Agricultural Water Management 152 (2015) 151–160

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Effect of long-term irrigation with wastewater on growth, biomass production and water use by Eucalyptus (*Eucalyptus tereticornis Sm.*) planted at variable stocking density

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A R T I C L E I N F O

Article history:
Received 16 July 2014
Accepted 11 January 2015

Keywords:
Wastewater use
High rate transpiration systems
Sewage disposal
Eucalyptus tereticronis
Stocking density
Tree water productivity

A B S T R A C T

Irrigation of high transpiring forest species has been put forward for recycling and reuse of wastewater and conservation of nutrient energy into biomass and thereby bringing multiple benefits such as fuel wood production, environmental sanitation and eco-restoration. But loading rates, the tree plantations can carry, continue to be contradictory. Therefore, the growth patterns, biomass production, water use and changes in soil properties were evaluated for a 10-year rotation of Eucalyptus (*Eucalyptus tereticornis Sm.*) plantations of variable stocking density and irrigated with either sewage (SW) or a good quality groundwater (GW). The irrigated trees grew rapidly and the stock volumes attained after 10 years were 164.0 and 127.1 m^3 ha^{-1} with SW and GW, respectively. The tree growth improved with stocking density and the maximum shoot biomass (262 Mg ha^{-1}) was produced under high (HD, 1993 stems ha^{-1}), followed by the recommended (RD, 517 stems ha^{-1}; 178 Mg ha^{-1}), very high (VHD, 6530 stems ha^{-1}; 127 Mg ha^{-1}) and low stocking density (LD, 163 stems ha^{-1}; 55 Mg ha^{-1}). Sap flow values almost coincided with growth rates and increased until sixth year of planting and stabilised thereafter. The annual sap flow values ranged between 418–473, 1373–1417 and 1567–1628 mm during 7–10 year of planting under LD, RD and HD, respectively. The daily sap flow values were 0.56*PAN-E (USWB Class A Open Pan Evaporation) during summer months of April–June, 1.24*PAN-E during August–October, i.e. active growth period and 1.12*PAN-E during winter months of December–February. Reference evapotranspiration (ETref) computed using Penman–Monteith method could better describe water use; the sap flow being 0.87–1.23*ETref with an average 1.03*ETref. The water productivity for timber was 1.54, 1.71 and 1.99 kg m^{-3} for LD, RD and HD, respectively. Similarly, the water use efficiency increased by about 40% with HD and also with SW (11%) under RD. The soil quality improved considerably with sewage irrigation and the plant absorbed carbon was also greater. The annual carbon absorption was 3.5, 12.0, 13.9 and 7.0 Mg ha^{-1} under LD, RD, HD and VHD, respectively. It is concluded that Eucalyptus plantations can act as potential sites for year round and about 1.5 fold recycling of sewage than the annual crops. However, cautions, rather regulatory mechanism should be devised to control loading rates since these are not as profligate consumers of water as has been claimed.

1. Introduction

Population growth along with increasing urbanisation and industrialisation is encroaching upon the share of agricultural water and is leading to production of quantities of wastewaters, which are beyond the capacity of natural systems to assimilate. Soils are considered to be the ultimate and probably the most logical sinks for the wastewaters particularly the land locked areas where their disposal into surface streams is banned. Farmers in peri-urban areas in arid and semiarid regions depend largely on these waters for their livelihood and supply of majority of the nutrients and also the organic matter for conditioning the soil. Since the present sewage irrigation practices in the most of developing countries are primitive, unscientific and more of disposal oriented (Minhas and Samra, 2004); their reuse results in progressive and irreversible accumulation of salts, toxic materials and heavy metals in soil and ground water (Yadav et al., 2002; Rattan

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http://dx.doi.org/10.1016/j.agwat.2015.01.009
0378-3774/

et al., 2005; Khan et al., 2008; Qadir et al., 2010). Health hazards from pathogenic contaminations further multiply the complexities from their reuse (Minhas et al., 2006; WHO, 2006; Drechel et al., 2010). The realisation that both controlled and uncontrolled disposal of waste waters can contaminate soils, surface and ground waters and that bio-transfer of pathogens and heavy metals occurs through the sewage–soil–vegetation–animal–human chain, has led to the development of considerable assortment of regulatory measures and guidelines aimed at reducing or eliminating waste water related pollution. However, long-term sustainability of irrigation with poor quality waters depends on several site-specific factors such as soil, climate, crop, application techniques and socio-political environment (Minhas and Gupta, 1992; Minhas, 2012). Efforts have therefore been made to optimise loading rates, methods of water application, capacity of the soils to act as sink and quality of the produce (Minhas and Samra, 2004; Qadir et al., 2010).

Irrigation of forest species grown for fuel and timber with wastewater is another approach, which can help in overcoming health hazards associated with sewage farming (Braatz and Kandiah, 1996; Thawale et al., 2006). Developing and enlivening the green belts around the cities with forest trees under wastewater irrigation can further revive the ecological balance and improve environmental quality by self-treatment of wastewater through land application and forest irrigation. Tree plantations are often expected to use water at higher rates than the shorter vegetation. This is because of greater aerodynamic roughness of tree plantations, clothesline effect in tree rows and deeper rooting system for accessing water down to several metres of soil. Thus the systems of agro-forestry, which have come to be known as HRTS (high rate transpiration systems) are the land application systems based upon the transpiration capacity of tree species those promote the treatment of wastewater through renovating capability of living soil filter enabling recycling and reuse of wastewater and conservation of nutrient energy into biomass and thereby bringing multiple benefits to society such as fuel wood, environmental sanitation and eco-restoration.

Although very tall claims (0.3–1.0 million litres per day, MLD ha^{-1}) have earlier been made for sewage disposal through tree plantations involving *Eucalyptus tereticornis*, *Leucaena leucocephala* and *Populus deltoide* (Chhabra, 1995) but the real estimates on the loading rates, such plantations can carry without the contamination of ground water, are still awaited. Morris and Wehner (1987) reported annual crop factors of 1.4–1.9 times the open pan evaporation (PAN-E) and the maximum daily water-use rates of 20 mm in summer (January) by 3-year-old Eucalypt plantations irrigated with effluent in arid western Victoria, Australia. Nevertheless, the thermo-electric heat pulse method is considered to be remarkable improvement with automatic and extraordinary accurate measurements of transpiration of trees and using this method, the transpiration of forest trees has been monitored world over. In Australia, water use by tree plantations rarely exceeded 0.5*PAN-E (Cramer et al., 1999; Morris and Collopy, 1999; Greenwood et al., 1985) while higher values (0.86*PAN-E) were reported from Pakistan even from the saline sites (Khanzada et al., 1998; Mahmood et al., 2001). Some of the recent studies (Minhas, 2006; Kallarackal and Somen, 2008; Forrester et al., 2010; Hubbard et al., 2010) show similar results but the overall water use by trees seems to vary a lot with the specific site conditions defining soil type, evaporative demands and even the salinity determines the actual water use by the species under consideration. Heuperman et al. (2002) have earlier also concluded the evapo-transpiration through so-called high transpiring species like Eucalyptus to be at the most 1.1–1.4 times the potential evaporation. If such is the case, there may little difference in quantities for land disposal and that through forestry plantations. However, the latter would still result in economic returns in terms of fuelwood production as well as the environmental benefits. Additional advantage of tree plantations would be harvest of large amount of metals as tree are known to tolerate and accumulate greater levels of these toxic metals (Heuperman et al., 2002; Tomar et al., 2003). Also the trees efficiently absorb carbon and have mitigating potential to counter the predicted increase in atmospheric carbon concentration (Kurz et al., 2009). Keeping above in view, a long term experiment was conducted to evaluate the water use of the sewage irrigated Eucalyptus, the best identified tree species for its profligate water use, and the sustainability of HRTS system by quantifying the potential risks and effects on soil properties.

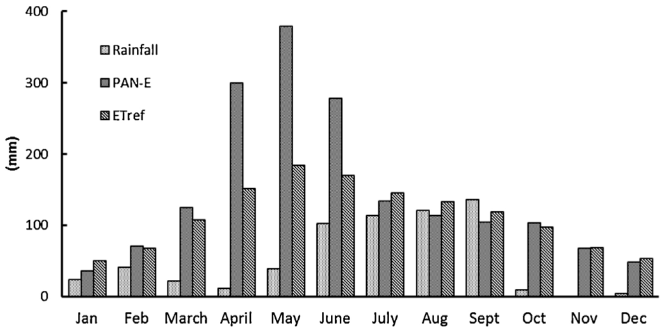

Fig. 1. Mean monthly rainfall (mm), Class A open pan evaporation (PAN-E, mm) and reference evapo-transpiration (ETref, mm, Penman–Monteith) for the 10 year rotation (September 2000–August 2010).

2. Materials and methods

The experiment was conducted at Research Farm of Central Soil Salinity Research Institute, Karnal, Haryana, India located at 75°57′ E longitude and 29°43′ N latitude and 243 m above mean sea level during October 2000–September 2010. The site has subtropical semi-arid monsoonal climate with about 80% of rainfall occurring during the months of July to September. The evaporation remains high during April to June and low during November to February. The mean monthly temperature is the maximum in May or June and the minimum during January. The USWB Class A Open pan evaporation (PAN-E) of the area generally exceeds rainfall except during rainy season (Fig. 1). The site, silt-loam at the surface, is an ex-improved sodic land still having high pH (8.7–9.2) in sub-surface layers and calcareous hard pan layer of variable thickness at a depth of 0.9–1.2 m. Some of the other physico-chemical characteristics for different depths of the initial soil are included in Table 1.

The experiment design chosen was a competition wheel of the type proposed by Nelder (1962) and also given by Cameron et al. (1989). Tree saplings were planted in two wheels having concentric circles with increasing stand density towards the centre. Each wheel consisted of 9 circles with radii of 1.98, 3.30, 4.62, 6.47, 9.06, 12.68, 17.75, 24.85 and 31.95 m from the centre in-filled with radii of 2 m. The angle between spokes of wheel was 20°, giving 18 trees around any circumference. Thus the stocking density in the wheels increased from 126 in the outermost to 10,823 stems ha^{-1} in the innermost ring (Table 2). For planting of tree saplings, bore holes (1.5 m deep, 0.3 m ID) were dug with a tractor mounted post-hole auger at the specified planting sites. Each auger bore hole was filled with a mixture of soil, sand and farmyard manure (FYM) in the ratio of 3:1:1 along with 2 kg gypsum. A total of 324 saplings (6 month old; height 1.07 ± 0.09 m) were planted in each of the wheels during October 2000. The plantations grown in two wheels were irrigated either with sewage water (SW) or groundwater (GW) drawn with a tube well. The irrigations were based upon the climatological approach, i.e. applying 75 mm of irrigation water when cumulative USWB Class A open pan evaporation (CPAN-E)

Table 1
Physico-chemical characteristics of the soil at different depths.

Depth (m)	Sand (%)	Silt (%)	Clay (%)	BD ($g\,cm^{-3}$)	WHC (v/v)	pHs	ECe ($dS\,m^{-3}$)	Avail-N ($kg\,ha^{-1}$)	Org-C (%)
0–0.15	40.5	46.3	13.2	1.48	19.2	8.27	1.28	167	0.43
0.15–0.30	41.0	45.4	13.6	1.47	19.4	8.34	1.09	148	0.34
0.30–0.60	41.4	45.8	14.3	1.45	19.6	8.41	1.13	114	0.24
0.60–0.90	40.2	44.9	14.9	1.44	18.9	8.68	1.21	98	0.18
0.90–1.20	39.3	44.3	16.4	1.42	20.1	9.12	0.63	74	0.18
1.20–1.50	44.5	45.8	9.7	1.55	16.4	9.23	0.58	63	0.12
1.50–1.80	45.2	43.0	11.8	1.52	17.9	9.37	0.61	47	0.14

Table 2
Specifications of Nelders' wheels formed with Eucalyptus plantation.

Wheel specifications	Ring number								
	1	2* VHD	3	4* HD	5	6* RD	7	8* LD	9
Radius (m)	1.98	3.30	4.62	6.47	9.06	12.68	17.75	24.85	31.95
Distance to next ring (m)	1.32	1.32	1.85	2.59	3.62	5.07	7.10	7.10	–
Distance between rows (m)	0.70	1.16	1.61	2.26	3.06	4.45	6.20	8.60	11.15
Density (stem ha^{-1})	10,823	6530	3918	1993	1019	517	264	163	126

Note: VHD, HD, RD and LD denote very high, high, recommended and low stocking density, respectively.

equalled irrigation depth (IW:CPAN-E 1.0). In the event of rainfall, irrigation was delayed for one day per 10 mm rainfall with a maximum of 75 mm rain per day. Because of interception losses, the rain of less than 10 mm per day was considered ineffective and was not accounted for scheduling of irrigation. The plantations received a total of 132 irrigations (9.90 m water) during the entire growth period of 10 years viz. from October 7, 2000 to September 24, 2010. The irrigation water received by plantations was about 15% more than the PAN-E minus rainfall. The composition of both SW and GW was analysed every month. The SW had an average biological oxygen demand (BOD), 82 ± 11 $mg\,L^{-1}$ and chemical oxygen demand (COD) 136 ± 14 $mg\,L^{-1}$ while BOD and COD were below detectable levels in GW. The EC of SW was 1.3 ± 0.3 $dS\,m^{-1}$ while NO_3-N, NH_4-N, P and K contents averaged 3.2 ± 0.4, 9.6 ± 0.5, 1.8 ± 0.3 and 6.4 ± 0.4 $mg\,L^{-1}$, respectively. EC of GW was 0.6 ± 0.2 $dS\,m^{-1}$ and its P and K contents were 0.03 and 3.5 ± 0.3 $mg\,L^{-1}$.

The growth was monitored in terms of plant height (H), diameter at stump height (5 cm, DSH) and at breast height (1.37 m, DBH) at monthly interval after planting. Trees in rings 2, 4, 6 and 8, with stocking densities of 6530, 1993, 517 and 163 stems ha^{-1} were selected for monitoring and hereafter are referred to as the very high (VHD), high (HD), recommended (RD) and low (LD) stocking densities, respectively. Stock volumes were determined by calculating the bole volume (V) of individual tree using the equation: $V = \pi/3 \times (DBH/2)^2 \times H$ as given by Cameron et al. (1989). Woody biomass (kg) was estimated by felling the trees in October, 2003, September 2007 and 2010 and above-ground fresh biomass (shoot) was portioned into timber, fuel wood and twigs/leaves. Thereafter these were air dried and weighed. Roots of the harvested trees were also dug out during 2010 and their biomass recorded. The air dry shoot and root biomass per ha was determined by multiplying the average biomass per tree with respective tree densities. For calculating carbon sequestration, oven dry timber, fuel wood, twigs/leaves and roots samples of felled trees were weighed and their carbon contents determined by CHNS analyser (Model Elementor Vario EL). In CHNS analyser particulate matter is combusted and measures weight percentage of C as CO_2. Weight of carbon sequestered per hectare was determined by summing the products of dry weight of every component with its carbon content.

Sap flow measurements were made using Dyanagage Sensors (Flow 32) system with weather shield during the period from August 2002 to July 2004. The Dyanagages were implanted of tree stem at 1.3 m height. Later on from August 2004 to September 2010, thermal dissipation probes (TDP, 50/80 mm, Dynamax, USA) were used. The TDP system measures the sapwood heat dissipation using a heated needle above and a reference one, placed 40 mm apart. The TDP needles were implanted in the stem sapwood at breast height. Since the whole tree transpiration rate and sap flow rate (Fs) are in close approximation, the transpiration was assumed to equal sap flow rate. The Dyanagages and Sap flow rate (Fs) was calculated from the sap flow index (K) using the equation: $K = (dTM/dT)/dT$, 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, $cm\,s^{-1}$) and sap flow rate (Fs, $cm^3\,h^{-1}$) were determined from sap flow index by using the equation: $V = 0.0119 \times k^{1.231}$ and $Fs = As \times V \times 3600$ where 'As' is the cross sectional area (cm^2) of sap conducting wood.

3. Results and discussion

3.1. Tree growth and biomass production

The plantations grew rapidly when irrigated with either sewage (SW) or ground (GW) water (Fig. 2). The growth rates showed a log pattern, the rate increasing initially with age, maximising between 4 and 6 years and declining there-after. The increments in height increased from 1.38 m in 2nd to 3.40 m in 5th year and decreased thereafter and were about 0.15 m only during the tenth year. The growth rates of trees were better with SW. Gains in girth diameter followed a similar pattern. The average height and DBH attained under recommended stocking density (RD) in 10 years was 16.1 and 0.19 m with SW, respectively and 15.2 and 0.16 m with GW. The similar growth patterns were also reflected in stock volumes. The increments in stock volumes increased with age and peaked during the 5th year of growth, remained almost similar between 6 and 7th years and declined thereafter. The stock volumes attained with SW and GW at the end of 10th year averaged 0.180 and 0.142 $m^3\,tree^{-1}$, respectively. The seasonal impacts could also be visualised on growth patterns. Major increments in growth parameters were monitored during the four months of May to August which accounted for 49–61% of annual growth while the growth slowed down during the months of October–December, contributing only 13%.

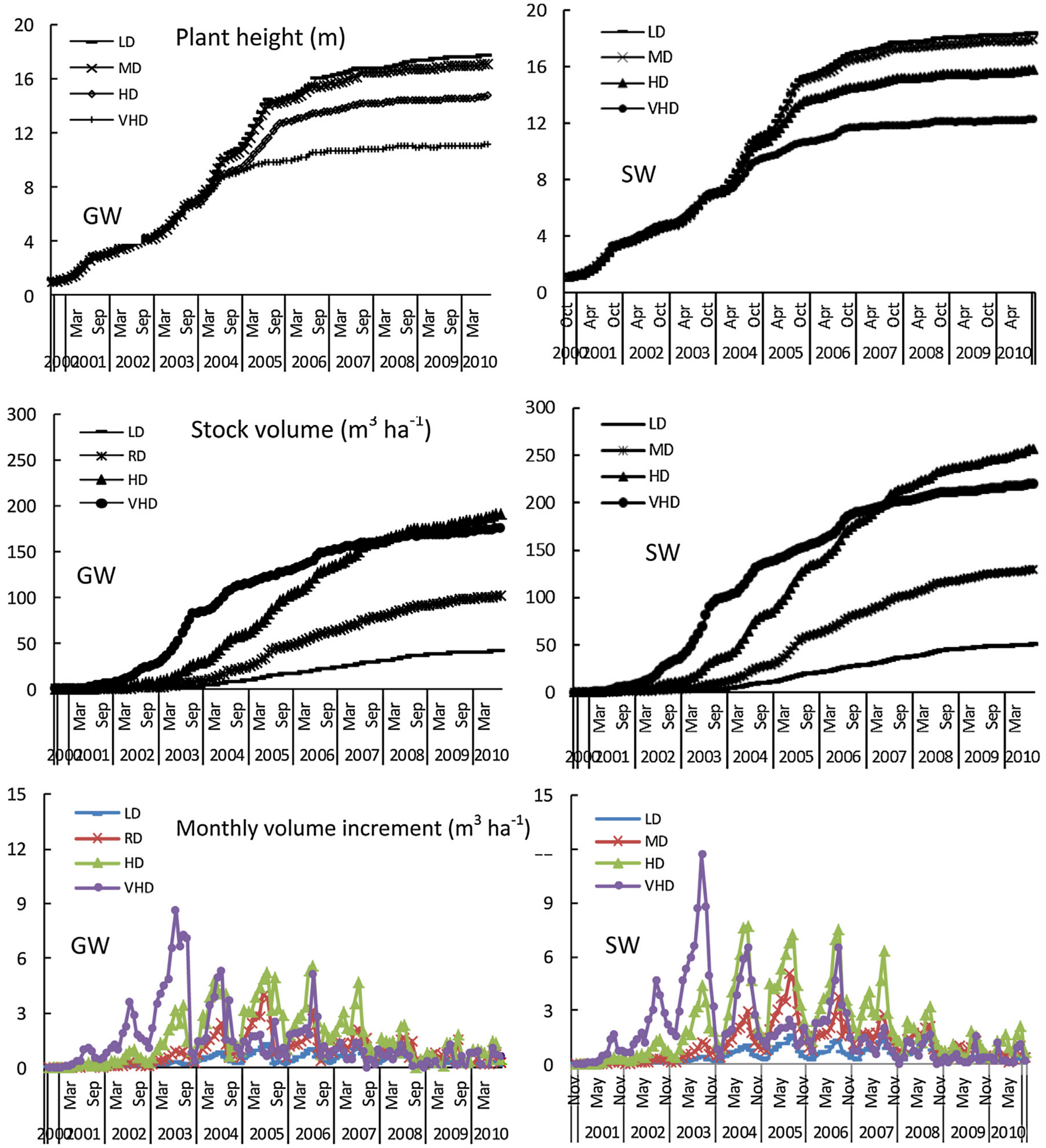

Fig. 2. Plant height, stock volumes and monthly volume increments under different planting densities (LD, RD, HD, VHD denote low (163), recommended (517), high (1993) and very high density (3520 stems ha^{-1}) for sewage (SW) and ground water (GW) irrigated plantations.

The trees growth was not affected by stocking densities during the initial three years. The height attained after three years of planting was 6.78 ± 0.10 m and 6.0 ± 0.06 m with SW and GW, respectively. Thereafter with closure of canopy, the growth slowed down initially under very high stocking density (VHD) and thereafter under high density plantation (HD). During the 4th and 5th years, growth rate in terms of increment in stem volume of individual trees under recommended density (RD; 0.54 m^3) and low density plantation (LD; 0.51 m^3) exceeded that of HD (0.23 m^3) and VHD (0.05 m^3). By the age of 6 years, total stock volumes achieved under VHD were the maximum and these equalled 185 and 148 m^3 ha^{-1} when irrigated with SW and GW, respectively. Ripple effect between VHD and HD could be visualised during 7th year of growth when stock volume under HD crossed the VHD. Final stock volumes attained after 10 years of growth were 50.1, 125.4, 256.8 and 219.8 m^3 ha^{-1} for LD, RD, HD and VHD, respectively under SW irrigation with an average of 164.0 m^3 ha^{-1} while the counter values for GW irrigation were 40.6, 101.6, 191.0 and 175.1 m^3 ha^{-1} and an average of 127.1 m^3 ha^{-1}.

The shoot and root biomass monitored after 3, 7 and 10 years of transplanting have been presented in Fig. 3. The timber component of the shoot biomass was the maximum (91%) followed by twigs plus leaves (5%) and branches (4%). Both the shoot and root biomass increased with stocking density but the maximum was observed under HD. The shoot biomass for individual trees at final harvest, i.e. after 10 years was highest under RD (343 kg) and followed by LD (323 kg), HD (131 kg) and VHD (35 kg), but on area basis (per hectare), biomass production improved with density and the maximum was produced under HD (261.5 Mg) followed by RD (177.5 Mg), VHD (122.5 Mg) and LD (54.6 Mg). Similarly, the root biomass monitored at final harvest averaged 22.4, 73.0, 107.3 and 50.5 Mg ha^{-1} for LD, RD, HD and VHD, respectively. Though

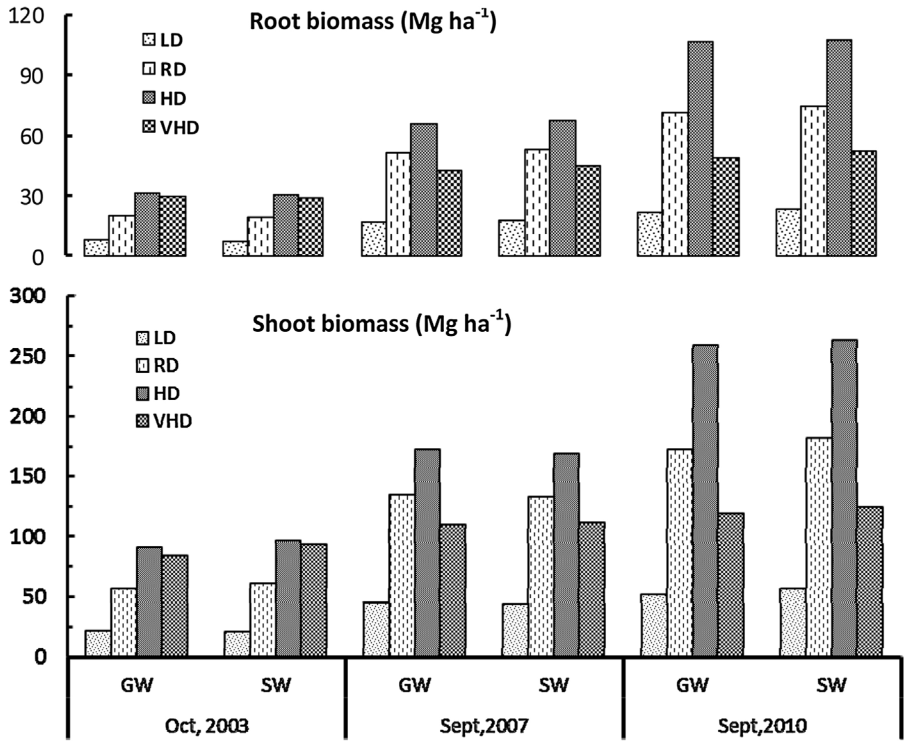

Fig. 3. Shoot (timber, branches and twigs + leaves) and root biomass under different planting densities (LD, RD, HD, VHD denote low (163), recommended (517), high (1993) and very high density (3520 stems ha^{-1}) for sewage (SW) and groundwater (GW) water irrigated plantations.

the nutrients contained in SW are known to boost the growth of plants but it has also been reported that the plantations irrigated with SW may suffer due to nutrient imbalances, especially with inducement of succulence with excessive nitrogen supplies and thereby, trees becoming prone to damage by wind throw and pathogens. Nevertheless such damages were not be visualised in this experiment since the creation of ridges along the planting rows to facilitate irrigation simultaneously avoided direct contact with sewage, in addition to providing the physical support. The overall growth of trees matched to those earlier reported for Eucalyptus, e.g. the fastest growing species had a mean height in excess of 9.5 m and volumes in excess of 50 m^3 in New South Wales and 10–35 m^3 in Victoria (Myers et al., 1998; Baker et al., 2005) but was higher than those reported for rainfed conditions even from high rainfall (>1100 mm) areas of Brazil, Africa and China (Morris et al., 2004; Almeida et al., 2007; Fonseca et al., 2007). Otherwise the sewage irrigated plantations also showed similar growth rates in Australia (Myers et al., 1997; Morris, 2005).

3.2. Water use and productivity

The main force behind the recycling of wastewater in plantations is their higher water use rates than the shorter vegetation. The combination of deeper roots, extended growing seasons and higher inputs of radiant energy because of lower albedos explain the high transpiration of tree plantation as compared with herbaceous covers or crop lands. But understanding the water balances is critical for design purpose since the water use also varies with climatic conditions and stage of canopy development and the species grown. Though the sap flow data were collected at half-hourly interval and then pooled on daily basis, the data presented are the monthly average of daily water use for GW and SW irrigated plantations starting from 3rd year onwards, when sap flow sensors were installed and continued up to final harvest of trees, i.e. after 10th year. There was an increasing trend with age up to 6th year that coincided with active growth phase of plants. Though the sap flows continued to increase thereafter also but at a slower rate (Fig. 4). Sap flow values also showed seasonal trends, the maximum occurring during the summer months of May–June (110 L d^{-1} under RD) and the minimum during winter months of December–January (35 L d^{-1}). When averaged for 3–10 years, individual trees under LD and RD transpired more but were almost similar water (58–62 L d^{-1}), and the values were markedly lower under HD (18.8 L d^{-1}) and VHD (6.6 L d^{-1}). The mean daily water use in terms of mm d^{-1} was determined by multiplying the respective average sap flow values per tree with respective tree densities (Fig. 5). The maximum monthly mean daily water use for GW and SW under RD were within 6 mm d^{-1} which in contrast to the very high rates reported in literature for effluent irrigated eucalyptus e.g. up to 20 mm d^{-1} by Morris and Wehner (1987). However, these rates are similar to those in recent reports (Patrick et al., 2004; Morris, 2005; Kallarackal and Somen, 2008; Albaugh et al., 2013). The total sap flow values averaged 392, 730, 952, 1204, 1373, 1389, 1417 and 1380 mm under RD during 3–10th years of planting. Similarly the average annual sap flows under HD were 768, 1071, 1367, 1500, 1567, 1570, 1628 and 1595 mm during 3–10th years of planting whereas the counter values under LD were 143, 252, 358, 418, 441, 456, 473 and 453 mm only. Thus the plantation water use increased markedly under high as compared with recommended stocking density and more so during the early years of growth. It has earlier been reported (Morris, 2005) that tree spacing or planting density influences the water use through effects on leaf area and sap wood area and the time taken by the plantations to reach the maximum leaf area index and for the roots to fully occupy the upper soil profile decreases with planting density. Nevertheless, the water use does not continue to increase throughout the life of a stand but attains an equilibrium level for the specific densities of planting. In this experiment also, the water use got stabilised at about 5–6 years of age under

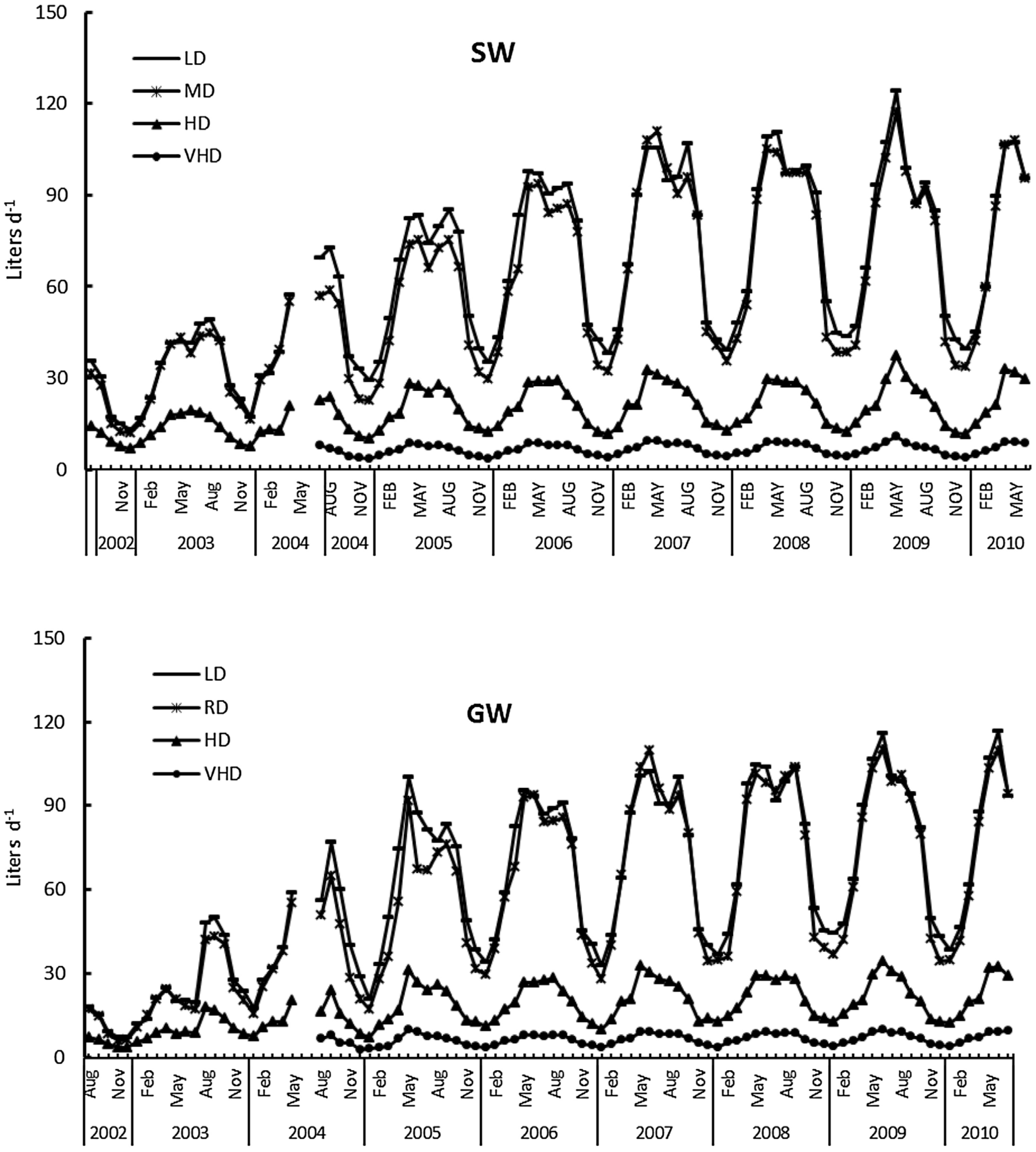

Fig. 4. Monthly average of mean daily sapflow values per tree for sewage (SW) and groundwater (GW) irrigated plantations.

different densities. Since the target is usually to maximise water use when plantations are established for waste water disposal, this may be served to some extent with increasing planting density. But the maximum rate of water use achievable would be also defined by soil and climatic conditions (Myers et al., 1998; Morris, 2005; Hubbard et al., 2010). It may be stated that sapflow system monitors only the transpiration component. The total water losses through tree plantations also include those by the rain interception and through understory vegetation which are anticipated to contribute about 10–20% to the annual evaporation losses (Morris, 2005). Thus the total water losses by Eucalyptus plantations should vary between 1500 and 1700 mm for recommended stocking density during 6–10 years of planting. Considering the total evaporation losses from annual crops of the area (paddy/cotton/maize–wheat–fallow) to vary between 1070 and 1240 mm (Prihar et al., 2010), Eucalyptus plantations would carry about one and a half time more wastewater loads. Therefore, plantations do not seem to be as profligate users of water as has been projected by the proposers of HRTS strategy for sewage water disposal.

The open pan evaporation (PAN-E) poorly defined the sap flow values/water use especially during summers when water vapour deficits are high. Even when the canopy grew almost fully after 5 years, the water use under RD was just 0.56*PAN-E during the summer months of April–June while it was 1.24*PAN-E during August–October when the maximum growth occurred. Again it came down to 1.12*PAN-E during winter month of December–February. The water use by trees is controlled by the regulation of leaf stomatal conductance and capacity of their hydraulic system to ensure continuity of flux from soil to leaves. The control of water losses (0.56*PAN-E) during the period of high vapour pressure deficit (May-June with PAN-E averaging 9.1 mm d^{-1}) was obviously due to stomata closures (Whitehead

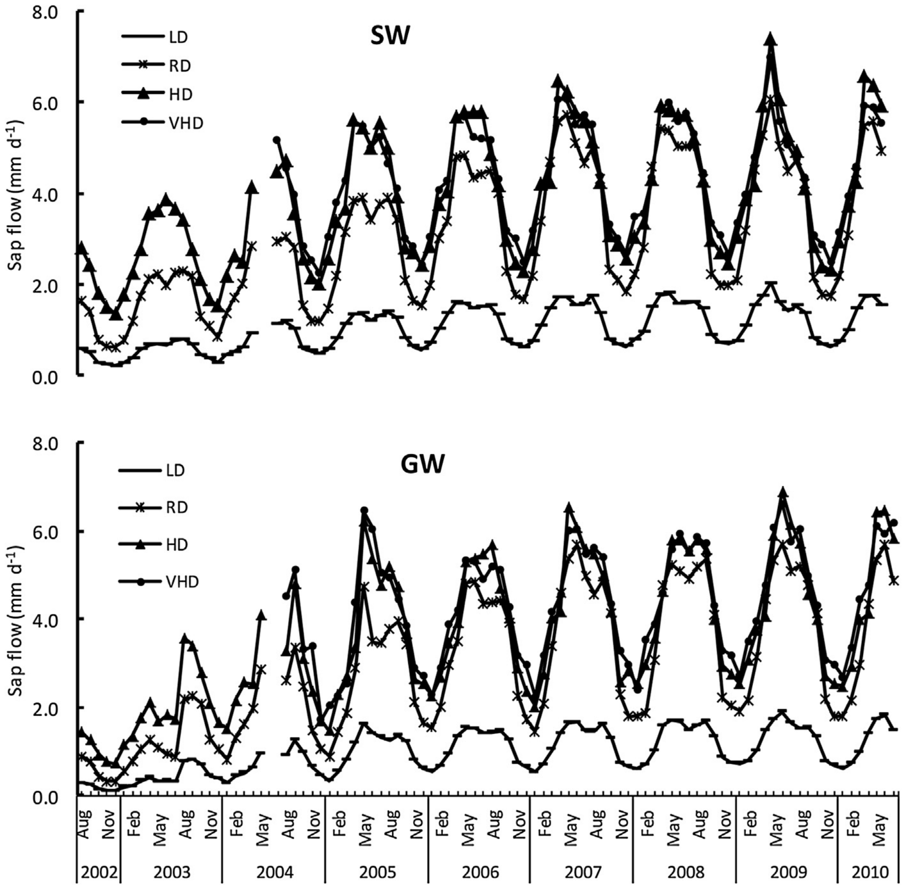

Fig. 5. Monthly average of mean daily sapflow values per hectare (mm d^{-1}) for sewage (SW) and groundwater (GW) irrigated plantations.

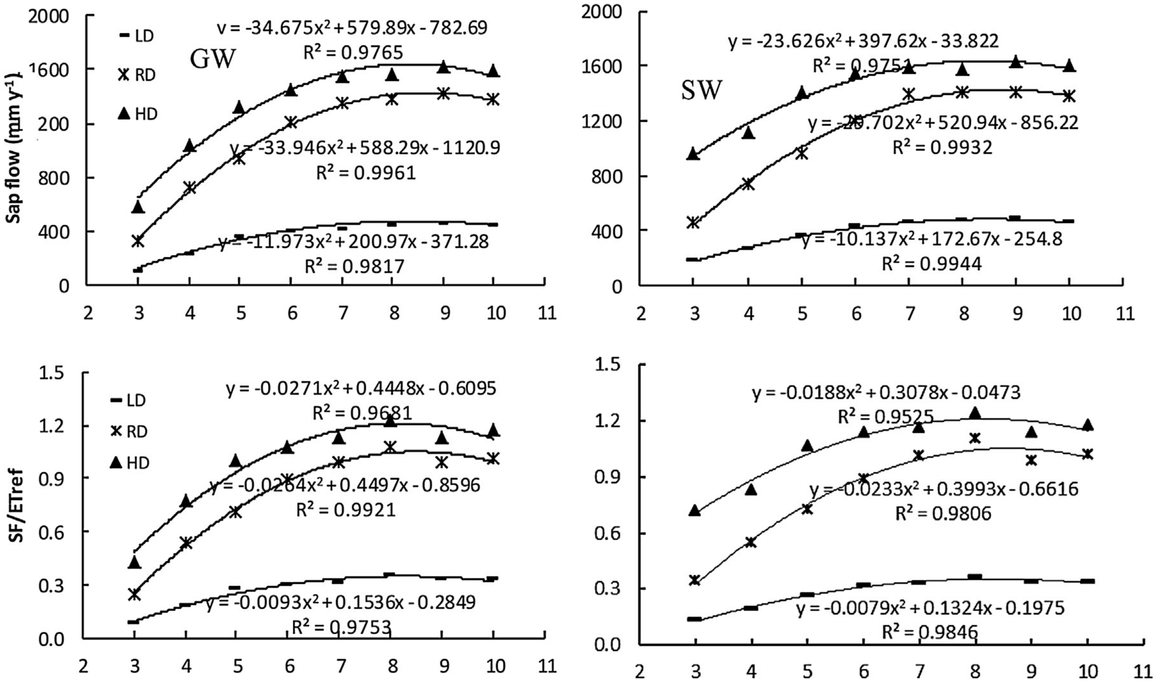

Fig. 6. Mean annual sapflow and the ratio of sapflow:ETref as a function of plantation age under different stocking densities.

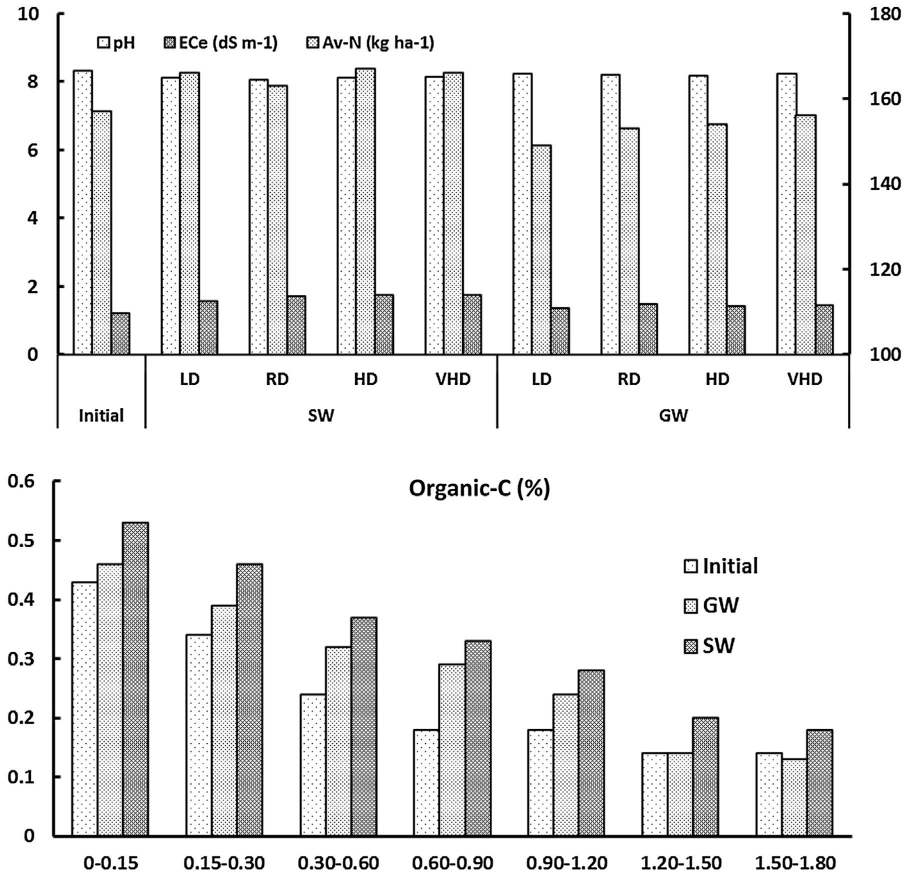

Fig. 7. Changes in soil properties after 10 years for sewage (SW) and groundwater (GW) irrigated plantations having different stocking densities.

and Beadle, 2004; Fonseca et al., 2007; Forrester et al., 2010; Aranda et al., 2012). A number of models have been tested for predicting plantation water use and the Penman–Monteith equation gave the best estimates since it considered the resistances imposed by canopy surface in regulating the evapo-transpiration (Myers et al., 1997). The predictions improved considerably when Penmen-Monteith method was used to compute ETref and related with sap flow values. The ratio of sap flow to ETref ranged between 0.87 and 1.24 with an average of 1.03. The second degree polynomials fitted for ratio of sap flow:ETref with growing period (Fig. 6) show that the ratio peaked at about 7–8 years of age and tended to decline thereafter. Similarly, Almeida et al. (2007) have earlier reported that Eucalypt plantations older than 5 years tend to reduce their water use mainly as a result of reduction in leaf area and growth in later stages of rotation. However, the maxima attained increased with stocking density and it was calculated to be 0.35, 1.1, and 1.23 under LD, RD and HD, respectively and thus indicating that improved growth of widely spaced individual trees under LD could not compensate water use of increased tree numbers under RD and HD. Water productivity (WP) for timber production was estimated as a ratio of timber produced and water use (sap flow) for 10 years. Total water use under each treatment was computed by cumulating the sap flow values monitored for 3–10 years of growth and those back calculated for years 1 and 2 from second degree polynomial passing through zero. On an average, about 575 L were required for producing one kg of timber, i.e. WP 1.74 kg m^{-3} water. WP increased with stocking density and it was calculated to be 1.54, 1.71 and 1.99 kg m^{-3} water in case of LD, RD and HD, respectively. Normally the WP of a particular tree plantation is known to vary according to the combination of site conditions, weather and tree age (Albaugh et al., 2013; Morris, 2005). The duration and frequency of water deficits are especially important which in turn are sensitive to year-to-year variations in rainfall and its distribution. Increased water availability because of irrigation and thus minimised water stress resulted in improvements in growth rates vis-à-vis WP. These WP values are almost 50–70% more than usually reported for rainfed Eucalyptus plantations under annual rainfall of 600–800 mm (Baker et al., 2005; Hubbard et al., 2010) and are similar to those reported from high rainfall (1147 mm) areas in Brazil (Almeida et al., 2007). Similarly, the water use efficiency (WUE), which is ratio of above ground biomass and total water use, i.e. applied irrigation water and effective rainfall, was calculated to be 0.37, 1.21, 1.80 and 0.84 kg m^{-3} for LD, RD, HD and VHD with GW, respectively whereas the counter values improved to 0.40, 1.38, 1.85 and 0.88 kg m^{-3} with SW. Thus the WUE increased by about 40% with HD and also with SW (11%) under RD.

3.3. Soil properties and carbon sequestration

One of the major constraints for sewage irrigation is its negative impacts on soil quality in terms of accumulation of heavy metal ions and the contamination of groundwater. However, the sewage utilised for this experiment was from domestic sources and its heavy metal contents were below the permissible limits. The changes in soil properties monitored after 10 years (Fig. 7) showed benefits in terms of lowering soil pH, improved contents of available nitrogen and phosphorus with marginal increase in salinity. The major benefit was incurred via improvement in organic matter that too down to almost 1.0 m depth. Amongst various tree parts, tree bole contributed more than 90% of the above ground C absorption and 61–71% of the total C absorbed (including below ground); while contribution of below ground biomass ranged between 23

Table 3
Carbon stocks (Mg C ha^{-1}) in Eucalyptus plantation irrigated with sewage (SW) and groundwater (GW) under different stocking densities.

Plant part	Carbon stocks (mg C ha^{-1}) at stocking density							
	Low		Recommended		High		Very high	
	GW	SW	GW	SW	GW	SW	GW	SW
Stem	22.4	24.6	73.9	78.4	110.0	114.0	92.8	97.7
Branches	1.0	1.0	3.2	3.2	4.7	4.7	4.0	4.1
Leaves and twigs	1.0	1.1	3.7	3.5	5.4	5.4	5.6	5.6
Above ground	24.4	26.7	80.7	85.0	120.2	124.1	102.4	107.4
Roots	10.2	11.9	33.3	36.8	31.7	32.0	41.9	46.3
Total	34.6	38.6	114.0	121.9	151.9	156.1	144.3	153.7

and 33% of the total C stock (Table 3) . Small branches, leaves and twigs contributed only 2.9 and 3.3% towards total C removal. The total C removed was about 7% more in plantation irrigated with SW. The C sequestered per tree was more in LD and RD compared with HD and VHD and the differences increased with age of the trees. In spite of better C removal per tree in lower densities, total C absorbed per hectare increased with stocking densities While increasing tree density can increase carbon storage, raising densities too high can reduce net C absorption due to an increase of suppressed trees (Naidu et al., 1998). Therefore, at the age of 10 years, C sequestered by HD exceeded than in case of VHD mainly because of poor growth rate. Pérez-Cruzado and Rodríguez-Soalleiro (2011) also reported lower carbon storage rates associated with larger plantation densities. Total C stocked in 10 year old Eucalyptus plantations was 38.6, 121.9, 156.1 and 153.7 mg ha^{-1} in LD, RD, HD and VHD respectively under sewage irrigation with mean annual increment of C absorption rate of 3.5, 12.0, 13.9 and 7.0 mg y^{-1} compared over 3 year old plantation. Whereas in case of groundwater irrigation, respective total C stocked was 34.6, 114.0, 151.9 and 144.3 mg ha^{-1} with mean annual increment of 2.9, 11.1, 13.7 and 6.7 mg C ha^{-1} y^{-1}. Similarly, the mean annual increments of total above ground carbon absorption rates were 2.4, 8.1, 11.3 and 3.9 mg C ha^{-1} y^{-1} for LD, RD, HD and VHD under sewage irrigation and 2.0, 7.7, 11.2, 4.3 mg C ha^{-1} y^{-1} under groundwater irrigation, respectively. Similar mean annual increment of total above-ground carbon absorption rates (4.7–6.7 mg ha^{-1} y^{-1}) for varying plantation density of *Eucalyptus globules* from 733 to 1300 trees ha^{-1} were observed at different sites in Uruguay (Vallejos et al., 2014) while carbon stock in *E. tereticornis* plantations per ha with tree density of 200 trees ha^{-1} was estimated to be 6.1, 11.9 and 16.6 mg ha^{-1} for 6, 8 and 10-year-old plantations in Western part of India (Rizvi et al., 2012).

4. Conclusions

The results of this long term study highlighted the strong effects of sewage irrigation and stocking density in enhancing growth, water use and timber productivity of Eucalyptus plantation. The effluent loads, even the high stocking density could carry almost matched the reference evapo-transpiration but Eucalyptus plantations showed the advantage over land disposal in terms of ~1.5 fold and year round sewage water usage. Hence, it can be stated that Eucalyptus plantations can act as potential sites for sewage disposal but cautions, rather regulatory mechanism should be devised to control loading rates since these are not as profligate consumers of water as has been claimed.

Acknowledgements

Experiment was a part of the Mission Mode Project “Use of urban and industrial effluents in agriculture' funded under National Agricultural Technology Project by Indian Council of Agricultural Research, New Delhi. The financial help is thankfully acknowledged. The authors are also grateful for the technical help and assistance rendered by Sh. N.S. Ahalawat, Sh. Jagdish Arora, Sh. Ajay Kumar and others from CSSRI, Karnal.

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