Agriculture, Ecosystems and Environment 161 (2012) 112–120

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

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

Carbon sequestration and land rehabilitation through *Jatropha curcas* (L.) plantation in degraded lands

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ARTICLE INFO

Article history:
Received 9 January 2012
Received in revised form 30 July 2012
Accepted 31 July 2012

Keywords:
Biofuel
Carbon sequestration
Degraded lands
Jatropha
Land rehabilitation
Nutrient recycling

ABSTRACT

The effects of growing *Jatropha* in on-farm and on-station degraded lands were evaluated on carbon (C) sequestration and soil properties. *Jatropha* accumulated and added to soil significant amounts of C (305 kg ha^{-1} year^{-1}) from the year one itself. Overall, a 3–5-year old plantation added per year around 4000 kg plant biomass equivalent to 1450 kg C ha^{-1} – 800 kg C through leaves, 150 kg C through pruned twigs, and 495 kg C as deoiled *Jatropha* cake. Biodiesel C replacement in the fossil fuel was 230 kg ha^{-1}. Besides adding biomass to the soil, and C replacement in fossil fuel; the standing *Jatropha* rendered ecosystem service by fixing 5100–6100 kg ha^{-1} C as the aboveground plus belowground biomass. Carbon additions by *Jatropha* during 4 years increased C content in the degraded surface soil layer by 19%, resulting in about 2500 kg ha^{-1} C sequestered. Huge C additions and live root activity under *Jatropha* increased microbial population, respiration rate and microbial biomass C and N in soil. Along with C additions, 4000 kg ha^{-1} year^{-1} plant biomass recycled into the soil 85.5 kg nitrogen, 7.67 kg phosphorus, 43.9 kg potassium, 5.20 kg sulphur, 0.11 kg boron, 0.12 kg zinc and other nutrients. The C additions improved water holding capacity of the soil under *Jatropha* as compared with the adjacent control soil which increased by 35% at 30 kPa and 21% at 1500 kPa soil water potential.

1. Introduction

1.1. Scope for Jatropha as biodisel in India

Depleting world's fossil fuel reserves, their escalating cost and the global warming problem caused by the fossil fuel combustion have attracted the attention of researchers, policy makers, environmentalists and industrialists (Wani et al., 2006). Since the early 1990s, oil imports in India have increased more than five-folds, putting pressure on foreign exchequer and moreover fast growing economy in India is expected to escalate current energy crisis. The oil imports in India are projected to reach 166 and 622 million tons by 2019 and 2047 (TERI, 2002), respectively as compared with the 111 million tons of crude oil imported in 2006–2007 (GOI, 2011). Using biofuels for carbon (C) replacement in fossil fuels in India as anywhere else in the world is considered as a strategy to address energy security and climate change related issues (Achten et al., 2010b; GOI, 2009; Phalan, 2009). Biofuel plants are a renewable source of energy as they photo-synthetically fix atmospheric carbon dioxide (CO_2), and offer an alternative for C replacement in fossil fuel with the recycled one, thereby minimizing C emission. India imports crude oil to meet nearly 70% of its petroleum requirements and 40% of total petroleum based fuel used in India is diesel, so the biodiesel promotion is a viable alternative to petroleum diesel (Kumar et al., 2009). *Jatropha* as a biodiesel plant is a good candidate as it can be cultivated on degraded low fertility soils (daSchio, 2010); its seeds yield 28–40% oil (Divakara et al., 2010; Wani et al., 2006), which can be used for producing biodiesel (Jain and Sharma, 2010; Koh and Ghazi, 2011); the plants are not browsed by cattle and goats, and hence recommended for the rehabilitation of open degraded lands (NABARD, 2012; Wani et al., 2006). The Government of India in this context has approved a "National Policy on Biofuels" in the year 2009 targeting a 20% blend of biofuels with gasoline and diesel by the year 2017 (Achten et al., 2010a).

1.2. Farm livelihoods and ecosystem service from Jatropha on degraded/waste lands

Making productive use of wastelands by growing *Jatropha* could help strengthen local livelihoods and income diversification, which is of high priority for land development (Mandal and Mitrha, 2004). Biofuel plantations are considered as an option for rehabilitating wastelands, enhancing energy security, and providing employment opportunities and livelihoods in rural areas (Achten et al., 2010b; Phalan, 2009; Sreedevi et al., 2009b; Wani and Sreedevi, 2005; Wani et al., 2006, 2009a). Large tracts of degraded lands in India

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http://dx.doi.org/10.1016/j.agee.2012.07.028

are owned by the poor farmers and/or are the common lands for use by the community particularly the vulnerable groups, and thus the biodiesel plantation to rehabilitate these lands, constitutes a pro-poor strategy to improve their livelihoods, by providing employment and additional sources of income (Wani et al., 2006). Earlier studies at the ICRISAT showed that *Jatropha* fulfills many of the required criteria as a biofuel crop, and has the potential to benefit the small and poor farmers (Brittaine, 2008). About 14 million ha degraded/marginal/waste lands in India have been identified for potential plantation with biofuels like *Jatropha* in the immediate future (Wani et al., 2009a).

Carbon fixation and addition to the soil under *biofuel* plantation through falling leaves, pruned twigs and deoiled cake to soil helps in reclamation of the degraded lands along with mitigation of global warming (Betts, 2007; Heruela, 2008; Sreedevi et al., 2009a; Wani et al., 2006, 2009b). In the context of reducing atmospheric CO_2 levels, degraded lands with very low C levels and large gap between current and inherent potential soil C levels, offer a relatively higher potential for C sequestration than their non-degraded counterparts (Bhattacharyya et al., 2006; ICRISAT, 2004; Shi et al., 2009; Wani et al., 2003). The Kyoto protocol (1997) envisages reducing the greenhouse gas emission by 5% or higher below the 1990 levels; and provides a mechanism by which a country that emits carbon in excess of the agreed upon limits, can purchase carbon offsets from a country or a region that manages C sinks (Hunt, 2009). And thus carbon credits gained through the fuel switch can be a source of income when traded with other developing or developed countries (D'Silva et al., 2004).

Much of the earlier research on *Jatropha* in India (Dubey et al., 2006; Francis et al., 2005) have focused on feasibility of greening waste lands, while simultaneously addressing the issues of fuel production and socio-economic development. Few studies (Firdaus et al., 2010) have calculated C in the above and belowground plant parts, while some (Ogunwole et al., 2008) have reported on the improvement of selected soil quality parameters like aggregate stability as a function of soil organic matter. In spite of the apparent ecosystem service through biofuel plantation in the wastelands, there is need for better understanding on C budgeting and C added to the soil, and its effects on soil biological, chemical and physical properties. The ICRISAT led consortium under research for development initiative undertook on-farm participatory *Jatropha* plantations during 2004 and 2006 in degraded common uplands in the selected watersheds, and in on-station degraded lands during 2005 to evaluate its suitability in rehabilitating degraded lands. Therefore, the present study was made to test and document the hypothesis that *Jatropha* has the potential to grow and establish itself on the degraded lands; and in return reclaim the degraded lands by adding C via litter fall and other biomass as indicated by improved soil quality in the medium to longer terms.

2. Materials and methods

2.1. Study sites and Jatropha plantation details

The *Jatropha* plantations were undertaken at the ICRISAT Center in Patancheru and the on-farm locations in Kothalapur, Velchal, Siddapur, Kothapally, Sri Rangarajupally and Sudepally in the Andhra Pradesh (AP) state, India (Fig. 1 and Table 1). The plants were established in a rectangular/square planting pattern at equal distances. The on-station plantations were established during 2004 and 2006, while the on-farm plantations were undertaken during 2005. The on-station plantation established during 2004 was used for extensive studies reported here, while the plantation established during 2006 was used to study C accumulation and addition to the soil through *Jatropha* leaves after 1 year of establishment.

Table 1
Description of the study sites in Andhra Pradesh, India used for C sequestration through *Jatropha curcas* (L.) plantation.

S. No.	Study site	District	Geolocation	Altitude (m amsl)	Rainfall[a] (mm)	Plant spacing (m × m)	No. of plants ha^{-1}	Total area (ha)	Fertilizers applied to *Jatropha* plantations	
									Quantity ($kg\ ha^{-1}$)	Frequency
1	ICRISAT, Patancheru	Medak	17°30′21″; 78°16′2.2″	538	822	2 × 3	1667	10	N (80), P_2O_5 (20)	Yearly
2	Velchal	Rangareddi	17°27′59.3″; 77°51′34.5″	671	822	2 × 2	2500	140	N (30–50), P_2O_5 (12–60)	2005, 2007
3	Siddapur	Medak	17°34′41.1″; 77°57′38.1″	521	878	2 × 3	1667	0.7	N (15), P_2O_5 (20), K_2O (20)	Yearly
4	Kothlapur	Rangareddi	17°31′26.4″; 77°48′24.5″	633	822	2 × 2	2500	160	N (30–50), P_2O_5 (12–60)	2005, 2007
5	Kothapally	Rangareddi	17°22′44.6″; 78°07′22.7″	593	822	2 × 2	2500	0.5	N (30–50), P_2O_5 (12–60)	2005, 2007
6	Sri Rangarajupally	Kadapa	14°28′33.6″; 78°45′50.4″	141	697	2 × 3	1667	0.7	N (15), P_2O_5 (20), K_2O (20)	Yearly
7	Sudepally	Kurnool	15°28′40.1″; 77°56′4.7″	356	768	2 × 3	1667	0.7	N (15), P_2O_5 (20), K_2O (20)	Yearly

[a] Average for the years 2004–2009.

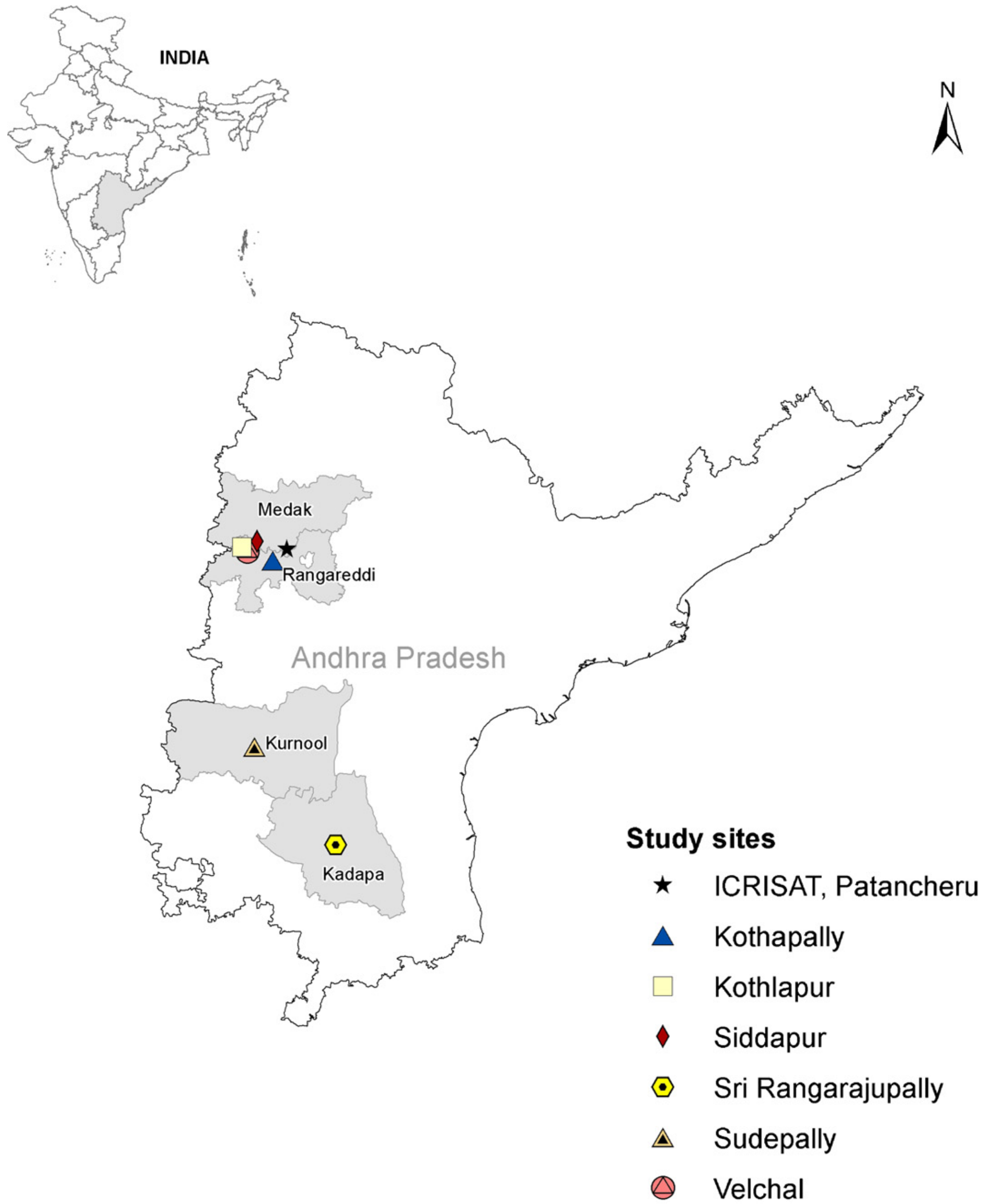

Fig. 1. Geo-location of study sites in Andhra Pradesh, India used for C sequestration through *Jatropha curcas* (L.) plantation.

For establishing *Jatropha* plantations, *Jatropha* seedlings were raised in nurseries through seeds, followed by their transplantation during the rainy season (June–July) in pits measuring 0.3 m × 0.3 m × 0.3 m. Nitrogen (N) and phosphorus (P) fertilizers were applied during the rainy seasons (June–July) to all the plantations, but the plantations at Sri Rangarajupally, Sudepally and Siddapur also received potassium (K) in addition to N and P (Table 1). On-station plantation used for current biomass accumulation and soil health studies at the ICRISAT Center received 80 kg N and 20 kg P_2O_5 ha^{-1} $year^{-1}$, while simultaneously evaluated in 2004 plantation the lower levels of N (40 kg), P_2O_5 (10 kg) in all possible combinations and there was also an absolute control, for yield studies. The on-farm plantations at Sudepally, Sri Rangarajupally and Siddapur received 15 kg N, 20 kg P_2O_5 and 20 kg K_2O ha^{-1} $year^{-1}$. The on-farm plantations at Velchal, Kothlapur and Kothapally received 30 kg N and 12 kg P_2O_5 ha^{-1} during 2005 rainy season and 50 kg N and 60 kg P_2O_5 ha^{-1} during 2007 rainy season.

Across all sites, replanting was done in the second year of establishing to fill the gaps (5–10%) created by non-establishment of *Jatropha* seedlings. Weeding was done every year during June–July months prior to fertilizer application. During weeding, soil across the plant was also tilled to create congenial environment for plant growth in the first 2 years of plant growth. Harvesting of pods was done 4th year onwards during September–December.

2.2. Biomass accumulation and carbon sequestration

For the estimation of the above ground biomass, a non destructive, indirect method based on partial sampling technique, was adopted. This method involves indirect and randomized branch sampling of the plant parts for biomass determination (Gregoire et al., 1995; Jessen, 1955). Randomized branch sampling is a multistage sampling procedure using natural branching in order to select samples for the estimation of tree characteristics, and is described in detail by Gregoire et al. (1995). The below ground

Table 2
Carbon added to the soil through leaf fall and pruned twigs of *Jatropha* in on-station experiment at ICRISAT Center, Patancheru, India, 2007–2009.

Age of the plant	Plant dry biomass (g plant^{-1})	SE±	Plant dry biomass (kg ha^{-1})	SE±	Plant biomass C (%)	Plant biomass C (kg ha^{-1})	SE±
Leaf fall							
1st year	550	51	920	85	33	305	28
3rd year	1450	264	2420	441	33	800	146
Pruned twigs							
5th year	245	71.6	410	119	36	150	43

biomass was estimated by multiplying the above ground biomass by root:shoot ratio factor of 0.2 (IPCC, 1996; MacDicken, 1997; Snowdon et al., 2002). Total biomass in live *Jatropha* plants was obtained by adding the aboveground and belowground biomass. The fallen leaf biomass was determined in the ICRISAT on-station plantations (2004 and 2006 established) during 2007 on 6 representative plants by periodically collecting the fallen leaves with the help of nylon net closures, the average of which was taken as leaf biomass added to soil through each plant. Similarly, pruned twigs biomass generated from the 2004 established on-station plantation was estimated during 2009 using 6 representative plants, the average was taken as twigs biomass added per plant. The leaf or pruned twigs biomass added per ha was worked out by multiplying average biomass added per plant by total plant population (1667 plants). As regards the seed yield estimation, the maturity of pods in *Jatropha* occurs in a sequential order on the plant; therefore repeated harvesting of the matured pods was done on sixty individual plants, and oven dry weights were recorded. Manual shelling of pods was done, to extract seeds from dried pods and seed yield was extrapolated to ha basis. Seeds were crushed to extract biodiesel (30%); and by-product deoiled cake was obtained. The samples of leaves, shoots/twigs, seed and deoiled seed cake collected were dried to a constant weight in an oven at $65 \pm 5\,^{\circ}$C before recording their biomass.

Carbon content (%) in composite plant materials (leaves, pruned twigs, seed and deoiled cake) was determined by a combustion method using C analyzer (PRIMACS^{SLC} TOC Analyzer-22) (Skalar, 2012). Carbon added per ha through leaves, pruned twigs and deoiled cake was worked out by multiplying C content by respective biomass yield. Biodiesel C was estimated by subtracting deoiled cake C from the C fixed as seed yield per ha. Carbon in the live *Jatropha* plants standing in field was estimated by using a carbon factor of 0.5 (IPCC, 2003).

2.3. Soil and plant analysis

For monitoring the changes in C and extractable P in the soil after 4 years of the plantation crop, 10 composite surface (0–0.15 m) soil samples were collected from randomly selected representative plants at Kothlapur site. Each composite sample composed of sub-samples collected from 3 spots at a distance of 0.30 m surrounding the main stem. Similarly, 2 composite samples, each composed of 3 sub-samples from randomly selected representative spots, were collected from adjoining untreated lands with sparce grassy vegetation (Grassland). Soil samples were collected using soil core sampler. The collected soil samples were air dried, ground and passed through a 0.25 mm sieve for C analysis and through a 2 mm sieve for available P determination. Organic carbon was determined using the Walkley Black method (Nelson and Sommers, 1996), and the available P by using the sodium bicarbonate ($NaHCO_3$) method (Olsen and Sommers, 1982). The respective values for soil C and P are averaged ones for the samples collected from plantation and grassland. Similarly, for estimating water-holding capacity, 15 composite soil samples each from the plantation and adjoining control grassland were collected at the Velchal site. For each composite sample under the plantation, soil samples were collected from 3 spots around the single plant at 0–0.15 m depth and homogenized to make one composite sample. Similarly, 15 representative composite samples from adjoining grasslands, each composed of 3 sub-samples, were collected for comparison. Water-holding capacity of soils under *Jatropha* plantation and grassland soils was measured at 2 moisture tensions of 30 kPa and 1500 kPa using the pressure plate method (Klute, 1986).

The *Jatropha* plant parts were ground finely before analyses. Total N, P and K in plant materials were determined by digesting them with sulfuric acid–selenium mixture, while N and P in the digests were analyzed using autoanalyser and K using atomic

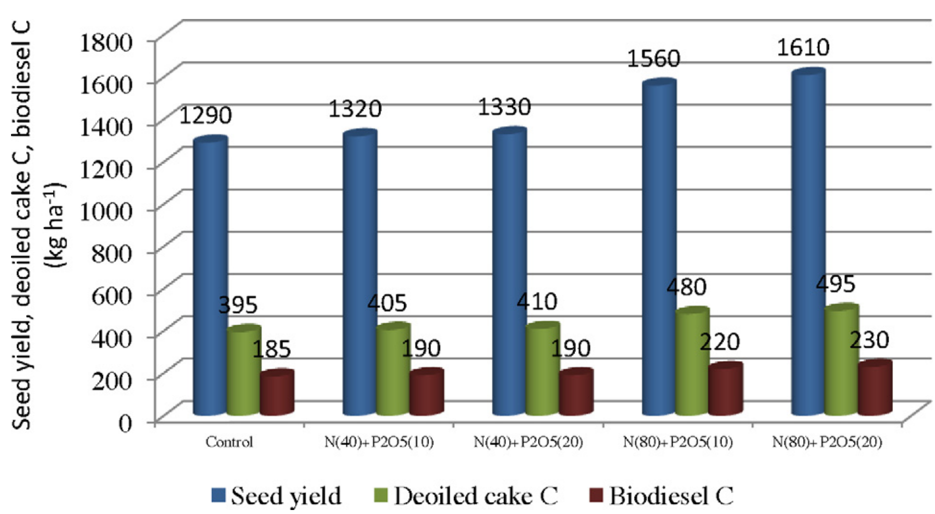

Fig. 2. *Jatropha* seed yield and C fixed in deoiled cake and biodiesel in an on station experiment at the ICRISAT Center in Patancheru, India, 2008.

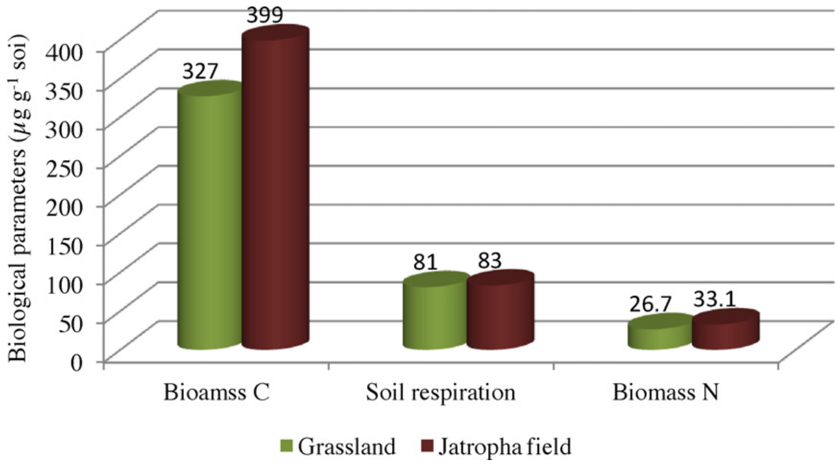

Fig. 3. Effects of the *Jatropha* plantation on the microbial biomass C, N and soil respiration at Velchal, Rangareddy district, Andhra Pradesh, India, 2009.

absorption spectrophotometer (Sahrawat et al., 2002a). Zinc (Zn) in the plant materials was determined by digesting them with triacid and Zn in the digests was determined using atomic absorption spectrophotometer (Sahrawat et al., 2002b). Total S and B in plant samples were determined by inductively coupled plasma emission spectrophotometer (ICP-AES) in the digests prepared by digesting the samples with nitric acid (Mills and Jone, 1996).

2.4. Microbial count and activity

The fungi, bacteria and actinomycetes counts were made in the composite surface (0–0.15 m) soil samples collected from the rhizosphere soils under *Jatropha* plantations and non-rhizosphere soils from adjoining grasslands. For microbial studies, 5–15 composite samples, each consisting of 3 sub-samples, were collected each from under the plantation and adjoining grasslands at all the sites. Microbial populations in the soil samples were measured using the standard dilution and plating method (Weaver et al., 1994). Nutrient agar, potato dextrose agar and actinomycetes agar were prepared for bacteria, fungi and actinomycetes, respectively. The growth media were sterilized in an autoclave at 121 °C and 1.05 kg cm^{-2} pressure. After sterilization, media were dispersed into petri plates (100 mm diameter × 15 mm height) and after solidification these plates were used for the enumeration of microorganisms. After incubation period, the colony forming units (cfu) were counted using the colony counter. The microbial biomass C and N in the soil samples were determined by the fumigation and extraction method as described by Anderson and Domsch (1978), and expressed as μg g^{-1} of dry soil. Carbon dioxide (CO_2) emitted during incubation of the soil samples was used as indirect measure of microbial activity, assuming that the amount of CO_2 released is only due to the respiration by microorganisms in the soil sample.

2.5. Statistical analysis

The data were statistically analyzed using completely randomized design in GenStat 13th statistical package, VSN International Ltd, UK (Ireland, 2010) to work out significance at 1% and 5% level.

3. Results

3.1. Carbon accumulation and addition to soil through Jatropha biomass

The results of the on-station study revealed an annual leaf fall of 550 g plant^{-1} in 1-year old plantation and this added 305 kg C ha^{-1} year^{-1} to the soil in year one itself (Table 2). By third year the leaf fall was as high as 1450 g plant^{-1}, which corresponds to 800 kg C ha^{-1} year^{-1} added to the soil. The *Jatropha* plant population in both cases was 1667 plants ha^{-1} with 2 m × 3 m spacing. The biomass generated through pruning of *Jatropha* plantations during the later years, is another good source of C, returned to soil. The mass of *Jatropha* pruned by fifth year was equivalent to 410 kg ha^{-1} dry biomass and it added 150 kg C ha^{-1} to the soil.

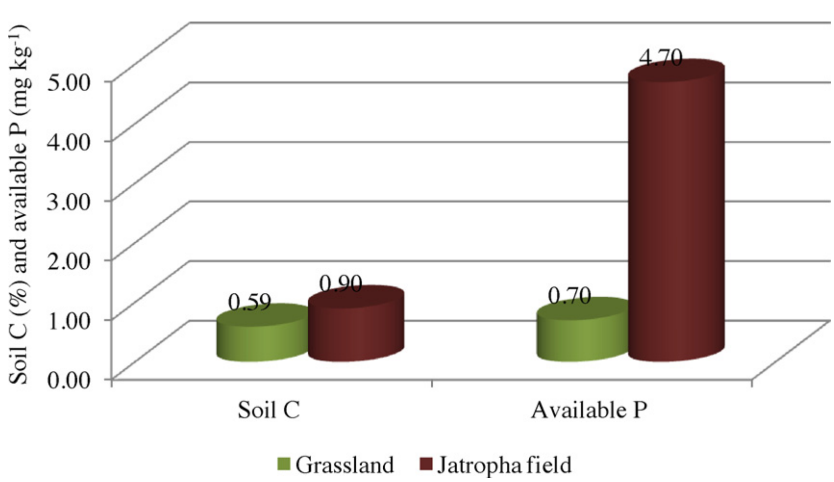

Fig. 4. Organic carbon and available P contents in surface (0.0–0.15 m) soil samples under *Jatropha* plantation in Kothlapur, Andhra Pradesh, India, 2009.

The seed yield in on-station 4-year *Jatropha* plantation under fertilized and unfertilized control plot varied from 1290 to 1610 kg ha^{-1} (Fig. 2) and accumulated 580–725 kg C ha^{-1} year^{-1}. Out of the total C accumulated by seeds, 185–230 kg C ha^{-1} year^{-1} is as biodiesel/oil C and an apparent replacement in the fossil fuel. The seed cake (900–1130 kg ha^{-1}) left after oil extraction is a good source of organic matter for improving soil health and returned 395–495 kg C ha^{-1} year^{-1} to the soil. The cake is also a source of plant nutrients for crops such as soybean and maize (Osman et al., 2009; Wani et al., 2006).

The live plant (shoot and root) biomass in the fields serves as a sink for C. The results from the on-station experiment at ICRISAT Center, Patancheru showed that 4-year old *Jatropha* plants fixed 3.07 kg C plant^{-1} (Table 3) in above and below ground biomass; and this amounts to 5120 kg C ha^{-1} for a plant population of 1667 plants ha^{-1}. Similarly, the on-farm plantation at the Kothlapur site with 2 m × 2 m spacing (2500 plants ha^{-1}) showed 2.44 kg C plant^{-1} was fixed; and this translates to 6100 kg C ha^{-1}.

3.2. Land rehabilitation through improved soil health

The soil samples from the on-farm Velchal plantation recorded increased microbial biomass C by 22%, soil respiration by 2.46% and microbial biomass N by 24% as compared to the adjoining grasslands (Fig. 3). A total of 894 kg ha^{-1} microbial biomass C was observed under *Jatropha* plantation as compared to 732 kg ha^{-1} in the grasslands, which amounts to an additional microbial biomass C of 162 kg C ha^{-1} under *Jatropha* plantation.

The results on the microbial population in the *Jatropha* root and non-root zone soil samples across the seven locations showed the highest populations of bacteria, followed by actinomycetes and fungi the least (Table 4). Across on-station and on-farm *Jatropha* plantations, the bacterial population increased from 4.24–87.5 × 10^{2} cfu g^{-1} in the non-rhizosphere soil to 64.5–946.5 × 10^{2} cfu g^{-1} in the rhizosphere soil; actinomycetes population increased from 4.28–13.7 × 10^{2} cfu g^{-1} in the non-rhizosphere soil to 9.51–121.0 × 10^{2} cfu g^{-1} in the rhizosphere soil and fungi population increased from 0.47–1.62 × 10^{2} cfu g^{-1} in the non-rhizosphere soil to 1.21–3.32 × 10^{2} cfu g^{-1} in the rhizosphere soil.

Increased microbial activity under *Jatropha* has implications for decomposition and recycling of the nutrients through biomass added and overall improved soil fertility. The analysis of plant parts (Table 5) revealed that among different plant parts, leaves are relatively good source of B (33.8 mg kg^{-1}); shoots are rich in K (23,300 mg kg^{-1}) and Zn (43.6 mg kg^{-1}); and the seed cake is rich in N (49,500 mg kg^{-1}), P (4400 mg kg^{-1}) and S (2114 mg kg^{-1}). Returning 2420 kg ha^{-1} year^{-1} leaves to soil added 23.0 kg N, 1.69 kg P, 24.2 kg K, 2.28 kg S, 0.08 kg B and 0.06 kg Zn. Similarly, the addition of 410 kg ha^{-1} *Jatropha* twigs pruned in a year added 6.60 kg N, 0.98 kg P, 9.55 kg K, 0.53 kg S, 0.005 kg B and 0.02 kg Zn; while 1130 kg *Jatropha* cake generated per ha in year returned 55.9 kg N, 5.00 kg P, 10.1 kg K, 2.39 kg S, 0.02 kg B and 0.04 kg Zn. Overall, around 4000 kg ha^{-1} recycled plant materials in 1 year added, in addition to 1450 kg C ha^{-1} year^{-1}, 85.5 kg N, 7.67 kg P, 43.9 kg K, 5.20 kg S, 0.11 kg B and 0.12 kg Zn plus other essential nutrients.

The cumulative C and nutrient added through the *Jatropha* biomass were documented from the on-farm study at Kothlapur site which indicated a higher concentration of soil C and available P under the *Jatropha* plantation as compared to the adjacent uncultivated control grasslands (Fig. 4). The soil C in the surface (0–0.15 m) soil under 4-year old *Jatropha* plantation increased by 19% as compared to the adjoining grasslands, which corresponds to about 2500 kg ha^{-1} additional C sequestered by the plantation

Table 3
Carbon fixed by live *Jatropha* plants at two locations in Andhra Pradesh, India, 2009.

Site name	Aboveground plant biomass (kg plant^{-1})		Belowground root biomass (kg plant^{-1})		Total plant biomass (kg plant^{-1})		Total plant biomass C (kg plant^{-1})		Total plant biomass (kg ha^{-1})		Total plant biomass C (kg ha^{-1})	
	Mean	SE±	Mean	SE±	Mean	SE±	Mean	SE±	Mean	SE±	Mean	SE±
ICRISAT	5.12	0.63	1.02	0.13	6.14	0.76	3.07	0.37	10,235	1265	5120	617
Kothlapur	4.07	0.30	0.81	0.06	4.88	0.36	2.44	0.18	12,200	898	6100	448

Table 4
Effects of *Jatropha* rhizosphere on the microbial population in on-station and on-farm plantations in Andhra Pradesh, India, 2007.

Location	No. of samples	Bacterial population (10^2 cfu g^{-1} soil)		Fungi population (10^2 cfu g^{-1} soil)		Actinomycetes population (10^2 cfu g^{-1} soil)	
		Non-root zone	Root zone	Non-root zone	Root zone	Non-root zone	Root zone
ICRISAT	10	56.9	946.5	0.67	1.72[a]	13.7	50.0[a]
Velchal	10	53.8	261.5[a]	1.62	3.32[a]	5.32	15.1[a]
Siddapur	5	60.4	77.5	0.91	1.87	7.17	33.8
Kothlapur	5	4.24	64.5[a]	0.47	1.21[a]	6.40	9.51
Kothapally	10	87.5	401.3[a]	1.19	2.39[a]	8.77	121.0[a]
Sri Rangarajupally	5	45.6	756.1[a]	0.51	1.72[a]	5.09	15.8
Sudepally	6	60.8	153.5[a]	0.73	1.90[a]	4.28	12.5[a]
Average	51	54.6	364.9	0.86	2.00	7.34	38.0

[a] Significant at 5%.

Table 5
Nutrient element contents in various plant parts of on-station 4-year old *Jatropha* plantation at ICRISAT Center, Patancheru, India.

Plant part	Nutrient content (mg kg^{-1})						
	Carbon	Nitrogen	Phosphorus	Potassium	Sulphur	Boron	Zinc
Shoots	360,000	16,100	2400	23,300	1289	11.2	43.6
Leaves	330,000	9500	700	10,000	941	33.8	23.3
Seeds	450,000	22,200	4800	8100	1400	15.0	17.8
Seed cake	440,000	49,500	4400	8900	2114	18.1	32.2

in 4 years. Similarly, available P in surface soil layer under *Jatropha* increased 5.2 folds.

The on-farm study at Velchal also recorded significant improvement in the water-holding capacity of the soils under *Jatropha* plantation as compared with the soils under grass (Table 6). Soil moisture holding capacity was higher by 35% at 30 kPa and by 21% at 1500 kPa soil water potential when compared with the soil under the adjoining grasslands.

4. Discussion

4.1. Carbon accumulation and addition to soil through Jatropha biomass

The present study supported the idea that the wastelands in a tropical Indian location with 800 mm annual rainfall that do not support conventional crop cultivation are suitable for growing *Jatropha* plantations. *Jatropha* is deciduous in nature, and sheds its leaves during dry season. Soil moisture starts depleting from December onwards and the plant sheds all leaves by January, which are added to the soil. A 4-year or older plantation also adds large quantities of biomass through addition of the by-product cake left after oil-extraction and pruning of dead and decayed twigs. A 3–5-year *Jatropha* plantations from eco-service point of view, generated and added to soil per year around 4000 kg plant biomass or 1450 kg ha^{-1} equivalent organic C through leaf fall, pruned twigs and deoiled cake (Table 7). The biodiesel/oil extracted replaced 230 kg C ha^{-1} in the fossil fuel. In addition to the C in the recycled plant material and C replacement in fossil fuel, the live plantation also contained more than 5100 kg C ha^{-1} equivalent in its biomass. As regards C sequestration by *Jatropha curcas* in its above and belowground biomass, earlier study in Plinthic Paleudult soil in Malaysia (Firdaus et al., 2010) reported a value of 13,000 kg C ha^{-1}. Studies in the tropics have identified the best of C sequestering systems in rainfed agriculture by the inclusion of leguminous crops including pigeonpea which under improved management have been reported to increase carbon sequestration maximum up to 330 kg C ha^{-1} $year^{-1}$ (Bhattacharyya et al., 2009, 2007; Wani et al., 2003, 2007). But *Jatropha* plantation brought in relatively far higher additions of C at 1450 kg ha^{-1} $year^{-1}$ even in the degraded soil. Carbon sequestration in these degraded infertile semi-arid tropical soils serves the dual purpose of reducing the atmospheric CO_2 concentration and increasing the soil organic carbon, which plays a crucial role in soil quality improvement and the availability of plant nutrients (Srinivasarao et al., 2009). Such large C credits if gained on larger tracts, can be traded with other regions or countries and can be a good source of income (Hunt, 2009).

Currently, the seed yields in *Jatropha* plantations under rainfed conditions are less than half of the achievable seed yields (2.5 tons ha^{-1}) (Wani et al., 2009a), which is a constraint to promoting *Jatropha* at farmer level. Productivity of *Jatropha* depends on precipitation rates, soil moisture availability, soil characteristics including fertility (daSchio, 2010; Francis et al., 2005; Jingura et al., 2011; Kumar and Sharma, 2008a,b), genetics (Divakara et al., 2010; Kaushik et al., 2007; Sunil et al., 2008), plant age (Carels, 2009) and various management factors like pruning, fertilization, and disease control (Achten et al., 2008; Behera et al., 2010; Ghosh et al., 2011;

Table 6
Effects of *Jatropha* plantation on moisture holding capacity of soil at Velchal site in Andhra Pradesh, India, 2009.

	Soil moisture at 30 kPa (g g^{-1})	Soil moisture at 1500 kPa (g g^{-1})
Jatropha plantation	0.23	0.17
Grass lands	0.17	0.14
Mean	0.20	0.16
P-value	0.0005[b]	0.0218[a]

[a] Significant at 5%,.
[b] Significant at 1%

Table 7
Balance sheet of C under *Jatropha* plantation as – C returned to soil, biodiesel C replacement per year and live plant C.

C through *Jatropha* plantation	Plant part involved	Organic-C (kg ha^{-1})
C returned back to soil	Leaf fall	800[a]
	Pruned twigs	150[a]
	Deoiled cake	495[b]
C replacement in fossil fuel	*Jatropha* oil	230[b]
C in live plant	Shoots and roots	5120

[a] Leaf and pruned twigs added C every year.
[b] *Jatropha* oil C (fuel replacement) and deoiled cake added C from fourth year onwards every year.

Jingura et al., 2011; Kaushik et al., 2007). The present study showed up to 25% higher yields and C accumulation under nutrient management practices and indicated need to increase it through tapping germplasm and other best cultivation practices.

4.2. Land rehabilitation through improved soil health

Jatropha plantations results in reduced soil erosion, a prerequisite for land rehabilitation (Garg et al., 2011); while large amount of organic matter added through fallen leaves and other tissues provide food for microbes to stimulate biological activity. Microbial activity is used as an indicator of soil health. The microbial population is higher in the rhizosphere soil apparently due to added plant biomass and presence of organic compounds, released by the plant roots, which stimulated the microbial activity in the rhizosphere (Bacilio-Jamenez et al., 2003). Increased microbial number and activity have implications in the decomposition and recycling of the *Jatropha* biomass, and overall soil fertility improvement. The current study showed improved soil P status under *Jatropha* plantation. A positive relationship between soil organic C and available P implies the role of increased organic matter in enhancing soil P and soil quality as a result of C sequestration (Wani et al., 2003).

Continuous addition of C to the soil apparently improved physical properties which brought in improvement in the water-holding capacity of the soil and benefited the growing plants (Zhu et al., 2010). Earlier studies (Ogunwole et al., 2008) showed that *Jatropha* plantation improves aggregate stability, resulting in enhanced water retention, as was observed in our study. The benefits of *Jatropha* for land rehabilitation by way of carbon addition through leaf fall and decaying tissues are along the expected lines.

5. Conclusions

The results of our study show that *Jatropha* grown on degraded lands fixes and adds large quantities of C to the soil, in addition to that accumulated by the standing crop; and that through biodiesel C replacement in the fossil fuel. Biomass added, and live plant root activity increased microbial activity; improved soil physical properties; recycled plant nutrients and improved soil fertility, and thus leading to the rehabilitation of degraded lands.

Acknowledgements

The support from Rain Shadow Area Development Program (RSADP), Government of Andhra Pradesh; National Oilseeds and Vegetable Oils Development Board (NOVOD), New Delhi, Government of India and International Fund for Agriculture Development (IFAD), Rome, Italy in carrying out the present study is gratefully acknowledged.

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