rate of *Eucalyptus* and found it more efficient in water use than many other native trees.

Table 4. Transpiration of groundwater by trees of clonal *E. tereticornis*

Girth class (cm)	No. of trees in girth class	Groundwater transpired (l)						
		Per day/plant					Per annum	
		May	July	October	January	Average	Per plant	Per ha
1	2	3	4	5	6	7	8	9 (2 × 8)
30–39	65	44.5	30.5	24.1	14.8	28.5	10,393	675,569
40–49	55	47.4	31.2	26.1	15.0	29.9	10,923	600,744
50–59	87	51.8	31.5	26.3	15.8	31.4	11,443	995,519
60–69	33	56.3	34.0	28.3	16.2	33.7	12,301	405,917
Total	240	200.0	127.2	104.8	61.8	123.5	45,059	2,677,750

Carbon sequestration

The carbon content was 47.0% in timber, 43.5% in fuel wood, 43.9% in twigs and leaves, and 48.0% in the roots. By multiplying the plant part dry weight with its C content, carbon sequestered in 240 5-yr and 4-month-old surviving trees ha^{-1} of clonal *E. tereticornis* was 10.4 t ha^{-1} in timber, 0.3 t ha^{-1} in fuel wood, 0.5 t ha^{-1} in twigs/leaves, and 4.3 t ha^{-1} in roots, resulting in a total carbon content of 15.5 t ha^{-1} (Table 3).

Reclaiming waterlogged, salt-affected lands which are low in organic carbon, through fast-growing plantations is a useful strategy for carbon sequestration. Increase in soil carbon through plantations may also act as an important carbon sink[11]. The present results show that by raising of strip-plantations of *Eucalyptus* (4% of total agricultural area) in waterlogged areas of Haryana, 1.33 mt additional C would be sequestered annum^{-1}. Therefore, apart from lowering the groundwater table, *Eucalyptus* plantation provides additional benefits in terms of carbon sequestration[12].

Rate of transpiration

The average rate of transpiration in *E. tereticornis* trees ranged from 44.5 to 56.3 in May, 30.5 to 34.0 in July, 24.1 to 28.3 in October, and 14.8 to 16.2 l day^{-1} tree^{-1} in January (Table 4). The transpiration values varied because of variation in radiation, temperature and vapour pressure gradient prevailing during the period. The overall average rate of transpiration in the 5-yr-old *E. tereticornis* was 30.9 l day^{-1} tree^{-1}, which was 268 mm annum^{-1} by 240 trees ha^{-1} against the mean annual rainfall of 212 mm. It clearly indicated that the discharge of groundwater by the strip-plantations of clonal *E. tereticornis* was 1.3 times more than the recharge by rainfall resulting in reclamation of waterlogged areas.

Eucalyptus grows fast and has good water-consumption capacity when the water is available in sufficient quantity[13]. There is a close relationship between growth and transpiration rate[14,15]. In the present study also, trees with better growth had higher transpiration rate round the year. Earlier work indicated that 6-yr-old block plantations of *E. tereticornis* at a density of 163 plants ha^{-1} had a transpiration rate of 56 l day^{-1} tree^{-1} during December 2005 and 60 l day^{-1} tree^{-1} in September 2006 (ref. 16). Others working on similar lines reported water-use figures of 300 mm per year by *Eucalyptus* grown on a shallow saline water table[17]. Later work reported transpiration rate of 1.6–1.9 mm day^{-1} by a stand of 1000 *Eucalyptus* trees ha^{-1} ageing between 5 and 7 years[18]. These values are in close agreement with the observations recorded in the present study when calculated for 300 trees ha^{-1} basis.

Wheat productivity

Grain yield of wheat near the tree lines was comparatively low, which could be due to shading effect and the strong root system of *Eucalyptus* competing for moisture and nutrients with the crops[19]. Total decline in wheat grain yield due to tree plantation estimated was 11.7%. As the distance increased, grain yield also increased. Previous work reported that *E. tereticornis* grown on field bunds had negligible negative effect on associated agricultural crops during the first two years; however, losses were 8.2% during the third and fourth years, and 13.6% during the fifth and sixth years[20].

In spite of the decline near the tree line, overall grain yield of wheat in Puthi research plot was 2.2 t ha^{-1} (3.4 times) compared to 0.6 t ha^{-1} in adjacent fields without plantation (Figure 5). Higher wheat yields in the research plot compared to untreated fields were due to lowering of the water table by tree plantation leading to percolation of rainwater. In untreated fields, high water table caused deficiency of oxygen and excess of carbon dioxide in the root zone of wheat, which finally reduced the yield.

Release of toxic chemicals from leaf, stem and roots extracts of *Eucalyptus* may inhibit the germination and seedling growth of crops[21]. But in the present study the main objective was to reclaim waterlogged fields by lowering the water table through trees having high transpiration system. There was visual increase in germination percentage and grain yield of wheat in treated plots compared to untreated fields. Microbial population studied was also maximum near the tree line of *Eucalyptus* plantation. The major leaf and litter fall took place on raised ridges, well above the surface. Moreover, allelopathic chemicals released, if any, would have been neutralized a few centimetres below the top soil. Therefore, the adverse effects of release of toxins from *Eucalyptus* were not expected on crops and soil microbes.

Changes in soil properties

Depth-wise soil samples from eight profiles in the control fields (without plantation, pertaining to observation well nos 1 and 11) and 14 profiles from the fields having *Eucalyptus* plantation (pertaining to observation well nos 2–10) in both transects were collected in May 2008. The mean values of EC_e and pH_s at different soil depths are plotted in Figure 6. EC_e was lower in the upper 30 cm soil layer, but higher in lower depths (>60 cm) in fields with plantation compared to fields without plantation. The effects were more conspicuous in the upper 0–15 cm soil layer. The lower groundwater table in plantation fields would have ceased the movement of salts to surface layers through capillaries, resulting in their accumulation in lower soil depths.

Eucalyptus plantation also lowered pH of the soil saturation paste in the surface 60 cm layer compared to fields without plantation. Lowering of water table by *Eucalyptus* would have induced higher root activities and secretion of organic acids in the surface layers. The average steady-state infiltration rate in fields with plantation was 8.3 mm h^{-1}, whereas it was only 5.1 mm h^{-1} in fields without plantation. The results indicated that *Eucalyptus* plantation improved overall surface soil properties.

Benefit–cost ratio

The cost for raising *E. tereticornis* plantations during 2002–03 was Rs 10,000 ha^{-1} and maintenance cost during 2003–04 was Rs 2000 ha^{-1}. Standing trees were sold at an average of Rs 300 $tree^{-1}$. Felling of trees was done in May 2008 and the expenditure for felling, conversion and extraction of tree produce was borne by the purchaser. The farmers earned Rs 72,000 ha^{-1} from the sale of 240 trees resulting in a benefit–cost ratio of 3.5 : 1 at 12% discount rate of interest, which was much higher than in the case of agricultural crops (1.3 : 1) in Haryana[22].

The stools of young felled trees of *E. tereticornis* gave excellent coppice shoots. The only operation carried out

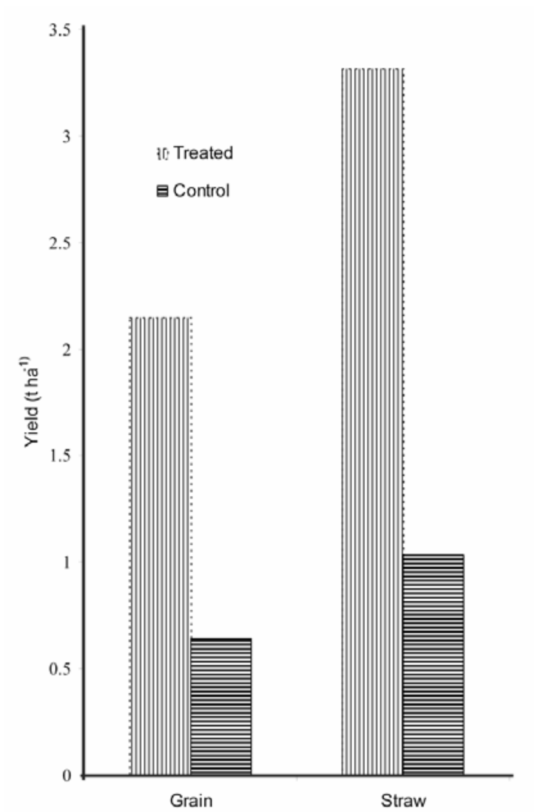

Figure 5. Wheat yield obtained with and without *Eucalyptus* plantation.

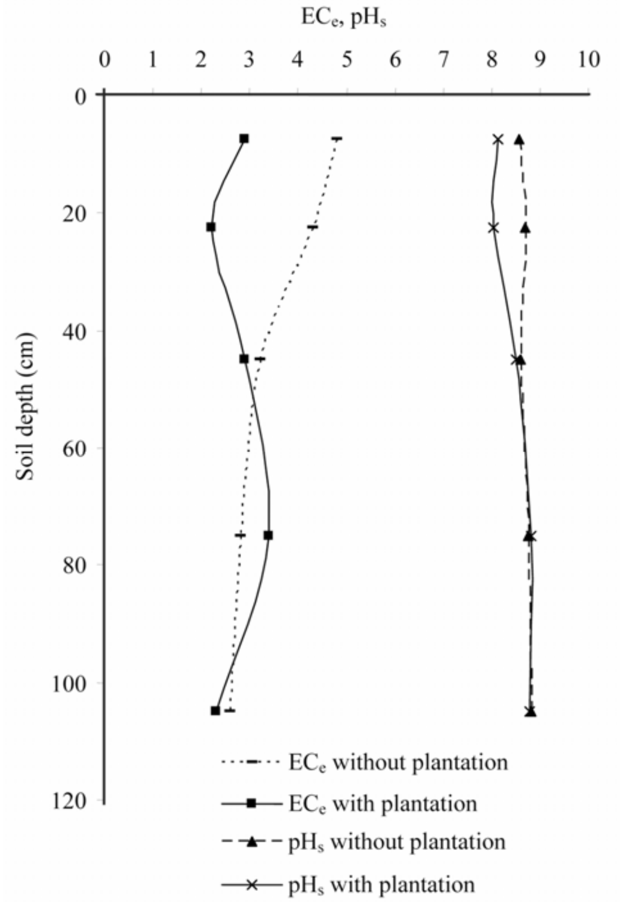

Figure 6. Effect of plantation on soil electrical conductivity of the saturation extract (EC_e) (dS m^{-1}) and pH of the soil saturation paste (pH_s).

was the singling of coppice shoots by incurring an expenditure of Rs 300 ha^{-1}. In this way, about 3 to 4 rotations of coppice crop (each of 5–6 years) can be harvested. Thus, the benefit–cost ratio of the next 3 to 4 rotations of coppice crop of *E. tereticornis*, each of 5–6 years, would be much higher (120 : 1) due to zero cost of raising and negligible (Rs 300 ha^{-1}) maintenance cost. Because of increased productivity and profitability, *Eucalyptus* clones were successfully adopted to make farm forestry an attractive land-use option[23].

Summary and conclusion

Four parallel strip-plantations (spaced at 66 m and each having two rows of trees at 1 m × 1 m spacing in north-south direction) of 5-yr 4-month-old clonal *E. tereticornis* worked as bio-pumps and lowered the water table by 0.85 m in 3 years in canal-irrigated, agricultural, waterlogged fields located in a semi-arid region with alluvial sandy-loam soil. The annual rate of transpiration by these plantations was 268 mm against the mean annual rainfall of 212 mm. These plantations generated 46.6 t ha^{-1} fresh biomass with benefit–cost ratio of 3.5 and also sequestered 15.5 t carbon ha^{-1}. Lowering of water table and associated soil improvement by *Eucalyptus* plantations increased the wheat grain yield by 3.4 times and resulted in reclamation of waterlogged areas.

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