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Biomass production, carbon sequestration and water transmission properties as influenced by densified plantations raised on old river bed lands in the north west Himalayas

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ABSTRACT

Old river bed lands in the North West Himalayas have generally been utilized for the production of fodder and firewood but its quantative biomass production and resource (carbon and water) conservation potential have not been worked out. Plantations of three tree species-*Grewia optiva* Drumm, *Bauhinia variegata* L. and *Dalbergia sissoo* Roxb.were raised during 1996, at 2x2m (close), 3x2m (medium) and 4x2 m (wide) spacings and were thinned mechanically at the age of 7, 12 and 15 years. The performance of *D.sissoo* was the best with trees attaining an average height of 9.87 m and 10.3 m in the 7th year and 12th year, respectively. *G.optiva* trees attained an average height of 5.67 m and 6.20 m at the same age. Foliage (as fodder) availability from annual prunings in *G.optiva* declined from the 11th year and woody biomass from the 8th year. More woody biomass was obtained at medium spacing and that of foliage at close spacing. First thinning in the 7th year yielded 54.70, 20.45 and 13.65 t ha^{-1} of woody biomass at close spacing in *D.sissoo*, *G.optiva* and *B.variegata*, respectively, followed by production from medium and wide spacing. During the 2nd thinning at the 12th year, maximum woody biomass (100.50 t ha^{-1}) was obtained from *D.sissoo* at medium spacing followed by 53.43 t ha^{-1} from *G.optiva* at wide spacing and 34.94 t ha^{-1} from *B.variegata* at medium spacing. Annual rate of increase of SOC in the 0-45 cm soil depth ranged from 502 to 1410 kg C ha^{-1}. The humification rate was determined to be 0.195. Carbon sequestration rate varied from 1.32 to 0.55 t ha^{-1} yr^{-1} and followed the trend of *D.sissoo* < *B.variegata* < *G.optiva*.

1. INTRODUCTION

Increasing demographic pressure along with a large grazing animal population and absence of scientific land use practices has led to serious land degradation problems in India. Nearly 32.67% of India's geographical area is affected by various forms of soil erosion and land degradation. The area reported to be degraded in India varies widely, ranging from 63.9 m ha (Anonymous, 2000) to 187.70 m ha (Sehgal and Abrol, 1994), due to variations in approaches used to define degraded lands. The area under wastelands is estimated to occupy 63.85 m ha, which is 20% of the country's geographical area. The per capita land availability in India has steadily declined from 0.89 ha in 1951 to 0.37 ha in 1991 and is expected to be only 0.20 ha by 2035 (Singh, 2005).

Nearly 80% of the wood in developing countries is consumed as fuel, while in the developed countries the same quantity is used for industrial uses (Goodman 1986). Estimates indicate that by 2025, the demand for green fodder in India would be about 1170 m tones, which is three times the existing supply of 411 m tonnes. Firewood continues to be a major source of energy for domestic use in India. Current production of firewood from forest areas is 98 m tonnes and a net deficit of 86 m tonnes is obtained illicitly from forest areas, leading to irreversible damage to forest ecosystems all over the country and hydrological imbalances in the mountainous regions.

Forests dominate terrestrial biosphere C cycle to their large C pools (phytomass and soil organic carbon) and associated fluxes. The energy captured in molecular bonds of carbon compounds generally represent 2-4% of the radiation absorbed by a tree canopy (Edwards *et al*., 1981). Vegetation and soil represent potential sinks for additional carbon (Winjum *et al*., 1992) and reforestation has been suggested as a possible means of mitigating global warming and to increase carbon level of tropical soils. A preliminary estimate of carbon fluxes in India was prepared by Dadhwal and Nayak, 1993; the litter fall carbon flux in various forest ecosystems determined by Dadhwal *et al*., 1997, while this flux in plantations of ten important species spread over 26 locations was estimated by Raizada *et al*. (2003). The storage and flux of organic carbon in *T. grandis* plantations in moist deciduous forests in the Terai region has also been estimated (Jha, 2005). More recently, Shah *et al.* (2013) estimated the carbon stock and carbon density in soils under *Pinus roxburghii* Sargent at 33 locations in Himachal Pradesh. Chaturvedi and Melkania (2012) evaluated the Roth C-26.3 model to predict the turnover rate of soil organic carbon in different forest soils in the Kumaon Himalayas.

The use of degraded lands to grow site suitable trees and grasses in various land use combinations have been proposed by several workers. Wastelands in India could be used for sequestering carbon by growing trees and grasses, which could sequester 0.84 and 1.06 Pg of carbon in vegetation and soil, respectively (Gupta and Rao 1994). Reduction in concentration of carbon dioxide (CO_2) in the atmosphere can be achieved by reducing the demand for energy, by altering the way energy is used and by increasing the removal of the atmospheric CO_2 through carbon sequestration (Rawat, 2005). Minor changes in the soil C pool can have important implications on C balance. Soil organic matter (SOM) greatly influences water transmission properties (Bhattacharya *et al*., 2009) which subsequently reduces surface run off and consequent land degradation.

Production of pulpwood for the paper industry through short rotation forestry (SRF) is widely practiced in many countries using intensive management techniques - Aspen coppice under SRF have been investigated in Germany (Liesebach *et al*., 1999), biomass production and C sequestration in poplar in China (Fang *et al*., 2007) and *Eucalyptus* under SRF in New Zealand (Ralph *et al*., 2001). The carbon storage potential of SRF in tropical trees has been reported by Schroeder (1992). In India, there have been a number of studies on biomass production from forests and plantations but very few studies on biomass production from high density plantations and SRF which had been raised on degraded lands. The productivity of *Acacia farnesiana*, *Acacia nilotica* subsp. *cupressiformis*, *Cassia siamea* grown in a highly alkaline soil site have been determined (Goel and Behl, 2004), that of *Terminalia arjuna* under different densities in sodic soil conditions (Srivastava *et al*., 1999), and biomass production from three clones of *Populus deltoides* (Singh, 1998). Biomass production from three species in arid environments in Rajasthan has also been reported (Singh and Toky, 1995).

In the foothills of the Western Himalayas, large areas are categorized as bouldery wastelands which have been formed due to the deposition of huge amounts of coarse soil forming material that has been brought down by seasonal torrents originating in the higher reaches. Deforestation, faulty land use practices and road construction in the upper reaches lead to soil displacement, which moves down the slopes and is deposited in the foothills in the form of gravel bars with coarser fractions spreading out over the original soil layers. Recent surveys indicate that the area affected by these deposits is about 2.73 m ha in the Himalayan foothills and 0.3 m ha occur in Doon Valley alone (Arora and Vishwanathan, 1995). Large areas of this type of land occur in the vicinity of villages along rivers and provide no economic returns. This study aims to develop practices to utilize these unproductive lands for the production of firewood and fodder using three trees species raised at close spacings and also to determine the carbon sequestration potential of these plantations and water transmission properties of soil.

2. MATERIALS AND METHODS

Location

The study was initiated in July, 1996 and the plantation was raised at the research farm of the C.S.W.C.R.T.I., Dehra Dun (30°19'N Lat and 78°02'E Long) at an elevation of 517 m a msl. Long term annual rainfall is 1646 mm received in about 82 rainy days. Summers are hot and dry while winters are quite cold (average 4.4°C) with occasional frost in January. The rainfall received during the study period averaged 1483.75 mm, with nearly 80% received during the monsoon period (July to September) and the rest during December-January (Fig.1). Vegetative growth of almost all

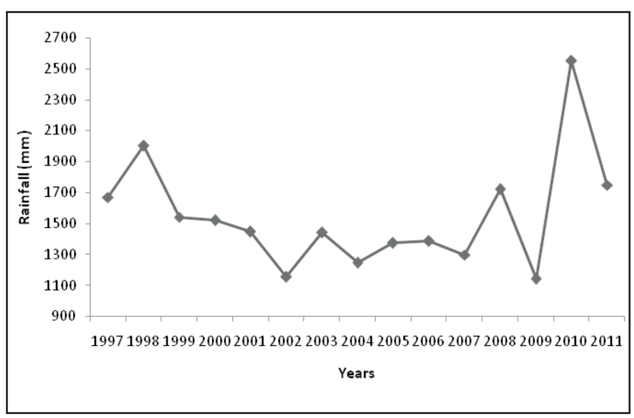

Fig.1. Trends of annual rainfall (mm) at the study site

plant forms takes place during the rainy season (July to September) with drought like condition experienced frequently during the hot Summers (April to June) and plants remain dormant during the winter season which are quite cold (Nov. to Feb.).

Soil Characteristics

The experimental site is an old riverbed wasteland and soils have been classified as sandy skeletal Typic Ustifluvent soils (Bharadwaj and Singh, 1981). Infiltration rates at these sites are high (2.13 to 3.0 cm hr^{-1}), which is due to their sandy soil texture and a permeable stony layer at lower depths of the profile. Gravels of sizes ranging from 0.2 to 10 cm constitute 60% of the total weight of the contents excavated from a one cubic meter pit. A detailed description of the soil conditions have been described earlier (Raizada *et al*., 2002).

Plantation Establishment

Three important tree species of the subtropical N.W. Himalayas were selected for the study. *Grewia optiva* (Drumm.) (Vern. *Bhimal*) and *Bauhinia variegata* L. (vern. - *Kachnaar*) are popular tree species of the region and grow over a wide range of situations (subtropical to sub-temperate). All parts of the tree are used and the species is usually retained on terraces formed on hill slopes. *Dalbergia sissoo* Roxb. (vern.-*Shisham*) is an important species of the subtropical region and is a primary colonizer in riverine sites. Quality timber from the tree is obtained when the trees are >60 years old, poor quality timber and poles are used as firewood and for agricultural implements. Young succulent leaves are eaten as fodder.

Plantation establishment activities were initiated in July 1996 over an area of 1.6 ha after scrub clearing and minor land leveling with tractor drawn implements. Pits of size $60cm^3$ were manually excavated as per experimental design at close (2x2 m; 2500 ha^{-1}), medium (3x2 m; 1666 ha^{-1}) and wide (4x2 m; 1250 ha^{-1}) spacing in separate plots (16m x 16m), which were randomly distributed over the area and were replicated three times. Row to row spacing was kept uniform to allow for the movement of shrub/weed clearing machinery. The number of seedlings which were planted in these plots was 64, 42 and 32 at close, medium and wide spacing, respectively.

One year old healthy seedlings of these three species were obtained from the state forest department and were planted in the excavated pits. Seedlings were firmly pressed back into the soil and staking carried out to keep the seedlings straight. The plantation was maintained under rainfed conditions and mortality replacement was completed in the first year. Annual tending and weeding were carried out before and after the monsoons and seedlings were kept disease free.

Measurement of Seedling Growth and Annual Prunings

Measurement of seedling height (m), collar diameter (CD, cm) diameter at breast height (dbh, cm) was done in November 1996 in the first year to give time for seedlings to establish themselves and increase their dimensions. Subsequently this was done every year during the month of October, when biomass accretion had ceased in the post-monsoon period. Fifteen nearly equal seedlings were randomly selected and tagged for measurements and average values have been reported. Collar diameter and dbh were measured using vernier calipers and height was measured using a calibrated staff. Annual pruning (during November) was initiated in the 4th year, with the sole objective of obtaining clean poles/stems of all the species, reduce the number of multiple shoots and side branches that often lead to deformed crooked stems. All side shoots were cleanly removed using a sharp axe and all branches removed up to a height of 1.5 m from the ground level. Components were segregated into green and non-green (woody) biomass and weighed at the site. A representative sample of woody material was oven dried at 70^{o}C till constant weight and dry weight recorded.

Thinning of Stands

The first, second and final thinning was carried out during 2003, 2008 and 2011, when the plantation was 7, 12 and 15 years old, respectively. During the first thinning every alternate tree in each row was harvested irrespective of its wider spacing were harvested, while in the final felling any tree (irrespective of growth) left in each plot after the first two harvests was harvested. Trees were removed by clear felling 10-12 cm from the ground level, making clean cuts using manually operated saws. After felling, each tree was measured for stem length and components like leaves, branches (with twigs) and bole (with bark) were separated and fresh weight recorded. Representative samples were oven dried at 70^{o}C till constant weight and dry weight estimated. Further calculations were carried out to convert per tree values into per hectare values.

Carbon Storage in Plants

Carbon concentration**:** Carbon concentration was determined by dry combustion method. Oven dry samples were grinded and 20 g of the powder sample was taken in a silica crucible. The powdered material was then burnt in a muffle furnace at 600^{o}C for 4-5 hours for obtaining ash. Carbon determined by this process was 50% of ash free dry mass.

Carbon Stock in Plants

Carbon stock in different plant component was obtained by multiplying the dry weight of the different plant components by their average carbon concentration. The carbon stock in different plant components was then summed up to obtain total carbon stock

Long Lived Carbon Storage

The exact life time of wood products is poorly known, but a reasonable assumption is that the life span is at least equal to the rotation length. The proportion of stem wood used as "long lived" product is estimated to be 42%. Long lived carbon storage was estimated by the method of Wang and Feng (1995) Long lived C storage = Carbon mass in stem wood x 42%.

Sampling Leaf Litterfall and Fine Roots

The surface area under each tree species was divided into 5 equal parts and litter traps of size 1 m x 1 m were randomly placed in parts of the stand and spacings. All together, 27 litter traps were used for collection of leaf biomass between August, 2007 and July, 2008 on 15 days interval. We estimated the annual mass litterfall as the sum of the litterfall collected fortnightly during the study period. Sequential coring was done to determine fine root mass. Although, sequential soil core method may lead to some underestimation in the fine root production (Makkonen and Helmisaari, 1999), it is one of the most widely used methods because it estimates directly fine root biomass (Hertel and Leuschner, 2002). The dry biomass of the litterfall and fine root were utilized for the determination of carbon content through dry combustion method.

Soil Sampling and Analysis

After 9 years of plantation establishment, soil samples were collected from different species and spacing in three replicates and composite samples were prepared. A reference soil samples (without trees and litter fall) from a nearby place was also collected and analyzed for desired soil properties. Oxidizable soil organic carbon (SOC) was determined by the method of Walkely and Black (1934) and total SOC by dry combustion method. Core sampler was used for the determination of bulk density, saturated hydraulic conductivity following constant head method, infiltration characteristics through double ring infiltrometer, sorptivity and transmissivity with Philip's model (Philip 1957) were determined which is as follows:

$$I(t)=St^{½}+At$$

$$q(T) = ½St^{-½}+A$$

Where, I(t)= Cumulative infiltration (cm) rate, q = Infiltration rate (cm min^{-1}), t = time (minutes), S = soil water sorptivity (cm /$min^{1/2}$) ; A=constant (cm/h).

Carbon Sequestration in Soil and Relationship between Addition and Storage

The relationship between C addition to the soil by different sources and storage within in the soil was determined. The rate constant of annual C inputs incorporated into SOM (h) and decay rate constant (k) of native SOC were calculated from the equation of Jenkinson (1988) assuming a single pool first order kinetic relationship between C addition and storage-

$$dcs/dt = h\,A – k\,SOC$$

Where SOC is the soil organic C, t is the time and A is annual input to soil. For computing the A value, we assumed that whole amount of biomass C from leaf litter fall and fine root turn over remained within 0-45 cm soil layer. Soil organic carbon sequestration was calculated as follows (Aulakh *et al.,* 2001):

$$\text{Organic C sequestration} = \frac{\text{SOC(t C ha}^{-1}\text{ treatment-Soc (t C ha}^{-1}\text{)initial x100}}{\text{SOC(t C ha}^{-1}\text{)initial}}$$

3. RESULTS AND DISCUSSION

Seedling Growth under Different Spacings

The first measurement of seedlings planted in August ,1996 was taken in November and the second during October, 1997, when the plantation was one year old (seedlings were two years old). *G.optiva* seedlings reached an average diameter of 0.92 cm in the first year, which increased to 1.92 cm in the 2^{nd} year and by the 12^{th} year had attained average dbh values of 7.32, 8.32 and 8.66 at close (2x2), medium (3x2) and wide (4x2m) spacings, respectively. In general, seedlings at wider spacings comparatively attained greater diameters (Fig.2b). In *B.variegata*, initial seedling growth was slow but improved in the 4^{th} year. Average seedling diameter over three spacings was 0.94, 1.1 and 1.6 cm at the end of the 3^{rd} year. By the end of the 12^{th} year, seedling diameters were 9.7,11.3 and 11.9 cm, at the same spacing sequence, respectively (Fig.2a), the differences being statistically significant ($P<0.05$).

The performance of *D.sissoo* was satisfactory, with the site conditions being conducive for the growth of seedlings, since the species is a primary colonizer in rivereine sites. Seedling diameters in the first year averaged 1.65 cm, which increased to 8.1, 8.95 and 9.55 cm at the 7^{th} year and further increased to 12.1, 12.25 and 13.80 cm at the end of the 12^{th} year, at close, medium and wide spacings, respectively at both the ages (Fig.2c). The differences in dbh were significant at both the ages and spacing ($P<0.05$).

Seedling height progressively increased in all the species at all the three spacings. In *G.optiva* seedling height increased from the 2^{nd} year and continued to increase till the 7^{th} year (increase of 86% over the 1^{st} year) after which increment was slow. By the 7^{th} year average height was recorded as 5.67m which reached 6.20 m by the 12^{th} year (Fig.3a). In *B.variegata*, seedling height increment was slow with an increase of 0.90 m in the 1^{st} year to 4.02 m in the 7^{th} year (Fig.3b) after which there was only a marginal increase. By the end of the 12^{th} year, *B.variegata* trees had an

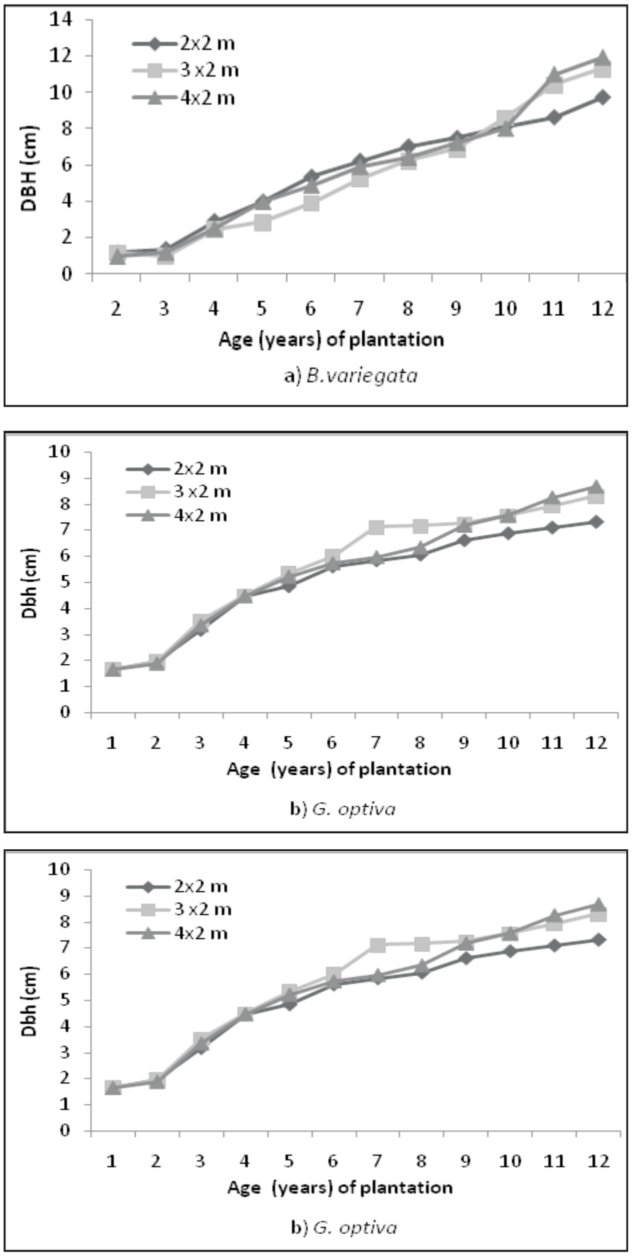

Fig. 2. Trends of increase in dbh (cm) of three species at three spacings raised on old river bed lands in the NW Himalayas

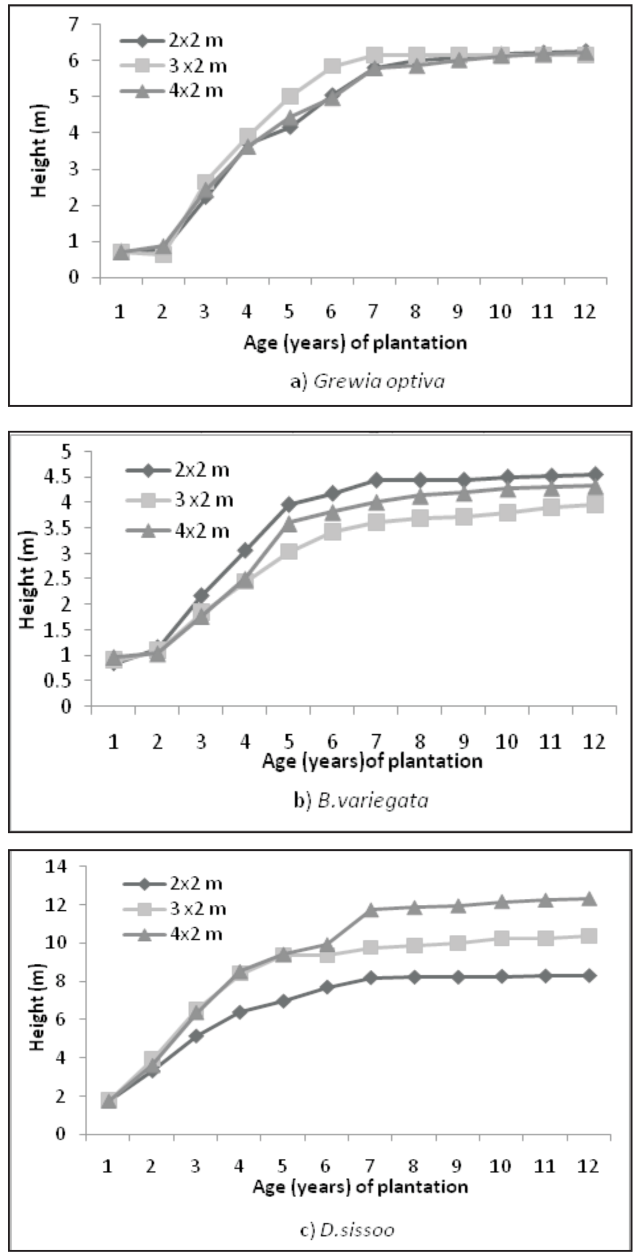

Fig. 3. Trends of increase in seedling height (m) of three species at three spacings raised on old river bed lands in the Himalayas

average height of 4.55, 3.98 and 4.33 m at 2x2 m, 3x2 m and 4x2 m, respectively. Top dying due to frost damage was noticed in several *Bauhinia* trees, which might have led to changes in the actual height the trees would have attained.

D.sissoo seedlings attained an average height of 1.75 m at the end of the 1st year, 9.87 m by the 7th year and by the end of the 12th year trees were 8.28 m, 10.36 m and 12.30 m tall at close, medium and wide spacings (Fig.3c), respectively. Trends indicate that *D.sissoo* seedlings placed at wider spacing were taller than those at close spacing, the differences being significant (P>0.05).

Biomass Production from Annual Prunings

Annual prunings were carried out for the first time in the 4th year. Perusal of Table 1 reveals that foliage biomass obtained in *G.optiva* stands at the three spacings was lower than the woody biomass. Highest quantity of woody biomass was obtained from trees growing at medium spacing followed by wide and close spacing. From the 8th till the 11th year, foliage biomass obtained from prunings increased, while woody biomass decreased due to the emergence of a number of small soft tissued branches with large number of leaves. Differences in the quantity of

Table: 1
Biomass (t ha^{-1}) obtained from annual prunings of three species at three spacings raised on old river bed lands in the N W Himalayas.

Species	Spacing (m)	Component	Age of plantation (years)									
			4	5	6	7	8	9	10	11	12	Total
G.optiva	2x2	Green Leaves	0.412	0.575	0.353	0.562	1.0	1.42	1.35	2.20	0.63	8.502
		woody	3.022	5.78	3.54	3.35	4.0	0.35	0.76	2.63	1.19	24.622
	3x2	Green Leaves	0.286	0.643	1.63	1.24	0.89	1.07	1.02	1.0	0.87	8.65
		woody	4.53	6.19	3.92	3.26	3.90	1.86	0.72	1.76	1.43	27.57
	4x2	Green Leaves	0.25	0.562	0.30	0.52	1.01	0.80	0.86	0.37	0.265	4.937
		woody	1.46	4.0	3.86	4.38	6.01	1.972	1.02	1.64	0.64	24.982
B.variegata	2x2	Green Leaves	0.332	0.612	0.240	0.68	1.07	2.66	1.27	2.42	0.036	9.32
		woody	0.785	3.00	1.77	1.84	2.85	3.60	0.88	3.33	0.087	18.142
	3x2	Green Leaves	0.238	0.354	0.140	0.46	0.768	1.13	0.86	2.35	0.26	6.56
		woody	1.038	4.726	1.44	1.52	1.83	2.01	0.46	3.02	0.145	16.189
	4x2	Green Leaves	0.235	0.446	1.22	0.82	0.50	1.236	1.12	1.40	0.053	7.03
		woody	0.278	2.207	2.18	2.02	2.07	1.61	1.68	2.95	0.045	15.04
D.sissoo	2x2	Green Leaves	-	-	-	-	-	-	-	-	-	-
		woody	-	2.35	2.61	1.32	1.83	-	-	-	-	8.11
	3x2	Green Leaves	-	-	-	-	-	-	-	-	-	-
		woody	-	5.84	4.32	1.44	1.78	-	-	-	-	13.38
	4x2	Green Leaves	-	-	-	-	-	-	-	-	-	-
		woody	-	5.51	4.64	1.02	1.73	-	-	-	-	12.90

pruned material obtained were statistically insignificant over years. No correlation was observed between foliage production and annual rainfall received over the years.

In *B.variegata*, biomass of pruned foliage was lower than the woody biomass in the initial years and no clear cut trend was observed over spacing or years. Over a period of 12 years, total green leaf fodder production (t ha^{-1}) was 9.32, 7.30 and 6.56 at close, medium and wide spacing, respectively (Table 1), while the total woody biomass (from prunings) was 18.14, 16.18 and 15.04 t ha^{-1} at the same spacing sequence. Foliage production was marginally correlated with annual rainfall (r^2= 0.501).

In case of *D.sissoo*, woody prunings were available only from the 5th year (average of 4.56 t ha^{-1}) which declined to 1.78 t ha^{-1} by the 8th year. By this time, most of the trees at all spacings had developed long clean boles and no pruning was necessary. Leaf shedding had been completed by the end of November, since the species is winter deciduous.

Biomass Production from Mechanical Thinnings

Fodder and firewood production from three spacings at two thinning intervals and the final felling are presented in Table 2. Perusal of table reveals that the maximum firewood production from all thinning was obtained from *D.sissoo*, followed by *G.optiva* and *B.variegata.*

At the age of 7 years when the first thinning was carried out, *G.optiva* trees had attained an average dbh of 5.98, 6.80 and 6.25cm at close, medium and wide spacings, respectively and an average height of 6.03 m. Leaf biomass as % of woody biomass was 26.1, 45 and 46.2 at the same spacing sequence, respectively, indicating increased phytomass at wider spacing, although the branch and twig biomass (t ha^{-1}) and their % contribution to total above ground biomass declined from 64.6% at 2x2 m to 27% at 3x2 m and 18.2% at 4x2 m spacing. Firewood biomass at close, medium and wide spacing was estimated to be 20.45,19 and 21.19 t ha^{-1}. By the time of the 2nd thinning at 12 years, the maximum quantity of firewood was obtained at wide spacing (53.4 t ha^{-1}) followed by close spacing (44.37 t ha^{-1}) and then from medium spacing (29.91 t ha^{-1}).

The remaining trees at the three spacings were harvested at the age of 15 years and highest biomass was recorded at close spacing (21.27 t ha^{-1}) followed by wide (19.88 tha^{-1}) and then medium spacing (11.64 t ha^{-1}). At this age, leaf biomass was 16.5% of the total woody biomass at close and medium spacing and only 7.6% at wide spacing.

In *B.variegata*, the average tree height attained during the 1st thinning (at 7 years) was 4.02 m while average dbh were 6.21, 5.20 and 5.73 cm at close, medium and wide spacing, respectively. Differences in tree diameter at breast height between the three spacings were significant ($P<0.05$). Fodder biomass was highest at close spacing and least at wide spacing during the first thinning but at the time of the 2nd thinning, highest leaf biomass was available at medium spacing (7.28 t ha^{-1}) but branch biomass (as % of stem biomass) was highest at close spacing and least at wide

Table: 2
Tree dimensions and biomass production (t ha^{-1}) from three species at three spacings raised on old river bed lands in the NW Himalayas during three thinning intervals

Species	Spacing(m)[a] at the time of planting	Thinning	Spacing after thinning	Dimensions*		Biomass production**			
				Dbh (cm)	Height (m)	Green Leaf	Branch & twig	Bole	Firewood
G.optiva	2x2	I[st]	2x2	5.98	5.80	5.35	8.03	12.42	20.45
	3x2		3x2	6.80	6.10	8.54	4.04	14.96	19.00
	4x2		4x2	6.25	6.21	3.07	2.86	14.10	16.96
	2x2	2[nd]	4x2	7.32	6.0	11.25	13.75	30.62	44.37
	3x2		6x2	8.30	6.14	3.93	12.86	17.04	29.91
	4x2		8x2	10.66	6.21	8.20	23.95	29.48	53.43
	2x2	Final	4x4	6.00	6.50	3.57	3.15	14.55	21.27
	3x2		6x4	7.42	7.00	1.92	1.62	7.89	11.64
	4x2		8x4	6.73	6.90	1.51	1.37	17.00	19.88
B.variegata	2x2	I[st]	2x2	6.21	4.44	7.20	2.21	11.46	13.67
	3x2		3x2	5.20	3.62	4.75	1.15	6.83	7.98
	4x2		4x2	5.73	4.02	2.62	0.61	4.78	5.40
	2x2	2[nd]	4x2	9.70	4.55	1.40	10.85	22.26	33.11
	3x2		6x2	11.30	3.98	7.28	10.56	24.38	34.94
	4x2		8x2	11.93	4.33	2.88	7.80	21.63	29.43
	2x2	Final	4x4	5.20	4.13	1.83	1.62	7.70	11.15
	3x2		6x4	4.93	4.00	0.23	0.56	4.93	5.72
	4x2		8x4	5.46	3.45	0.34	4.64	1.62	6.60
D.sissoo	2x2	I[st]	2x2	8.02	7.63	2.90	6.90	47.80	54.70
	3x2		3x2	9.36	7.90	8.80	5.86	32.80	38.65
	4x2		x2	9.55	7.71	7.55	5.30	31.75	37.05
	2x2	2[nd]	4x2	12.10	8.20	-	20.76	67.06	87.82
	3x2		6x2	12.25	8.13	-	41.34	59.15	100.50
	4x2		8x2	13.80	8.23	-	25.70	48.0	73.70
	2x2	Final	4x4	9.83	8.60	-	2.90	3.66	6.56
	3x2		6x4	11.10	8.44	-	1.67	6.92	8.60
	4x2		8x4	11.50	8.60	-	4.64	6.96	11.60

*All values are average of 10 trees harvested in each plot; ** All values are oven dry weight except leaves which are weighed green; 1[st] thinning at 7 years, 2[nd] at 12 years and final at 15 years; [a]tree densities are 2500, 1666 and 1250 at 2x2, 3x2 and 4x2 m spacing, respectively. After 2[nd] thinning, the densities ha^{-1} are 1250, 833 and 625 at spacings of 4x2, 6x2 and 8x2 m; at the final felling stage, the densities ha^{-1} are 625, 416 and 312 at spacings of 4x4 6x4 and 8x4 m, respectively.

spacing, indicating reduced foliage development at close spacing. At the first thinning, maximum woody biomass was obtained from trees at close spacing (13.67 t ha^{-1}) while during the 2[nd] thinning maximum biomass was obtained from trees at medium spacing (34.94 t ha^{-1}). During the last felling cycle, the maximum woody biomass (11.15 t ha^{-1}) was obtained from trees at close spacing. The total amount of woody biomass obtained from this species was 57.93, 48.64 and 41.43 t ha^{-1} at close, medium and wide spacing, respectively.

Growth and biomass accretion in *D.sissoo* was the maximum at all the three spacings, since site conditions were conducive for the species, which is a primary colonizer on riverine sites. Average tree diameter (dbh) and height at the age of 7 years across the three spacings were 8.97cm and 7.74 m, respectively. Branch biomass as % of stem biomass averaged 16% with non-significant differences among spacings. Firewood (stem and branch biomass) production was highest at close spacing and nearly similar at the other two spacings (Table 2). At the age of 12 years, average tree diameters were 12.71 cm, with the highest diameter (dbh) of 13.80 cm and height of 8.18 m being recorded at wide spacing. At the age of 15 years when final felling was carried out, the diameters averaged 10.81 cm and height 8.54 m.

Firewood production during the 1st thinning was highest at close spacing (54.70 t ha^{-1}) with the bole biomass contributing 86% of the total biomass. By the time of the 2nd thinning, the highest firewood production was obtained from medium (3x2m) spacing (100.50 t ha^{-1}) followed by 87.8 and 73.7 t ha^{-1} at close and wide spacing, respectively. Branch biomass of *D.sissoo* trees as % of stem biomass averaged 16.3% during the first thinning which increased to 51.5% by the 12th year. The percent contribution of branch biomass to stem biomass was least at close spacing and highest at medium spacing, indicating enhanced vertical growth at close spacings. Contribution of bole biomass to total firewood production ranged between 60-76%, the remaining being contributed by the branch biomass.

Carbon Stock in Tree Biomass

Carbon concentration in tissues depends upon the ash content in different components. Carbon concentration in the above ground components varied between 33.6-44.6%, with higher values in woody material and lower in green leaves (Table 3). Carbon storage is directly proportional to biomass of different tree components at the three spacings (Table 4). At the first and second harvesting stage, the trends of carbon accumulation was *D.sissoo*>*G.optiva*> *B.variegata*. However, the average increase in carbon stock between 7 and 12 years was highest in *G.optiva* followed by *B.variegata* and *D.sissoo,* indicating that biomass accretion in *D.sissoo* was fairly rapid in the initial years while in the other two species growth and biomass accretion rate increased during the later years.

Table: 3
Carbon content (%) of tissues of different species

Species	Components				
	Leaf	Branches	Twigs	Stem	Bark
G.optiva	36.5	45.30	43.8	44.6	42.7
B.variegata	33.6	37.95	38.31	43.10	35.40
D.sissoo	34.7	40.16	39.42	44.60	39.8

Table: 4
Carbon stock (t ha^{-1}) in three species at three spacings raised on old riverbed lands in the NW Himalayas during three thinning intervals

Species	Spacing(m)[a]	Thinning	Tree component			
			Leaves	Branch and twig	Stem	Total
G.optiva	2x2	Ist	1.95	3.63	5.54	11.12
	3x2		3.11	1.83	6.67	11.61
	4x2		1.12	1.29	6.28	8.69
	4x2	2nd	4.10	6.22	13.65	23.97
	6x2		1.43	5.82	7.60	14.85
	8x2		2.99	10.41	13.14	26.54
	4x4	Final	1.30	1.42	6.49	9.21
	6x4		0.70	0.70	3.52	4.92
	8x4		0.55	0.60	7.58	8.73
B.variegata	2x2	Ist	2.41	0.84	4.92	8.17
	3x2		1.59	0.43	2.93	4.95
	4x2		0.88	0.23	2.05	3.16
	4x2	2nd	0.47	4.12	9.57	14.16
	6x2		2.44	4.01	10.48	16.93
	8x2		0.96	2.96	9.30	13.22
	4x4	Final	0.06	0.61	3.32	3.99
	6x4		0.07	0.21	2.12	2.40
	8x4		0.11	1.76	0.70	2.57
D.sissoo	2x2	Ist	1.00	2.76	21.31	25.07
	3x2		3.05	2.34	14.63	20.02
	4x2		2.60	2.12	14.16	18.88
	4x2	2nd	-	8.30	29.91	38.21
	6x2		-	16.53	26.38	42.91
	8x2		-	10.28	21.40	31.68
	4x4	Final		1.16	1.63	2.79
	6x4			0.67	3.08	3.75
	8x4			1.86	3.10	4.96

1st thinning at 7 years, 2nd thinning at 12 years, Final felling at 15 years; [a]tree densities are 2500, 1666 and 1250 at 2x2, 3x2 and 4x2 m spacing, respectively. After 2nd thinning, the densities ha^{-1} are 1250, 833 and 625 at spacings of 4x2, 6x2 and 8x2 m; at the final felling stage, the densities ha^{-1} are 625, 416 and 312 at spacings of 4x4, 6x4 and 8x4 m, respectively.

Table : 5
Long lived carbon storage (t ha^{-1}) in stem biomass of three species at three spacings and at three ages

Species	Age (years)	Original spacing (m)		
		2x2	3x2	4x2
G.optiva	7	2.32	2.80	3.17
	12	5.73	3.20	5.52
	15	2.63	1.48	3.18
B.variegata	7	2.07	1.23	0.86
	12	4.03	4.41	3.91
	15	1.44	0.92	0.30
D.sissoo	7	8.95	6.14	5.94
	12	12.56	11.08	9.00
	15	0.68	1.30	1.30

1st thinning at 7 years, 2nd thinning at 12 years, Final felling at 15 years; [a] tree densities are 2500, 1666 and 1250 at 2x2, 3x2 and 4x2 m spacing, respectively. After 2nd thinning, the densities ha^{-1} are 1250, 833 and 625 at spacings of 4x2, 6x2 and 8x2 m; at the final felling stage, the densities ha^{-1} are 625, 416 and 312 at spacings of 4x4, 6x4 and 8x4 m, respectively.

Long lived carbon storage in the stem component was highest in *D.sissoo* in comparison to other species at both the ages (Table 5). Across different spacings, highest values were recorded for close spacings followed by medium and wider spacings, in all the three species.

Annual Carbon Input and Humification Rate Constant

Annual addition of C inputs through leaf litter of trees and fine root to the soil under different treatments showed large variation due to differences in litter production and fine root turnover rates of tree species and spacings. The annual rate of increase of soil organic carbon (SOC) content in 0.45 cm soil profile ranged from 502 kg C ha^{-1} in *G.optiva* at wide spacing to 1410 kg C ha^{-1} in *D.sissoo* at wide spacing

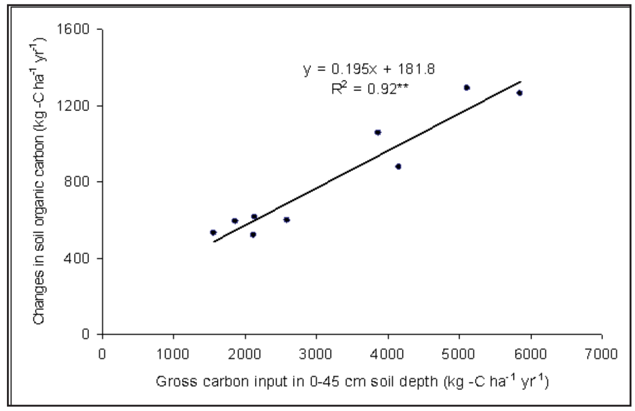

Fig. 4. Relationship between total carbon input and changes in SOC in a sub-humid tropical climate

(Table 6). The observed value of annual rate of changes in SOC in the 0- 45 cm soil depth was linearly related with the annual gross C input (A) to the soil in the form of dC_s/dt = 0.195A 181.8 (Fig. 4, R^2 = 0.92**). The value of humification rate constant (h) of annually added biomass C was 0.195, suggesting that 19.5 % of the added biomass C was annually humified in the soil to contribute towards the increase in SOC content. The intercept of the equation represented the annual loss of C from the native soil organic matter. The intersection of the curve with the Y axis at 181.8 suggests that under the present situation, C loss during nine years of plantation from the native soil organic matter averaged 181.8 kg- C ha^{-1} yr^{-1}. Equating this intercept value with k x Cs of the equation of Jenkinson (1988) and placing initial SOC content value (Cs = 51128 kg C ha^{-1}) for 0 - 45 cm soil depth, we calculated the decay rate (k) of the native SOC. The value of k, thus computed was 0.0035. This indicates that C losses from native SOC during the period was at the rate of 0.35 % of the initial SOC content. At equilibrium, when addition of C inputs to the soil equals

Table: 6
Effect of tree species raised on bouldery river bed land and spacings on total soil organic carbon and changes in SOC

Tree sp.	Spacings(m)	Soil organic carbon (g kg^{-1})				B.D.(g cc^{-1})	Soil (%)	Changes in SOC (kg $ha^{-1}$$yr^{-1}$)
		0-7.5 cm	7.5-15 cm	15-30 cm	30-45 cm			
G. optiva	2x2	8.3	7.1	5.5	3.6	1.59	65	557.1
	2x3	9.6	7.3	4.7	3.3	1.53	70	502.0
	2x4	10.3	6.8	4.7	3.1	1.46	90	591.3
B.variegata	2x2	9.4	8.3	6.5	3.9	1.39	76.4	1055.3
	2x3	8.2	7.1	5.3	3.6	1.58	72	559.9
	2x4	10	8.2	6.4	4.6	1.43	78.5	1294.4
D.sissoo	2x2	9.9	7.3	5.2	3.7	1.53	75.6	769.9
	2x3	8.0	6.8	5.8	3.8	1.44	74.2	616.0
	2x4	10.9	7.8	6.4	4.8	1.54	74.0	1410.3
	Initial (F)*	7.8	6.7	4.2	2.5			

losses of C (*i.e.* dCs/dt = 0), annual C input (A) becomes 932.3 kg- C ha^{-1} yr^{-1}. The decomposition rate constant and equilibrium carbon input determined in this tree based system is slightly higher than a field crop system in a similar agro-climate condition (Kundu *et al*., 2006), which might be ascribed to the nature of leaf litter and their decomposition rates (Raizada *et al*., 2002). This amount is required to compensate the native loss of soil organic carbon from crop residues, roots and/or manure for 0 45 cm soil depth. The carbon sequestration rate varied widely with trees species and spacings but highest sequestration was observed in *D.sissoo* followed by *B.variegata* and *G.optiva* at wide spacings to the tune of 1.32, 1.20 and 0.55 t ha^{-1} yr^{-1}, respectively (Fig.4). The sequestration rate is low irrespective of trees, though a considerable amount leaf litter is received as carbon input, which might be due to leaching loss of carbon due to the nature of the underlying stratum.

Changes in Water Transmission Properties

Variations in root system development, rooting patterns, root biomass and microbial activities might, to some extent, explain the observed differences among plots under different trees in the soil water transmission properties. Soil bulk density decreased (Table 7) due to the loosening effects of roots along with increase in soil organic carbon content. The observed increase in soil water infiltration and saturated hydraulic conductivity was a result of better porosity (due to decreased bulk density) and better pore size distribution (size, shape and arrangement of pores) due to improved soil structure. An appreciable higher value of cumulative infiltration under trees may be traced to the considerably higher amount of root proliferation, high litter biomass production and subsequent decomposition. Sorptivity and transmissivity, the indicator of water transmission properties in Philip's model, were minimum in *G. optiva* and maximum in *D.sissoo* with per cent increase of 23 and 14.4%, respectively in *D. sissoo* as compared to *G.optiva*. However, the spacings within trees showed non-significant relationship in respect of water transmission properties.

Growth patterns of the three species raised on the old river bed land differed within species and spacings. These differences can be attributed to the preferred ecological niche by the species and growing conditions available. *G.optiva*, a species of the sub-tropical and sub-temperate zone grew well in the degraded site and produced sufficient quantities of fodder and firewood. *G.optiva* is the only species which is able to provide green fodder even during the winters, when other species are leafless or leaves have turned senescent; its leaves are usually fed to animals mixed with dry straw. In an earlier study (Singh *et al*., 2008) with this species and hybrid Napier (in a tree -grass combination), its fodder yielding potential under different management techniques was reported. *B.variegata,* a tree of the sub-humid and sub- tropical region, usually occupies sites with deep soils and sufficient moisture retention properties. Performance of this species on this site was unsatisfactory with slow growth and occasional frost damage leading to "top dying". Apparently, the species was not able to adapt itself to grow under moisture stressed situations for nearly eight months a year (Nov. to June). *D.sissoo* a pioneer tree species in riverine succession was the best performer in terms of height and diameter increment and reached an average diameter of 8.18 cm and height of 12.71 m by the twelfth year.

Table: 7

Effect of tree species and spacings on water transmission properties of surface soil (0-15 cm) after nine years of plantation

Treatment	Infiltration characteristis			Saturated	Philip's model		
	i_5 ($cm\ hr^{-1}$)	i_c ($cm\ h^{-1}$)	I (cm)	hydraulic conductivity ($cm\ hr^{-1}$)	Sorptivity ($cm\ min^{-1/2}$)	Transmissivity ($cm\ min^{-1/2}$)	R^2
Tree species							
G. optiva	9.25	1.24	312	318	0.26	1.38	0.72**
B.variegata	9.45	1.58	390	389	0.27	1.42	0.78**
D.sisso	10.24	1.84	415	419	0.32	1.58	0.81**
C.D. (P=0.05)	1.47	0.04	8.7	7.8	0.023	0.18	-
Spacings (m)							
2 x 2	9.15	1.15	345	296	0.23	1.35	0.23*
2 x 3	9.40	1.25	378	368	0.24	1.36	0.28*
2 x 4	9.85	1.42	410	396	0.25	1.35	0.45*
C.D (P=0.05)	NS	NS	6.4	12.4	NS	NS	-

**Statistically significant; * Non-significant

According to the size-density theory, height growth is relatively unaffected by the competition of trees (Daniel *et al*., 1979) but diameter growth decreases with increasing tree density (Harper, 1977). In this study, spacing did not influence tree height with taller trees being observed in medium and wide spacing in *D.sissoo* (Fig.3) which was apparently caused by the conducive site conditions and availability of sufficient light. Under the existing site conditions, trees responded to wider spacing and lower competition with greater individual diameter growth and no significant differences in vertical (height) growth unlike that reported earlier by Jonestone (1985).

Yields from pruned material are related to branching patterns of the species. *G.optiva* is reported to be an early successional species in the Himalayas (Khosla *et al*., 1995) and such species tend to maintain a comparatively narrow crown and a multilayered canopy. While late successional species show a proleptic type of bud and branch production, early successional trees grow through syllepsis. Branching patterns and canopy geometry of early successional species like *D.sissoo* (in the sub-tropical region) is more efficient and they have lower light extinction co-efficients (Horn, 1971) than those which appear later. Higher rates of photosynthesis and hence rapid growth are generally associated with species adapted to well illuminated environments that are usually occupied by early colonizers (Bazzaz and Pickett, 1980). *B.variegata*, a late colonizer and slow growing species has a proleptic type of branching pattern, the branches themselves being short in length and with little foliage. Even with a typical branching pattern, *G.optiva* trees produced a number of shoots that arise from the stem at the ground level and grow rapidly in length and thickness, which were pruned annually. Similar type of sprouting of shoots was also noticed in *D.sissoo* at younger ages which ceased once the trees were seven to eight years old.

The relative proportion of contribution by the main stem to firewood production decreased at wider spacing in general till the first harvest, although by the time of the 2nd thinning no clear cut trend was evident. These results do not directly agree with results of similar studies by other workers (Harrison *et al*., 2000). The changes in relative amounts of material allocated to various tree parts as a function of spacing show in general, that when trees are planted at increasing spacing levels, they do not necessarily respond by allocating more growth to branches and foliage. Instead, early sucessional trees tend to grow taller rapidly. In our study, we observed that within the three species studied, more branch biomass was available at medium (3x2 m) spacing during the time of second harvest than at wider (4x2 m) spacing, as was observed in *D.sissoo* and *G.optiva* but not in *B.variegata,* which is a slow growing species.

Though the relative sizes of trees are important from the biomass point of view, the important component is the amount of stem wood material per hectare. It can be seen from Table 2, that the biomass of the main stem were higher at close spacing during the first harvest in case of *G.optiva*, *B.variegata* and *D.sissoo*. However, by the time of the 2nd harvest, highest stem biomass per ha from *G.optiva* and *D.sissoo* was obtained at wide spacing and at medium spacing in case of *B.variegata*. In summary, total firewood production from these three species followed the trend of *D.sissoo*> *G.optiva* > *B.variegata* with the highest production at close spacing. Water transmission properties are affected by organic matter accumulation on the surface soil from tree detritus leading to reduction of bulk density and increase in the volume of micro-pores which subsequently reduces surface run off. Plantations of *D.sissoo* can be successfully raised at a spacing of 2x2 m and *G.optiva* at wide (4x2 m) spacings in the sub-tropical regions to mitigate green house gas emission, increase carbon sequestration and produce higher biomass for meeting energy requirements.

4. CONCLUSIONS

This study clearly indicates that old river bed lands in the valley portions of the North west Himalayan region can potentially be used for the production of firewood and fodder. Cycling of nutrients through detritus and build up of organic matter in the soil can lead to enhanced carbon sequestration in the soil layer. Raising *D.sissoo* as a densifed plantation was the best practice for rehabilitation of these riverbed lands and protecting the soil resource through accelerated water transmission properties which may contribute to groundwater recharge. Rehabilitation of these unproductive lands using biological can lead to the reduction of biotic pressure on forests areas for the extraction of firewood and fodder by indiscriminate lopping of fodder yielding trees. These 'foster' ecosystems, if properly managed, will also lead to improved edaphic conditions and allow for secondary succession to begin leading to development of natural forests in the region.

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