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Influence of Assisted Natural Regeneration in Increasing Carbon Stocks of Tropical Deciduous Forests

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ABSTRACT

Primary forests have attracted more attention for carbon sequestration as compared to active planting or avoided deforestation. The contribution of old-growth natural regenerating forest to the tropical carbon sinks is well known, but estimates of carbon uptake and storage in secondary forests is warranted. It is also not known at what age the secondary forests raised through assisted natural regeneration (ANR) achieve equivalent indices of carbon stocks, species richness in comparison to primary forests. The present study was undertaken to assess the carbon stocks and species richness indices in primary forests (Narsapur, Zaheerabad and Ramyampet) and secondary forests (Narsampalle,Gouraram,and Peerlapalle) available in the Medak Circle of Telangana State in South India. Sample plots (20 x 20 m) were established to represent 0.1% of the total area. Diameter at breast height (DBH) and height were measured, species were counted, and soil samples were collected from 0-10 cm depths. The carbon stock in the primary and ANR sites were 22.5±5.8, 21.5±8.5, 18.06±5.48 Mg/ha and 11.72±3.40, 9.42±2.45 19.09±3.36 Mg/ha, respectively. Biomass accumulation was ~2-fold higher in primary forest sites as compared to ANR sites, largely due to high stem density as well as the old age. Although the species richness indices did not vary between the forest types, soil organic carbon was twofold higher in the primary forests.

Keywords Undisturbed forests, Secondary forests, Biomass accumulation; Carbon sequestration, Tropical forests.

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INTRODUCTION

Forests serve as a natural sink for carbon and thus contribute to more than 80% of the terrestrial above ground and 40% of the terrestrial below ground biomass (Kirschbaum, 1996). Forest vegetation plays a crucial role in attenuating ambient CO_2 levels, through sequestration of the atmospheric C into the woody biomass and also through enhancing the soil organic carbon (SOC) content (Brown and Pearce, 1994). Carbon sequestration from atmospheric sources is advantageous as it removes the CO_2 , while improving the soil quality and biodiversity (Batjes and Sombroek, 1997). It can also raise the monetary income from potential carbon trading schemes (McDowell 2002).

Considering the historical depletion of forest cover, the National Forestry Action Program 1999 envisaged not only rehabilitating and enhancing the forest cover to 1/3rd of the land area all across India, but also enhancing the productivity of forests (Environment and Forests 1999).Yet, in the last decade, India has suffered 4.5% tree cover loss. In 2010, India had 31.3 Mha of natural forest, extending over 11% of its land area. In 2019, it lost 115 kha of natural forest, equivalent to 43.5Mt of CO_2 emissions. In the last decade, India has lost ~ 328 kha of forest cover accounting for a decrease of 3.2% of the total area (Watch 2020).

The Kyoto Protocol recognized the importance of forest in mitigating the greenhouse gas emission (i.e., carbon dioxide, methane and other compounds) and has included forest and soil C sequestration in the list of acceptable offsets (Dawson and Spannagle, 2008, Protocol 1997, van Noordwijk *et al.*1997). Thus, reducing emission from deforestation and forest degradation has emerged as an incentive mechanism for developing countries. Accounting of changes in forest cover, biomass stock, carbon emission and carbon removal are limited in the developing world. Therefore, this study has endeavored to assess the carbon stocks in both the primary and secondary forest types of Medak region of Telangana.

The importance of tropical primary forests in boosting the carbon stocks has been well studied, but data on carbon sequestration and its incorporation into vegetation biomass raised through assisted natural regeneration is limited. Assisted Natural Regeneration (ANR) is considered a reforestation method for rejuvenation of degraded forests, while improving the ecological function. It is classified as an afforestation/reforestation (A/R) strategy under the Kyoto Protocol (Smith 2002), yet its relevance and effectiveness as a carbon sequestration mechanism has not received significant attention (Niles *et al.* 2002). ANR solely relies on the leftover native plants and seeds at the site or scattered from surrounding vegetation. This kind of regeneration involves fencing around the area to reduce access to cattle, prohibiting burning and machinery activities and adopting thinning practices so as to avoid competition and additional planting of species native to the location (Smith and Scherr 2003). ANR has been routinely applied in tropical forests with native species that can grow well under the local climatic conditions (Benayas *et al.* 2009, Shono *et al.* 2007).

We therefore determined if the ANR forests are on par with the old-growth primary forests in their carbon sequestration abilities and accumulation of biomass. A comprehensive study of the growth and development of biomass along with carbon stock density from the ANR may provide better insights into their role in global carbon cycling. The study thus aimed at comparing the biomass accumulation and carbon stocks viz., a viz., species richness in secondary forests developed using assisted natural regeneration with the natural forests of the Medak Circle, Telangana State in South India.

Aim and objectives : To assess the carbon stocks contributed by the primary and secondary forest tree species in the Medak forests

(i) To enumerate the tree species of both primary and secondary forests in Medak,

(ii) To estimate the associated carbon stocks of the tree species in primary and secondary forests of Medak,

(iii) To determine the soil organic carbon of primary and secondary forest types of Medak,

(iv) To study the biodiversity indices of these forest types in the Medak.

MATERIALS AND METHODS

Geographical details of study area

Medak Circle is located in the Central Telangana

Table 1. Wood density and allometric growth equations used to estimate biomass. Source: FSI (1996); D and H are diameter at 1.3 m height (cm) and tree height (m), respectively.

Sl. No.	Species	Volume equation	Wood density (g/cm^3)
1	*Annona squamosa*	V=0.058237+4.597986D*D*D	0.73
2	*Azadirachta indica*	V=0.058237+4.597986D*D*D	0.69
3	*Buchanaia lanzan*	V=0.058237+4.597986D*D*D	0.45
4	*Butea monosperma*	V=0.058237+4.597986D*D*D	0.48
5	*Careya arborea*	V=0.003-0.848D+7.342D*D	0.80
6	*Cassia fistula* L	V=0.066+0.287D*D H	0.71
7	*Chloroxylon swietenia*	V=-0.094+0.376D+2.817D*D	0.80
8	*Dalbergial atifolia Roxb.*	V=0.265-3.135D +12.771 D*D	0.75
9	*Dalbergia paniculata*	V=0.058237+4.597986D*D*D	0.64
10	*Diospyros chloroxylon*	V=0.02481-0.578532D + 6.017D*D	0.66
11	*Diospyros melanoxylon*	V=0.043-0.457 D + 5.230 D*D	0.68
12	*Eucalyptus* spp.	V=0.02894-0.89284D+8.72416 D*D	0.64
13	*Ficusbengalensis*	V=0.03629+3.95389D-0.84421D	0.39
14	*Gme linaarborea*	V=0.25058-3.55124D+16.41720D^2-8.32129D^3	0.45
15	*Holoptelia integrifolia*	V=-0.82942+0.196873D*D*H+0.008401 H	0.58
16	*Lagerstroemia parviflora*	V=-0.023-0.546D+6.274D*D	0.62
17	*Lannea coromandelica*	V=-0.027403+3.069449D*D	0.54
18	*Madhuca indica*	V=-0.051-0.034D+4.542 D*D	0.74
19	*Tectona grandis*	V=-1.123+6.532D-2.536D*D	0.50
20	*Terminalia alata*	V=0.012763+9.281920D^3	0.63
21	*Terminalia arjuna*	V=0.058237+4.597986D*D*D	0.68
22	*Wrightia tinctoria*	V=0.23229+4.41646D-1.55899 D	0.75

agro-climatic zone of the Deccan plateau and forms part of the Table land of the Deccan plateau and is lined by a series of hill ranges. The land area for the most part is occupied by plains lying elevated between 500-600 m above the mean sea level. The soils are primarily red earths that are non-saline and non-alkaline. The study sites include both primary and secondary forests. Majority of the secondary forests were raised through assisted natural regeneration. Secondary forest sites unplanned deforestation and forest degradation due to severe biotic pressures due to unsustainable fuel wood collection, high weed density, soil degradation, uncontrolled grazing and wild fires resulting in weak potential for regeneration. As part of the ANR scheme, operations including digging trenches all along the periphery of the forest area to avoid biotic intrusion, better management of stock through preservation of soil and moisture content, prevention of fires, weed management and supplemental planting were taken up by the Telangana State Forest Department in the open forest areas, with a canopy cover < 40%. A large portion of the ANR sites are covered by young stands with not more than 20 varieties of tree species.

The study was conducted between March, 2020-May, 2021. Primary forests of Ramayampet, Narsapur and Zaheerabad along with secondary forests of Gouraram, Narsampally and Peerlapally were randomly chosen for the study. Plots of 20 x 20 m distributed within each site were established to represent 0.1% of the total area. The plot size of 20 m x 20 m was selected to represent the forest vegetation with canopy height < 20 m.

Determination of above and below ground biomass

Species richness for each plot was calculated as the number of total tree species existing among which a minimum of one individual tree has height and diameter at breast height (DBH) ≥ 10 cm. Above and below ground biomass for the tree layer and associated carbon stocks were determined using species-specific allometric equations (Table 1).

Above Ground Biomass (AGB) was obtained

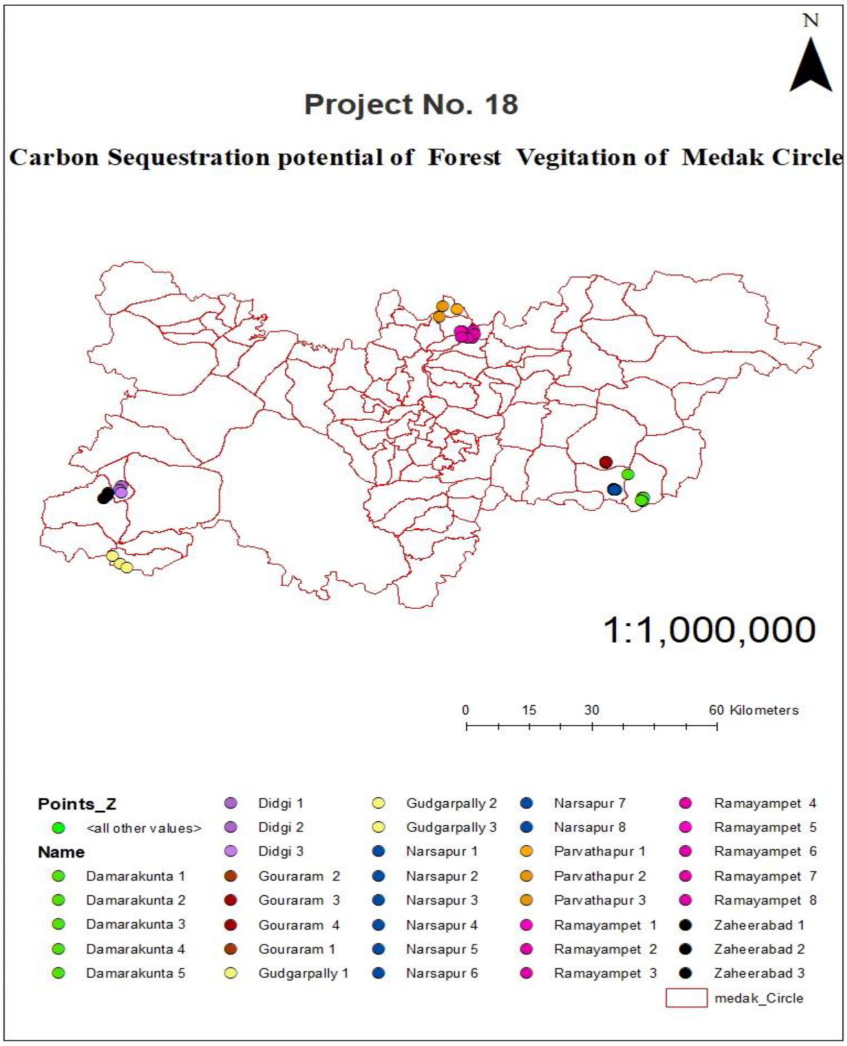

Fig. 1. Location of primary and secondary forests of Medak district assessed in the present study.

as product of volume (cm3) and density (g/cm^3) of the biomass (Ravindranath and Ostwald 2007). The Below Ground Biomass (BGB) has been determined as 26% of the AGB, based on the proportion of root to shoot (Cairns, Brown and Pearce 1994). Carbon stock refers to the quantity of carbon accumulated in the living biomass and soil. The total biomass so obtained is transformed to carbon stock density using a conversion factor of 0.47 (Change, 2006). Assuming that the carbon content of tree biomass can range between 45-50%, depending on the species and tree component (Thomas and Martin 2012), a conversion factor of 47% was adopted for determining the extent of carbon sequestered. The carbon stocks were multiplied by a factor of 3.67 (atomic mass of CO_2 / atomic mass of C) to determine the carbon sequestered. All the trees falling in the plot (20 × 20 m^2) were listed to estimate biomass. Diameter at breast height (DBH at 1.37 m) of individual trees in each quadrant were measured; biomass was determined for individual trees in each quadrant and expressed per hectare. Species-specific allometric equations incorporating DBH and height

Table 2. Tree density, basal area of tree species and species richness indices of Ramayampet range.

Tree species	Number of trees (per 3200 m²)	(per ha)	Basal area (m²) (per 3200 m²)	(per ha)
Buchanania lanzan	13	81	0.9	2.69
Butea monosperma	18	113	5.5	17.03
Cassia fistula	17	106	1.2	3.88
Chloroxylon swietenia	68	425	12.9	40.31
Dalbergia paniculata	128	800	20.5	63.94
Diospyros melanoxylon	18	113	5.3	16.44
Eucalyptus	16	100	4.8	14.94
Ficus bengalensis	13	81	0.8	2.53
Gmelina arborea	73	456	13.3	41.47
Holoptelia intergrefolia	17	106	1.3	4.16
Lagerstroemia parviflora	21	131	5.9	18.34
Lannea coromandelica	21	131	5.9	18.50
Madhuca indica	14	88	1.0	3.00
Semicarpus anacardium	46	288	9.3	28.97
Tectona grandis	15	94	1.3	3.94
Terminalia alata	18	113	5.6	17.38
Terminalia arjuna	15	94	1.2	3.69
Total	531	3320	96.7	301.21
Shannon's index		2.48		
Simpson's index		0.88		

Table 3. Tree density, basal area of tree species and species richness indices of Narsapur range.

Tree species	Number of trees (per 4800 m²)	(per ha)	Basal area (m²) (per 4800 m²)	(per ha)
Acacia leucocephala	54	386	15.6	39.42
Acacia nilotica	32	206	3.1	10.31
Buchanania lanzan	42	286	5.6	17.38
Butea monosperma	73	478	18.3	48.47
Chloroxylon swietenia	22	103	2.6	9.94
Dalbergia paniculata	36	229	5.3	14.44
Diospyrosmelanoxylon	21	131	3.3	11.50
Eucalyptus	79	496	21.6	64.31
Holptelia integrifolia	28	132	4.5	14.88
Lagerstroemia parviflora	31	164	4.8	18.94
Lannea coromandelica	28	136	4.2	13.63
Madhuca indica	26	128	2.4	6.69
Pongamia pinnata	24	125	0.9	4.69
Switenia mircophylla	14	88	2.6	8.00
Tectona grandis	21	131	3.2	10.34
Terminalia arjuna	34	176	5.5	19.03
Total	546	3395	103.5	311.97
Shannon's index		2.52		
Simpson's index		0.90		

measurements for biomass estimation were adopted from the Forest Survey of India database (FSI 1996). These equations necessitate specific gravity measurements of the wood (Little and Wadsworth, 1964).

Soil organic carbon (SOC) determination

At least ten soil samples within 0-10 cm depth were randomly acquired from each quadrant using a 7.5 cm diameter auger. All samples were cleared off any organic components including roots and leaves and then carried to the laboratory in zip-lock bags. A composite consisting of equal proportions of all the ten samples was prepared and oven dried at 65°C. SOC was measured by oxidizing with a mixture of acid and dichromate solution and then titrating the unutilized dichromate with ferrous ammonium sulfate in the presence of diphenyl amine indicator (Walkley and Black 1934).

Biodiversity indices

Simpson's diversity index was calculated using the equation:

$$D = \sum n_i (n_i-1)/N (N-1)$$

where N is the total number of all trees and n_i represents the numbers of individuals of each individual species.

Simpson's diversity index = $1/p_i^2$, where p_i is the total individuals in a species community. Species richness S is the number of species in the community or sample

Simpson's evenness E=D/S, where D is the Simpson's diversity index and S is the species richness.

Shannon-Wiener biodiversity index $H = -\sum s_i=1 (p_i) (\ln p_i)$, where pi is the total individuals in a species community (Barlow *et al.* 2007).

Statistical analysis

Students t-test was used to examine differences of each parameter between old-growth primary forests and ANR secondary forests, including soil organic

Table 4. Tree density, basal area of tree species and species richness indices of Zaheerabad range.

Tree species	Number of trees (per 7200 m²)	(per ha)	Basal area (m²) (per 7200 m²)	(per ha)
Acacia sundra	13	81	0.9	2.69
Albizia amara	18	113	5.3	16.44
Albizia lebbeck	17	106	1.3	3.97
Anacardium occidentalis	128	800	20.5	63.94
Azadirachta indica	46	288	9.3	28.97
Buchanania lanzan	21	131	5.9	18.50
Butea monosperma	18	113	5.5	17.03
chloroxylon switenia	14	88	1.0	3.00
Dalbergia sissoo	17	106	1.2	3.88
Dendrocalamus strictus				
Diospyrous melanoxylon	18	113	5.6	17.38
Eucalyptus	17	106	1.3	4.16
Holptelia integrifolia	73	456	13.3	41.47
Lagerstroemia parviflora	15	94	1.3	3.94
Madhuca indica	16	100	4.8	14.94
Phyllanthus emblica	15	94	1.3	4.09
Pongamia pinnata	15	94	1.2	3.69
Santalum album	13	81	0.8	2.53
Tectona grandis	18	113	5.3	16.63
Terminalia bellirica	68	425	12.9	40.31
Zyziphus mauritiana	21	131	5.9	18.34
Total	581	3633	104.6	325.9
Shannon's index		2.45		
Simpson's index		0.88		

Table 5. Tree density, basal area of tree species and species richness indices of Gouraram site.

Tree species	Number of trees (per 1600 m²)	(per ha)	Basal area (m²) (per 1600 m²)	(per ha)
Acacia leucophloea	36	225	0.99	6.18
Aegle marmelos	9	56	0.43	2.69
Annona squamosa	18	113	0.79	4.94
Azadirachta indica	19	119	0.86	5.38
Buchanania lanzan	82	513	2.50	15.63
Cassia fistula	11	69	0.59	3.69
Diospyrous chloroxylon	12	75	0.68	4.25
Diospyrous melanoxylon	52	325	0.78	4.88
Eucalyptus	13	81	0.52	3.25
Lagerstroemia parviflora	42	263	1.37	8.56
Madhuca indica	23	144	0.99	6.19
Tectona grandis	46	288	1.32	8.25
Terminalia arjuna	10	63	0.46	2.88
Terminalia tomentosa	12	75	0.49	3.06
Total	385	2409	12.77	79.83
Shannon's index		2.53		
Simpson's index		0.90		

carbon concentrations.

RESULTS

The study was conducted covering the major primary and secondary forest sites in the erstwhile Medak district of Telangana region. Specific sites included the primary forests of Ramayampet, Narsapur and Zaheerabad, along with secondary forests of Gouraram, Narsampally and Peerlapally.

The structural attributes such as species richness, density, basal area and biodiversity indices are shown in Tables 2-7, for each of the primary and secondary forests studied. Primary forests at Ramayampet, Narsapur and Zaheerabad are dense forest with canopy cover > 40%, comprising of 17, 16 and 21 different species, respectively.

Major species in Ramayampet forest were *Dalbergia paniculata, Gmelina arborea, Chloroxylon swietenia* and *Semicarpus anacardium*.Narsapur forest was dominated by *Eucalyptus* spp., *Butea monosperma, Acacic leucocephala, Buchanania lanzan, Dalbergia paniculata* and *Terminalia arjuna.* Zaheerabad primary forest was rich of *Anacardium occidentalis, Holptelia integrifolia, Terminalia bellirica* and *Azadirachta indica.* Secondary forest sites at Gouraram, Narsampally and Peerlapally were raised through assisted natural regeneration in 2014 with 14,14 and 10 types of tree species, respectively. The major tree species in Gouraram ANR forest consisted of *Buchanania lanzan, Disopyros melanoxylon, Tectona grandis, Lagerstroemia parviflora, and Acacia leucocephala.* Narsampally ANR forest was dominated by *Buchania lanzan, Semicarpus anacardium, Annona squamosa, Butea monosperma,* and *Lagerstroemia parviflora*. Peerlapally secondary forest dominantly comprised of *Syzygium cumini, Azadirachta indica, Ficus racemosa,* and *Holoptelia integrifilia.*

Total biomass and carbon stocks

Table 8 presents the biomass and carbon stock densities of primary forests in Medak. Above ground biomass (AGB) in Ramayampet, Narsapur and Za-

Table 6. Tree density, basal area of tree species and species richness indices of Narsampalle site.

Tree species	Number of trees (per 3200 m²)	(per ha)	Basal area (m²) (per 3200 m²)	(per ha)
Acacia leucophloea	12	75	0.78	3.06
Albizia amara	11	69	0.61	3.69
Annona squamosa	52	325	1.76	7.88
Azadirachta indica	18	113	0.75	4.94
Buchanania lanzan	82	513	2.50	17.63
Butea monosperma	46	288	1.64	9.25
Diospyrous melanoxylon	8	50	0.39	2.44
Lagerstroemia parviflora	42	263	1.37	8.56
Pongamia pinnnata	13	81	0.52	3.25
Santalum album	9	56	0.43	2.69
Semicarpus anacardium	61	381	2.26	11.50
Swetiana macrophylla	12	75	0.68	4.25
Tectona grandis	10	63	0.46	2.88
Terminalia arjuna	19	119	0.86	5.38
Total	395	2471	15.01	87.4
Shannon's index		2.33		
Simpson's index		0.89		

Table 7. Tree density, basal area of tree species and species richness indices of Peerlapalle site.

Tree species	Number of trees (per 1600 m²	(per ha)	Basal Area (m²) (per1600 m²	(per ha)
Azadirachta indica	52	325	0.78	4.88
Cassia fistula	13	81	0.52	3.25
Ficus racemosa	46	288	1.32	8.25
Ficus benghalensis	11	69	0.59	3.69
Ficus religiosa	8	50	0.39	2.44
Ficus virens	18	113	0.79	4.94
Holoptelia integrifolia	42	263	1.37	8.56
Pongamia pinnata	9	56	0.43	2.69
Syzygium cumini	82	513	2.50	15.63
Tamarindus indica	12	75	0.49	3.06
Total	293	1833	9.18	57.39
Shannon's index		1.96		
Simpson's index		0.84		

heerabad forests was 30.5, 38.0 and 36.3 Mg/ha, respectively. Below Ground Biomass (BGB) computed as 26% of the AGB, based on the proportion of root to shoot was 7.9 Mg/ha in Ramayampet, 9.9 Mg/ha in Narsapur and 9.4 Mg/ha in Zaheerabad forests. Combining these two indices, the total biomass was found to be 47.9 Mg/ha in Narsapur, followed by 45.7 Mg/ha in Zaheerabad and 38.4 Mg/ha in Ramayampet. The total biomass so obtained was transformed to carbon stock density using a conversion factor of 0.47 (Change, 2006), which indicated that the total carbon stocks in Ramayampet, Narsapur and Zaheerabad forests was 18.1, 22.5 and 21.5 Mg/ha, respectively. The carbon stocks were multiplied by a factor of 3.67 (atomic mass of CO_2 / atomic mass of C) to determine the carbon sequestered. Thus, the total estimate of carbon sequestered in Ramayampet, Narsapur and Zaheerabad forests was found to be 66.3, 82.7 and 78.8 Mg/ha, respectively. Soil organic carbon determined in Ramayampet, Narsapur and Zaheerabad forests was 1.37, 1.33 and 1.31 Mg/ha, respectively.

Table 9 presents the biomass and carbon stock densities of secondary forests in Medak. Above ground biomass (AGB) in Gouraram, Narsampally and Peerlapally secondary forests was 15.9, 19.8, and 32.3 Mg/ha, respectively. Below Ground Biomass (BGB) computed as 26% of the AGB, based on the proportion of root to shoot was 4.1 Mg/ha in Gouraram, 5.2 Mg/ha in Narsampally and 8.4 Mg/ha in Peerlapally secondary forests. Combining these two indices, the total biomass was found to be 40.7 Mg/ha in Peerlapally, followed by 25.0 Mg/ha in Narsampally and 20.0 Mg/ha in Gouraram forests. The total biomass so obtained was transformed to

Table 8. Biomass and carbon stock densities for primary forests in Medak. Values indicate mean±SD. Means with different superscripts are significantly different from each other at P< 0.05. Mg is Megagram = 1000 kg = 1 metric tonne; Ha is hectares.

	Ramayampet	Narsapur	Zaheerabad
Total aboveground biomass (Mg/ha)	30.5 ± 9.25	38.0 ± 9.9	36.3 ± 14.5
Total belowground biomass (Mg/ha)	7.9 ± 2.41	9.9 ± 2.6	9.4 ± 3.77
Total biomass (Mg/ha)	38.4 ±11.66	47.9 ± 12.4	45.7 ± 18.27
Total carbon stocks (Mg/ha)	18.1 ±5.48	22.5 ± 5.8	21.5 ± 8.5
Total C sequestered (Mg/ha)	66.3 ± 20.11	82.7 ± 21.4	78.8 ± 31.51
Soil organic carbon (Mg/ha)	1.37^a ± 0.22	1.33^b ± 0.43	1.31^c ± 0.60

Table 9. Biomass and carbon stock densities for secondary forests of Medak. Values indicate mean ± SD. Means with different superscripts are significantly different from each other at $p< 0.05$. Mg is Megagram = 1000 Kg = 1 metric tonne; Ha is hectares.

	Gouraram	Narsampally	Peerlapally
Total aboveground biomass (Mg/ha)	15.9 ± 4.13	19.8 ± 5.74	32.3^{a} ± 5.68
Total belowground biomass (Mg/ha)	4.1 ± 1.07	5.2 ± 1.49	8.4^{a} ±1.47
Total biomass (Mg/ha)	20.0 ± 5.21	25.0 ± 7.24	40.7^{a}±7.15
Total carbon stocks(Mg/ha)	9.4 ± 2.45	11.8 ± 3.40	19.1^{a}±3.36
Total C sequestered (Mg/ha)	34.5± 8.98	43.3 ± 12.48	70.1^{a}±12.33
Soil organic carbon (Mg/ha)	0.58 ± 0.18	0.89^{a} ± 0.43	0.78^{b} ± 0.13

carbon stock density using a conversion factor of 0.47 (Change 2006), which indicated that the total carbon stocks in Gouraram, Narsampally and Peerlapally forests was 9.4, 11.8 and 19.1 Mg/ha, respectively. The carbon stocks were multiplied by a factor of 3.67 (atomic mass of CO_2 / atomic mass of C) to determine the carbon sequestered. Thus, the total amount of carbon sequestered in Gouraram, Narsampally and Peerlapally forests was found to be 34.5, 43.3, and 70.1 Mg/ha, respectively. Soil organic carbon content in Gouraram, Narsampally and Peerlapally forests was 0.58, 0.89 and 0.78 Mg/ha, respectively.

Species richness, diversity and stand characteristics

A total of 25 tree species representing 14 families were recorded from both forest types. The number of species of the tree layer in the ANR stands was similar to that in the natural forest. Exponential of Shannon entropy of plants in the tree layer was slightly lower for secondary forest than primary forests. Simpson's diversity index was not different between primary and secondary forests.

Correlation between carbon stocks and species richness

A poor correlation was observed between the carbon stocks and species richness, both in primary or secondary forests (Figs. 2 and 3).

DISCUSSION

In the present study, we have assessed the extent of recovery of carbon stocks and measures of tree species richness in secondary forest sites located in Medak, Telangana State. These data, although limited to a few secondary forest sites within the Telangana state indicate that carbon stock accumulation is more in the primary, natural forests in the region. The secondary (ANR) forests being young appear to be catching up

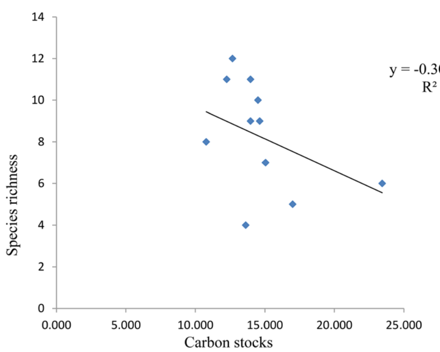

Fig. 2. Correlation between carbon stocks and species richness in secondary forests.

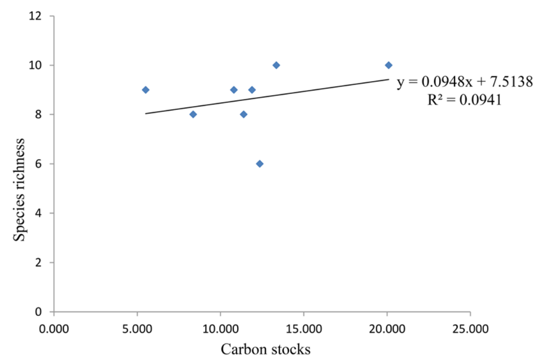

Fig. 3. Correlation between carbon stocks and species richness in primary forests.

with carbon sequestration and biomass accumulation. The biomass recovery in the secondary forests was lesser than that of primary forests, despite no significant differences in terms of species richness. It should be noted that the secondary forests in our study exhibited relatively small-stemmed trees and lacked the characteristics of old- growth natural forests, and accordingly relative lower biomass was observed.

The total tree layer biomass values from either the primary or secondary forests obtained in the present study were observed to be lower than 46.7 t/ha reported earlier for dry deciduous forests in Karnataka (Singh and Singh, 1991). The AGB showed 3-fold variation within the dry deciduous forests across districts in south western part of Karnataka (Devagiri *et al*. 2013). Our estimates of AGB in secondary forest sites are within the reported range of 7.69-20.48 t/ha. Similarly, the AGB in primary forest site was on par with the reported values. However, the biomass indices reported in the current study are lower than those reported elsewhere in India (42-78 t/ha) (Singh & Singh, 1991). Majority of the forests in Telangana are dry deciduous and scrub forests. AGB and carbon density of primary forests were only slightly higher than the reported values of 24 Mg/ha of AGB and 12 Mg/ha of carbon density (Devagiri *et al*. 2013). The present AGB estimates in secondary forests are less when compared with the global estimates of 30-273 t/ha for tropical dry forests (Murphy and Lugo, 1986).The carbon density indices of primary forests are lower than the average carbon density in India 35 Mg/ha as estimated by the FAO (FAO 2007).

Above ground biomass of the ANR forest was approximately 2 times lower than that in the natural forest, due to the fact that ANR forest consisted of relatively young stands as compared to the natural forest. Rapid accumulation of biomass in ANR forests may be attributed to the much higher seedling densities. Cessation of burning appears to preserve the seed bank and root systems providing a more efficient nutrient uptake during the early successional period. The greater vegetation cover associated with diversity of species also likely contributes to minimize nutrient leaching. The improved nutrient availability may contribute to the greater biomass accumulation after the ANR practices. In later stages, when trees further grow, the more diverse tree species may use different proportions of resources (nutrients in different depths of soil) and contribute to the greater biomass accumulation through the complementary effect. The greater accumulation of above ground biomass in the primary forests in turn led to the greater litter fall production which also contributed to the greater below ground biomass and soil organic carbon content. Secondary forests also appear to show dramatic biomass resilience, partly due to water availability, although other factors play a role as well (Erskine, Lamb and Bristow 2006).

A total number of 2349 stems/ha was observed in primary forests as compared to 2237 stems/ha in the secondary forests; However, majority of the stems exhibited DBH $\geq$ 10 cm in the primary forests. The observed stem density in primary forest sites are much higher than the reported values of 890 stems/ha for the dry deciduous primary forests of Bhadra Wildlife Sanctuary in Karnataka, India (Krishnamurthy *et al*. 2010).

Soils serve as huge reservoirs of carbon, 66% of which is organic form and is obtained as a product of metabolic turnover. Global soil organic carbon stores are estimated to be 1500 Pg of carbon, at least 2-3 fold higher than the atmospheric carbon (Scharlemann et al. 2014). Soil organic carbon content was found to be significantly lower in secondary ANR forests compared to primary forest in the present study. It is known that the capacity of soils to sequester carbon varies depending on the vegetation it holds. Despite a similar species profile across both primary and secondary forests in the present study, the secondary forest sites in our study exhibited ~3 fold lower organic carbon stocks in soil. These observations are in line with earlier reports wherein SOC content in plantations is lowered by ~20% when compared to primary forests (Guo and Gifford 2002, Liao *et al.* 2010) Although SOC storage is closely linked to soil properties and vegetation inputs, we have observed higher SOC in primary forests, which are relatively less disturbed when compared to secondary forests, despite similar soil properties and the type of vegetation.

Although earlier studies in experimental plantations aimed at investigating the relationship between tree diversity and carbon stock densities, it lacked the features of natural variability and largely undermined the species richness of old growth primary forests (Scherer-Lorenzen *et al.* 2005). Thus, it is argued if the data from experimental plantations holds good for natural forests. Average species diversity expressed per hectare in majority of the tropical plantations and natural forests was similar (Erskine *et al.* 2006, Healy *et al.* 2008, Piotto 2008, Scherer-Lorenzen *et al.* 2005), however the latter have a maximum diversity ≥ 300 species (Condit *et al*. 2005). In the present study, both primary and secondary forests had a similar tree species diversity, and therefore there was only a weak correlation between carbon stock and tree species diversity (r^2=0.09 to 0.17). These results do not conform with the fact that species richness tends to promote plant productivity and carbon cycling (Grace *et al.* 2016, Hooper *et al.* 2012). Although species richness did not vary between the primary and secondary forest sites, the latter exhibited larger C stocks per area solely due to higher stem density, rather than resource use and nutrient retention. It is not known if the variability in C stocks as seen between secondary vs primary forest sites, would decrease over longer time periods, as the young stands begin to age in secondary forests.

The data supports the previous observations that regeneration of sub-tropical secondary forests is possible with actively stored carbon in above ground biomass. ANR thus has great potential in tropical forests that have not been intensively degraded or used and proves to be effective in achieving significant carbon outcomes. One of the important drawbacks of the study is the use of allometric equations for estimation of biomass which are actually derived from the undisturbed forest plots of primary forests. This may have resulted in overestimation of the biomass despite the trees having a low DBH (Van Breugel *et al.* 2011) and a lack of relationship between forest height-diameter relationships (Montgomery and Chazdon 2001).

CONCLUSION

Carbon pools and tree species richness in the sub-tropical secondary forests have the potential to recover quickly through adopting assisted natural regeneration. Assisted natural regeneration offers a productive and socio-economically viable landscape restoration strategy for climate change adaptation and mitigation and biodiversity conservation. Although ANR forests have rapid rates of carbon sequestration, with potential significance for global carbon cycle and improving biodiversity, the commercial value of the ANR forests is not investigated in depth.

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