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Carbon Sequestration Potential of Tropical Dry Deciduous Forests in Southern Haryana, India

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ABSTRACT

This study analyzes plant biomass, and carbon sequestration in the soil –plant system of the tropical dry deciduous forest ecosystems. The study was carried out in three protected forests in the tropical dry deciduous forest region in Gurgaon district (27^0 27' to 28^0 32' N; 76^0 39' to 77^0 32' E; 186 to 437 m altitude), southern Haryana, India. The forests are dominated by *Ailanthus excelsa* and *Cassia fistula* (AE-CF) at Bhondsi; *Acacia leucophloea* and *Balanites aegyptiaca* (AL-BA) at Gawalpahari; *Anogeissus pendula* and *Acacia leucophloea* (AP-AL) at Raisina. The tree density was 492.5 to 642.5 trees ha^{-1} with a total basal area of 14.62 to 23.54 m^2 ha^{-1}. The aboveground biomass of trees in the three forests was 37.93 to 63.73 Mg ha^{-1}; the belowground biomass being 11.12 to 17.81 Mg ha^{-1}. The total net productivity of trees in the three forests was 6.17 to 12.06 Mg ha^{-1} yr^{-1}. Total carbon pool in the three forests was (Mg ha^{-1}) 52.59 AE-CF forest, Bhondsi; 34.17 AL-BA forest, Gawalpahari; 33.61 AP-AL forest, Raisina. The contribution of shrubs to total carbon pool varied from 12.59 to 19.78 %. The herb layer accounted for 3.48 to 11.48% of total carbon stock in plants. Net carbon flux in the three forests ranged from 2.91 to 5.55 Mg C $ha^{-1}yr^{-1}$. The soil carbon pool was regulated by vegetation composition and the spatial distribution of carbon in the soil profile. The soil organic carbon pool (Mg C ha^{-1}) was : 7.383 to 4.923 (0-15cm); 6.693 to 4.183 (15-30cm); 4.166 to 3.335 (30-45cm); 3.590 to 2.500 (45-60cm).The soil organic carbon pool at 0-30cm soil depth was 54.73% to 64.52 % of the total organic carbon pool up to 60cm soil depth. The studied forests showed an appreciable carbon sequestration potential in the plant soil system which could play an important role in climate change mitigation and adaptation.

Key Words: Biomass; Litter Fall; Carbon Pool; Carbon Flux; Net Primary Productivity (NPP)

INTRODUCTION

Dry forests once covered more than 40% of tropical lands worldwide before large scale deforestation (Murphy and Lugo 1986). Nearly 30% of forests in mainland Southeast Asia are dry forests (Poffenberger 2000), whereas up to 60% of forests in India are comprised of tropical dry forests (Waeber et al. 2012). Tropical dry forests occur in climates exhibiting distinct alternating wet and dry seasons of four to six months or more over the annual cycle (Olivares and Medina 1992). These forests are considered to be highly threatened of all major tropical forest habitats in different regions of the world (Murphy and Lugo 1986, Gillespie et al. 2012, Sunderland et al. 2015) and are attracting the attention of workers for their sustainable management and conservation (Janzen 1988). The timber and non-timber products of these forests are essential to the livelihoods and well-being of millions of the poorest people globally (Waeber et al. 2012). The quantification of biomass stocks in mature and regenerating seasonally dry tropical forests is important for assessing carbon budgets and for designing appropriate local policy and management tools to sequester and store carbon (Becknell et al. 2012).

The continuous and rapid increase in carbon dioxide and other green house gases (GHGs) in the atmosphere could lead to significant climate change (IPCC 2007). Forests considered to be a sink as well as

a source of carbon dioxide, are reported to be a major component of the carbon reserves in the world's ecosystems (Houghton 2007). Carbon sequestration can occur in plant biomass, organic and inorganic carbon in surface soil and carbon storage in soil profiles. In terrestrial ecosystems (i.e., soils, trees and other vegetation), carbon sequestration is a natural process based on photosynthesis and humification of biomass (Lal 2009). Plant biomass and soil organic matter constitute the major pool of carbon in terrestrial ecosystems. The biotic pool in vegetation stores about 610 Pg C at any given time (Amundson 2001). The significant influence of tropical forests on carbon cycle is attributed to the high rate of primary production besides the large pool and flux sizes (Brown and Lugo 1984). The quantity of biomass in a forest determines the potential amount of carbon (Brown et al. 1999).

Estimating the amount of forest biomass is required for estimating the forest's potential to sequester and store carbon in the forest ecosystem. The carbon stocks in different types of forests ecosystems have been estimated on the basis of forest inventories and using appropriate conversion factor of biomass to carbon (Lal and Singh 2000, Chhabra et al. 2002, Dadhwal et al. 2009, Patil et al. 2010, Kumar et al. 2011, Sahu et al. 2015). Carbon sequestration in dry forests can help mitigate the processes associated with climate change (Becknell et al. 2012).

The role of understorey plants in the net carbon and nitrogen fluxes of forests has been emphasized by only a few workers (Lodhiyal et al 2002, Moore et al. 2007, Powell et al. 2008). In forest ecosystems, shrubs represent a moderate to large biomass and carbon pool which has not been given much weight age in carbon storage assessments (Conti and Díaz 2013, Conti et al. 2013). Relatively few studies have been carried out on biomass production of herbaceous layer in forest ecosystems of India (Joshi et al.1991; Saxena et al. 1996).

Soil organic carbon is controlled by the balance of carbon inputs from plant production and outputs through decomposition (Schlesinger 1977) and its storage is the most accepted method for long term carbon sequestration in terrestrial ecosystems. Soil carbon sequestration is also important in maintaining a balance in greenhouse gas emissions and is strongly related to site conditions, i.e., soil structure, initial soil carbon content, climate (Montagnini and Nair 2004, Nair et al. 2009). Soil carbon in its various pools within the soil, provides structure and stability to soil (Palm et al. 2007). Soil carbon pool enhancement and optimization is essential for social, ecological and economic sustainability.

Keeping in view the importance of tropical dry forests in regional carbon budget, the aim of this study was to analyze plant biomass, and carbon storage in the tropical dry deciduous forest ecosystems in a semi-arid region of southern Haryana. It was also aimed to analyze soil carbon storage in relation to vegetation composition.

STUDY SITES

The protected dry deciduous forests selected for the study are located at Bhondsi, Gawalpahari and Raisina in Gurgaon district in northern India (27º 27' to 28º 32'N latitude and 76º 39' to 77º 32' E longitude; Figure 1). Altitude varies from 186 m to 437 m above mean sea level (msl)**.** The forest at Bhondsi is located on plain soil at an altitude of 186 m above msl. The soil has an undulating topography at Gawalpahari whereas at Raisina, the forest is located on a low lying hill with an altitude of 437 m above msl**.** The climate of the study area is semi-arid and monsoonal with distinct winter, summer and rainy seasons (Singh et al. 2016). During the study period maximum and minimum temperatures were 41ºC and 3.2 ºC respectively and the total annual rainfall was 645.9mm. A major portion of rainfall is received during the rainy months from June to September. Vegetation composition and species diversity of the three forest ecosystems have been described by Singh et al. (2014). Some characteristics of the dry deciduous forests at the study sites are given in Table 1. The forests are dominated by *Ailanthus excelsa* and *Cassia fistula* (AE-CF) at Bhondsi, *Acacia leucophloea* and *Balanites aegyptiaca* (AL-BA) at Gawalpahari and *Anogeissus pendula* and *Acacia leucophloea* (AP-AL) at Raisina. The tree density was 492.5 to 642.5 trees ha^{-1} with a total basal area of 14.62 to 23.54 m^2 ha^{-1}.Dominant shrubs in the three forests are *Capparis sepiaria*, *Adhatoda vasica*, *Carissa spinarum* and *Lycium europaeum*.

The soils at Bhondsi and Gawalpahari are old alluvium and sandy. At Raisina, the soil is sandy-loam and underlying rocks are quartzite, gritty quartzite, with thin intercalations of micaceous schist. The soil organic carbon concentration in the three forests varied from 0.21% to 0.31%; soil pH varied from 7.29 to 8.46. The bulk density of soil, based weight/ volume relationship as determined using the soil core method, ranged from 1.48 to 1.56 g cm^3 (Table 2).

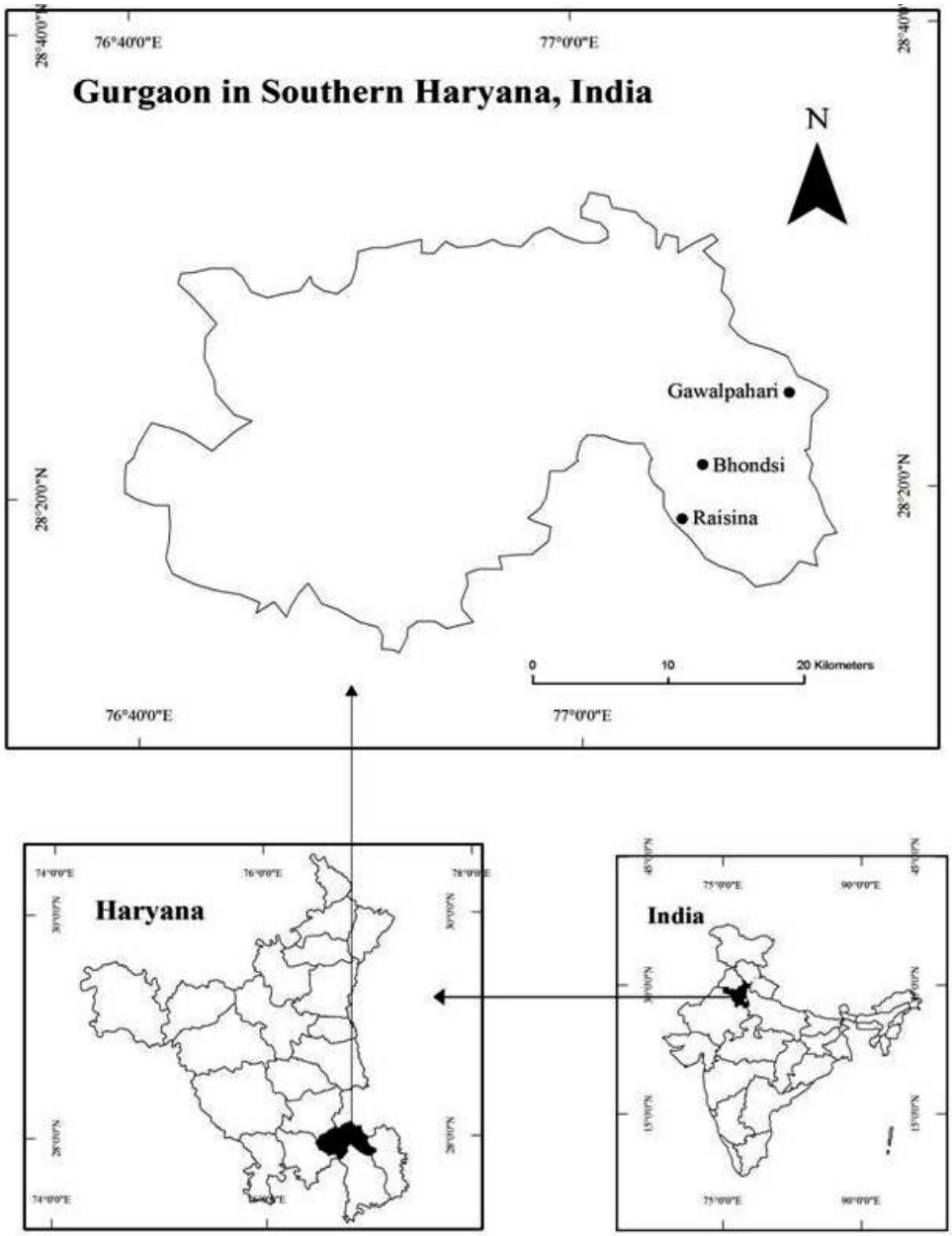

Figure 1. Location of Gurgaon district in Haryana

Table 1. Some characteristics of the dry deciduous forests at Bhondsi, Gawalpahari and Raisina in Gurgaon.

Forest type	Site	Density trees (trees ha^{-1})	Basal area trees (m^2 ha^{-1})	Density shrubs (stems ha^{-1})	Basal area shrubs (m^2 ha^{-1})
Ailanthus excelsa-Cassia fistula (AE-CF) forest	Bhondsi	642.5	23.54	2400	2.54
Acacia leucophloea-Balanites aegyptiaca (AL-BA) forest	Gawalpahari	599.5	15.52	2100	2.84
Anogeissus pendula-Acacia leucophloea (AP-AL) forest	Raisina	492.5	14.62	1700	0.77

Table 2. Some physical and chemical soil characteristics at different soil depth in the dry deciduous forests at Bhondsi, Gawalpahari and Raisina in Gurgaon. (Mean± 1 SE)

Forest/ Site	Soil depth (cm)	pH (1:2)	Organic carbon (%)	Inorganic carbon (%)	Bulk density (g cm^{-3})
Ailanthus excelsa-Cassia fistula forest, Bhondsi	0-15	8.46^{a} ±0.052	0.31^{a} ±0.014	0.42^{b}±0.004	1.48^{c} ±0.008
	15-30	8.52^{a} ±0.054	0.27^{a} ±0.012	0.43^{ab}±0.003	1.54^{b} ±0.009
	30-45	8.57^{a} ±0.063	0.17^{b} ±0.023	0.43^{a} ±0.004	1.57^{a} ±0.004
	45-60	8.61^{a} ±0.043	0.14^{b}±0.015	0.44^{a} ±0.005	1.59^{a} ±0.004
LSD (P<0.05)		0.164	0.0511	0.0127	0.0216
F value		1.425^{NS}	24.115**	3.315*	43.319**
Acacia leucophloea- Balanites aegyptiaca forest Gawalpahari	0-15	8.11^{c}±0.051	0.21^{a}±0.011	0.42^{b}±0.005	1.56^{c}±0.016
	15-30	8.41^{b}±0.043	0.17^{ab}±0.010	0.43^{ab}±0.005	1.62^{b}±0.010
	30-45	8.52^{ab}±0.036	0.16^{b}±0.012	0.44^{ab}±0.003	1.66^{a}±0.091
	45-60	8.60^{a}±0.043	0.14^{b}±0.017	0.44^{a}±0.003	1.69^{a}±0.005
LSD (P<0.05)		0.1347	0.0385	0.0131	0.0332
F value		23.785**	5.602*	3.699*	30.184**
Anogeissus pendula- Acacia leucophloea forest Raisina	0-15	7.29^{c}±0.049	0.29^{a}±0.011	0.43^{b}±0.006	1.50^{d}±0.010
	15-30	7.42^{bc}±0.043	0.18^{b}±0.014	0.44^{ab}±0.005	1.58^{c}±0.008
	30-45	7.51^{ab}±0.041	0.14^{c}±0.014	0.45^{ab}±0.005	1.62^{b}±0.006
	45-60	7.62^{a}±0.041	0.10^{c}±0.008	0.47^{a}±0.009	1.65^{a}±0.004
LSD (P<0.05)		0.1334	0.0383	0.0167	0.0246
F value		10.169**	40.828**	2.764^{NS}	63.115**

d.f. =3, 12 * P<0.05; **P<0.01; NS=not significant; Different superscript letters indicate a significant difference (P<0.05) among soil depths by Duncan's multiple range test.

METHODS

Analysis of Plant Biomass

The quadrat method was used for analyzing plant biomass in the selected forests at the three sites, i.e., Bhondsi, Gawalpahadi and Raisina, by sampling 12 randomly placed quadrats of 20×20m. The number of trees occurring within in each quadrat was noted and marked during second week of March 2011. The circumference of trees (> 31.5 cm) was measured at 1.37 m height from above the ground in the second week of March, 2011 and 2012. For determining the density of shrubs observations were recorded from sample plots of 5×5m laid within 20×20m quadrats. The plant biomass of the herbaceous layer was determined by using the harvest method (Gupta and Singh 1982).

Aboveground biomass of trees was estimated by using local species specific volume equations and specific gravity for each tree species. The volume was multiplied by species specific gravity to obtain the biomass, which requires DBH measurements of the trees, volume equations and species specific gravity of each tree. The Species specific volume equations and species gravity of trees for 15 species were used following FSI (2011) and are summarized in Table 3. For the remaining species general equation was used (Table 3). Below ground biomass was computed by using the regression equation of Cairns et al. (1997) for tropical trees for each forest type as follows: BGB = exp {-1.0587 + 0.8836 × ln(AGB) }. AGB and BGB were added to calculate total plant biomass. The mean biomass of the trees was added to find the total biomass of each site.

Estimation of Shrub Biomass

Two sub plots of 5×5m were laid within the 20×20m plots (12 sampling plots) on all the three sites. The number of plants of different shrub species was counted in marked plots. Three to four shrub plants of each species representing smallest to largest expanse were selected for the measurement of length and diameter of

Table 3. Volume equations and specific gravity (g cm^{-3}) used for computing biomass of different tree species (based on FSI 1996)

Tree species	Volume Equation	Specific gravity
Acacia leucophloea (Roxb.) Willd.	$\sqrt{V}$=-0.00142+2.61911*D-0.54703*$\sqrt{D}$	0.660
Acacia senegal (L.) Willd.	$\sqrt{V}$=-0.00142+2.61911*D-0.54703*$\sqrt{D}$	0.660
Acacia nilotica Willd.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.879
Acacia tortilis (Roxb.) Crab	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.610
Ailanthus excelsa Roxb.	V/D^2=0.32056+5.16781*D-1.83345*$\sqrt{D}$	0.356
Albizia lebbeck (L.) Benth.	V=-0.032056+5.87369*D^2	0.534
Anogeissus pendula Edegw	V/D^2=-0.011053/D^2+0.087418/D+2.54570+4.766918*D	0.757
Azadirachta indica A. Juss.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.693
Balanites aegyptiaca (L.) Del.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.630
Butea monosperma (Lamk.) Taub.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.465
Cassia fistula L.	V=0.066+0.287*D^2*H	0.746
Cordia dichotoma Forster f.	V=-0.49388+7.56417*D-31.453730*D^2+50.9377*D^3	0.733
Dalbergia sissoo Roxb.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.692
Derris indica (Lamk.) Bennet	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.609
Diospyros cordifolia Roxb.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.610
Kigellia pinnata (Jacq.) DC.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.720
Leucaena leucocephala (Lamk.) de Wit	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.550
Maytenus emarginatus Ding Hou	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.710
Nyctanthes arbor-tristis L.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.610
Prosopis cineraria (L.) Druce	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.666
Prosopis juliflora (Sw.) DC.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.850
Salvadora oleoides Decne.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.865
Syzygium cumini (L.) Skeels	V/D^2=0.098909/D^2-1.94468/D+13.36728-6.33263*D	0.647
Tamarix articulata Vahl.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.620
Tecomella undulata (Sm.) Seem.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.570
Ziziphus mauritiana Lamk.	V/D^2=-0.00342/D^2 -0.0922/D+2.28178+9.46641*D	0.597

one plant/stem of thick, medium and thin circumference was measured using the measuring tape. Shrub biomass was calculated by developing species specific regression equations developed on the basis of diameter at 10cm above the ground level and dry weight of 30 stems harvested during sampling period second week of March, 2011 and 2012. The biomass equations for the dominant shrubs i.e. *Capparis sepiaria*, *Adhatoda vasica*, *Carissa spinarum* and *Lycium europaeum* are given in Table 4. The total biomass of shrubs was calculated of the basis of computed biomass and density.

Analysis of Litter Fall and Forest Floor Litter

The litter fall was measured using the litter trap method from 1x1m litterfall traps at monthly intervals from second week of March 2011 to second week of March 2012. The forest floor litter was collected at the first week of October, March and June by placing ten 1x1m quadrats within the sampling plots during the study period. The litter samples were separated into twig, and leaf litter. The samples were freed from adhering soil particles and oven dried at 65°C for determining dry weight. Sub samples were washed with deionised water, oven dried at 45°C and stored for chemical analysis.

Estimation of Net Primary Productivity

Aboveground net primary productivity (ANP) of trees was calculated as the sum of increment in biomass of non-photosynthetic parts over a time of one year from the second week of March, 2011 to second week of March, 2012 and the annual litter production during the same period (Olson 1975). The belowground net primary productivity was calculated as the sum of increment in belowground biomass over one year.

Aboveground and belowground net primary productivity of shrubs was calculated on the basis of increment

Table 4. Species specific biomass equation developed for the dominant shrubs. Regression of $\log_{10}$ dry weight of different components (Y) on $\log_{10}$ dia (X)

Shrub components	Intercept (a)	Slope (b)	Correlation coefficient
Adhatoda vasica			
Stem	0.977	-0.035	0.956
Branches	0.996	-0.006	0.972
Roots	0.975	-0.026	0.952
Capparis sepiaria			
Stem	0.968	-0.134	0.938
Branches	1.065	-0.224	0.943
Roots	0.985	-0.185	0.944
Carissa spinarum			
Stem	0.994	-0.034	0.989
Branches	0.996	-0.004	0.993
Roots	0.993	-0.017	0.986
Lycium europaeum			
Stem	0.998	-0.114	0.996
Branches	0.996	-0.124	0.992
Roots	0.994	-0.027	0.989

in biomass of stems, leaves and roots from the second week of March, 2011 to second week of March, 2012.

Aboveground net primary productivity (ANP) of herbaceous plants was estimated using trough peak analysis of the seasonal biomass data on live and dead shoots (Singh et al. 1975). Belowground net production (BNP) was calculated by summing all positive changes in belowground biomass as recorded during different months. The values of ANP and BNP were summed to represent total net primary production (TNP).

Analysis of Plant Carbon Pool

The aboveground biomass carbon stock of trees was calculated by assuming that the carbon content is 50% of the total biomass (Brown and Lugo 1982, Dixon 1994, Ravindranath et al. 1997). Carbon concentration in composite samples of shoots and roots of shrubs and herbs was estimated by Ash Method as described by Negi et al. (2003). Oven dried plant samples were burnt in electric furnace at 400C temperature. The ash content after burning was weighed and carbon was calculated by using the equation: C% = 100-(Ash weight+ molecular weight of O_2 (53.3) in $C_6H_{12}O_6$. Carbon pool was calculated by multiplying the dry matter of plant biomass with respective average carbon concentration for the shrub and herb species.

Analysis of Soil Carbon Pool

Soil samples were collected from 0-60cm soil depth within experimental plots of 20x20 m using the split soil corer. The soil samples were sieved through 2mm sieve and air dried. Soil pH was measured by glass electrode (1:2 soils, water). Bulk density was determined by measuring the weight of dry soil of a unit volume at different depth. Soil Organic Carbon was determined by using the dichromate oxidation method (Kalembasa and Jenkinson 1973). Inorganic carbon in soil was estimated by rapid titration method. The amount of organic carbon in the soil was estimated from the bulk density, soil depth, and organic carbon concentration in soil of the respective depth.

Statistical Analysis

One-way ANOVA was used to evaluate the influence of forest systems on soil organic and inorganic carbon at various soil depths. A significance level of $P<0.05$ was used for all tests. All analyses were conducted following the SPSS program, ver. 16.0.

RESULTS

Litter Fall and Forest Floor Litter

The litter fall in the three forests was greatest in winter and lowest in summer months. Leaf litter was found to be almost two times higher than twig litter. The litter production was found to be higher in the AE-CF forest at Bhondsi (3.42Mg ha^{-1}) as compared to that of the AL-BA forest at Gawalpahari (1.62Mg ha^{-1}) and AP-AL forest Raisina (1.93 Mg ha^{-1}) (Figure 2). In the AE-CF forest at Bhondsi, leaf litter fall contributed 65.28%, whereas twig litter fall contributed 34.72% of total litter fall, where as leaf and twig litter contribution in AL-BA forest at Gawalpahari was observed to be 64.88% and 35.12% respectively. In AP-AL forest at Raisina, the annual litter fall was 1.93 Mg ha^{-1}, leaves contributed 63.08% and twigs contributed 36.92% of total litter fall. Peak values of litter fall were observed in March.

The forest floor litter was high in winter and summer. In the case of AE-CF forest Bhondsi, standing crop of leaf litter varied from 1461 kg ha^{-1} to 4421 kg ha^{-1} where as twig litter ranged from 1091 kg ha^{-1} to 2223 kg ha^{-1} across seasons (Table 5). The leaf litter accounted for 57 to 66% of total litter deposition on the ground.

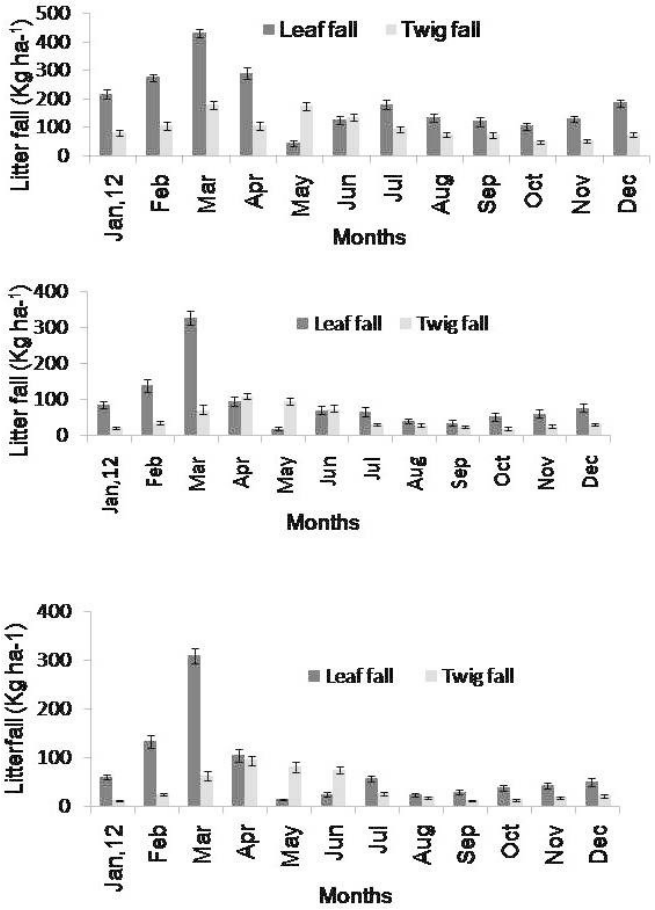

Figure 2. Monthly variations in litterfall under forest ecosystems at Bhondsi (upper), Gawalpahari (middle) and Raisina (lower) in Gurgaon District

Seasonal variations in standing crop of leaf and twig litter in AL-BA forest Gawalpahari was estimated from 785 kg ha^{-1} to 2061 kg ha^{-1} and 530 to 1213 kg ha^{-1} respectively (Table 5). Standing crop of leaf and twig litter was comparatively low in AP-AL forest Raisina, value being 718 kg ha^{-1} to 2045 kg ha^{-1} for leaf litter and 432 kg ha^{-1} to 1084 kg ha^{-1} for twig litter (Table 5).The forest floor litter exhibited significant differences between three seasons (F= 848.42, d.f. =2, 12, 14, P<0.05).

Plant Biomass and Productivity

The aboveground biomass of trees in the three forests was 37.93 to 63.73 Mg ha^{-1}; the belowground biomass being 11.12 to 17.81 Mg ha^{-1} (Table 6). Aboveground biomass accounted for 74.86 to 76.42% of total biomass, whereas belowground biomass contributed 23.58 to 25.14% of the total tree biomass in all the three forests.

Table 5. Standing crop of forest floor litter (kg ha^{-1}) in the forest ecosystems at Bhondsi, Gawalpahari and Raisina in Gurgaon

Sites/Litter components	Standing crop of litter (kg ha^{-1}) Summer season	Rainy season	Winter season	Annual mean
AE-CF forest, Bhondsi				
Leaf litter	3193^{b}±44.98	1461^{c}±42.84	4421^{a}±51.68	3025
Twig litter	1618^{b}±28.69	1091^{c}±23.06	2223^{a}±33.28	1644
Total	3811	2552	6644	4669
AL-BA forest, Gawalpahari				
Leaf litter	1573^{b}±42.79	785^{c}±32.57	2061^{a}±45.81	1473
Twig litter	906^{b}±20.49	530^{c}±13.79	1213^{a}±26.05	883
Total	2479	1315	3274	2356
AP-AL forest, Raisina				
Leaf litter	1665^{b}±44.54	718^{c}±29.53	2045^{a}±42.21	1476
Twig litter	863^{b}±17.79	432^{c}±15.81	1084^{a}±18.58	793
Total	2528	1150	3129	2269

Different superscript letters indicate a significant difference (P<0.05) by Duncan's multiple range test

Table 6. Biomass in various plant components of trees and net primary productivity (NPP) in the forests at Bhondsi, Gawalpahari and Raisina in Gurgaon district during March 2011- March 2012. Values in bold stand for tree biomass during March 2012

Plant components	Biomass (Mg ha^{-1}) Bhondsi	Gawalpahari	Raisina
Leaf+Twig*	3.42±0.01	1.62±0.01	1.93±0.02
Aboveground (bole+branches)	63.73±0.20	37.93±0.30	42.50±0.30
	70.63±0.24	**41.90±0.31**	**46.08±0.31**
Belowground	17.81±0.08	11.12±0.12	11.18±0.09
	19.55±0.29	**11.88±0.42**	**12.01±0.31**
Total	84.96±0.32	50.67±0.32	55.61±0.32
	93.50±0.34	**55.40±0.34**	**59.09±0.34**

Plant components	NPP (Mg ha^{-1}yr^{-1})		
Foliage*	3.42	1.62	1.76
Aboveground (bole+branches)	6.90	3.97	3.58
Belowground	1.74	12.06	0.96
Total	6.55	0.83	6.17

* From litterfall data

Highest total tree biomass excluding leaves and twigs (76.40±0.31 Mg ha^{-1}) was observed in the forest at Bhondsi followed that of the forests at Raisina (55.61 ±0.32 Mg ha^{-1}) and Gawalpahari (50.67±0.32 Mg ha^{-1}). Biomass of different plant species in the three forest sites are shown in Figures 3 and 4. In the AE-CF forest at Bhondsi, *Azadirachta indica, Albizia lebbeck, Cassia fistula, Derris indica,* and *Kigellia pinnata* contributed 13.20, 11.28, 10.80, 6.81 and 5.59 Mg ha^{-1} of aboveground biomass, and 3.39, 2.95, 2.84, 1.89, and 1.59 Mg ha^{-1} of belowground biomass (Figure 3a). In this forest other species (n=9) accounted for 16.05 Mg ha^{-1} aboveground biomass and 5.14 Mg ha^{-1} belowground biomass, respectively (Figure 3a).

In the AL-BA forest at Gawalpahari, the aboveground biomass (Mg ha^{-1}) of different tree species was: 7.76 *Albizia lebbeck,* 5.13 *Prosopis cineraria,* 4.06 *Balanites aegyptiaca,* 4.57 *Butea monosperma,* 3.89 *Dalbergia sissoo,* 12.53 others (n= 5) (Figure 3b). The belowground biomass of trees was (Mg ha^{-1}): 2.12 *Albizia lebbeck,* 1.47 *Prosopis cineraria,* 1.20 *Balanites aegyptiaca,* 1.33 *Butea monosperma,* 1.15 *Dalbergia sissoo,* 3.85 others (n=5). The predominant trees accounted for 66.98 % total aboveground biomass and 65.38 % of the belowground biomass.

In the AP-AL forest at Raisina, the aboveground biomass of different tree species was (Mg ha^{-1}): 5.53 *Acacia leucophloea,* 5.33 *Acacia senegal,* 16.01 *Anogeissus pendula,* 0.23 *Boswellia serrata,* 0.59 *Diospyros cordifolia,* 14.81 *Prosopis juliflora.* The belowground biomass of trees varied from 0.09 to 3.76 Mg ha^{-1} (Figure 4A). The predominant trees *Anogeissus pendula* and *Prosopis juliflora* accounted for 71.89 % total biomass.

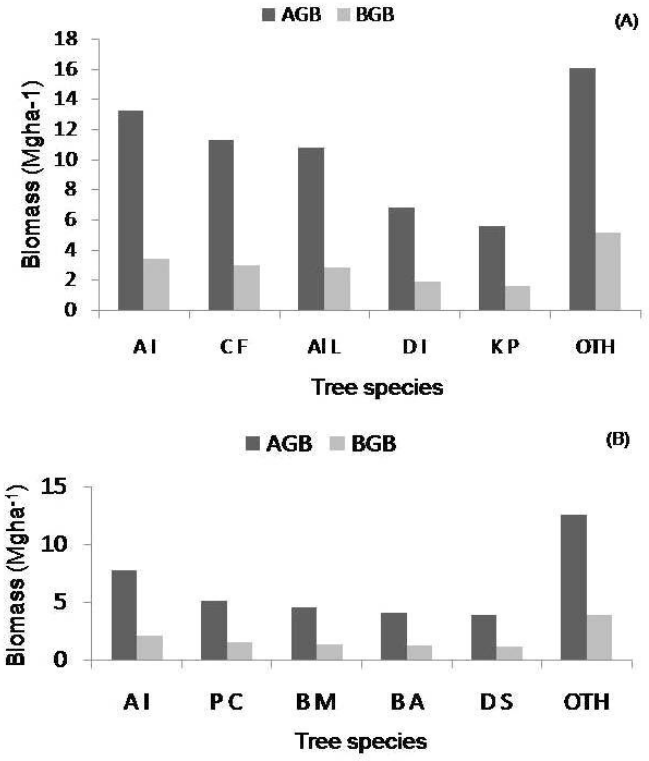

Figure 3. Aboveground and belowground biomass of different tree species in the mixed forest at (A) Bhondsi and (B) Gawalpahari in Gurgaon district.

AlL =*Albizia lebbeck;* AI =*Azadirachta indica ;* BA =*Balanites aegyptiaca ;* BM =*Butea monosperma ;* CF =*Cassia fistula ;* DI =*Derris indica ;* DS =*Dalbergia sissoo;* KP =*Kigellia pinnata ;* PC =*Prosopis cineraria ;* OTH = Other species

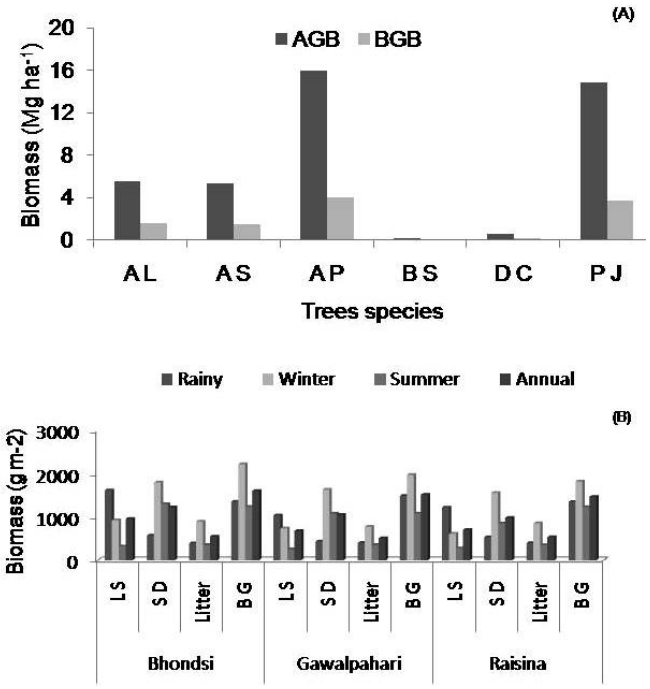

Figure 4. (A) Above ground and belowground biomass of different tree species in forest ecosystems at Raisina. AL = *Acacia leucophloea*; AS = *Acacia senegal*; AP =*Anogeissus pendula;* BS= *Boswellia serrata;* DC = *Diospyros cordifolia;* PJ= *Prosopis juliflora*

(B) Seasonal variations in live shoots, standing dead, litter and roots biomass of herbaceous plants in the forest ecosystems

The total net productivity of trees was also higher for AE-CF dry deciduous forest at Bhondsi (12.06 Mg ha^{-1} yr^{-1}) as compared to AL-BA forest at Gawalpahari (6.55 Mg ha^{-1} yr^{-1}) and AP-AL Raisina (6.17 Mg ha^{-1} yr^{-1}) (Table 6).

The total biomass in different components of shrub was 18.91Mg ha^{-1} in the AE-CF forest at Bhondsi, 17.01Mg ha^{-1} at AL-BA forest Gawalpahari and 9.79 Mg ha^{-1} at AP-AL forest Raisina (Table 7). Biomass in aboveground component (stem+ branches) of shrubs was in the order: Bhondsi (12.76 Mg ha^{-1}) > Gawalpahari (11.41 Mg ha^{-1}) > Raisina (6.54 Mg ha^{-1}). The root biomass of shrubs was also comparatively higher in AE-CF forest at Bhondsi (6.15Mg ha^{-1}) followed by AL-BA forest at Gawalpahari (5.67 Mg ha^{-1}) and lowest in AP-AL forest Raisina (3.25 Mg ha^{-1}) (Table 7). In the AE-CF forest at Bhondsi, aboveground biomass of dominant shrub species was in the order: *Capparis sepiaria* (0.50 Mg ha^{-1}), *Adhatoda vasica* (0.26 Mg ha^{-1}) and *Carissa spinarum* (0.23 Mg ha^{-1}).Belowground biomass of these species was 0.23 Mg ha^{-1},0.13 Mg ha^{-1} and 0.11 Mg ha^{-1} respectively. In the case of AL-BA forest at Gawalpahari *Carissa spinarum* (0.35 Mg ha^{-1}), *Capparis sepiaria* (0.32 Mg ha^{-1}) and *Adhatoda vasica* (0.16 Mg ha^{-1}), contributed highest aboveground shrub biomass. Net primary productivity of shrubs was also high in AE-CF forest Bhondsi (2.71 Mg ha^{-1} yr^{-1}) and lowest in AP-AL forest Raisina, (2.27 Mg ha^{-1} yr^{-1}) (Table 7).

Table 7. Biomass (Mg ha^{-1}) in various plant components of shrub species in the forest ecosystems during March 2011 and March 2012 in different forest ecosystems

Plant components	Biomass (Mg ha^{-1}) I year (March 2011)	Biomass (Mg ha^{-1}) II year (March 2012)
AE-CF forest Bhondsi		
Aboveground (Stem+branches)	12.76±0.172	14.54±0.353
Belowground	6.15±0.128	7.08±0.362
Total	18.91	21.62
AL-BA forest Gawalpahari		
Aboveground (Stem+branches)	11.41±0.377	13.03±0.591
Belowground	5.67±0.173	6.39±0.539
Total	17.01	19.42
AP-AL forest Raisina		
Aboveground (Stem+branches)	6.54±0.114	8.07±0.581
Belowground	3.25±0.168	3.99±0.187
Total	9.79	12.06

Plant components	NPP (Mg ha^{-1} yr^{-1}) Bhondsi	Gawalpahari	Raisina
Aboveground (Stem+branches)	1.78	1.62	1.53
Belowground	0.93	0.79	0.74
Total	2.71	2.41	2.27

Biomass and Productivity in Herbaceous Layer

The live shoot biomass of herbaceous plants in all the three forest ecosystems was highest in rainy season (June to September); and declined during summer and winter months. The average live shoot biomass of herbaceous plants in the three forests was: 955.1 g m^{-2} AE-CF forest Bhondsi; 678.5 g m^{-2} AL-BA forest Gawalpahari; 704.9 g m^{-2} AP-AL forest Raisina (Figure 4B). The standing dead shoots attained peak values during winter and summer months. The seasonal average value of root biomass of herbaceous plants also showed similar pattern with value being 1604.4 g m^{-2} at AE-CF forest Bhondsi; 1518.0 g m^{-2} at AL-BA forest Gawalpahari and 1467.4 g m^{-2}) at AP-AL forest Raisina (Figure 4B).

Seasonal variation in net primary production (g m^{-2}) of herbaceous vegetation in dry deciduous forests at Bhondsi, Gawalpahari and Raisina were found to be 949.8 g m^{-2}, 803.2 g m^{-2} and 832.2 g m^{-2} respectively (Table 8). The aboveground net productivity (ANP) was

Table 8. Seasonal variation in net primary production (g m^{-2}) of herbaceous vegetation in the three forests at Bhondsi, Gawalpahari and Raisina

Sites/seasons	ANP	BNP	TNP
AE-CF forest (Bhondsi)			
Rainy (June–September)	536.1	141.6	677.7
Winter (October–February)	49.8	123.0	172.8
Summer (March–May)	25.8	73.5	99.3
Annual	611.8	227.4	949.8
AL-BA forest (Gawalpahari)			
Rainy (June–September)	481.2	64.6	545.8
Winter (October–February)	47.9	116.3	164.2
Summer (March–May)	27.1	66.2	93.3
Annual	516.2	187.1	803.3
AP-AL forest (Raisina)			
Rainy (June–September)	520.9	44.6	565.5
Winter (October–February)	48.1	121.5	169.6
Summer (March–May)	27.2	69.9	97.1
Annual	596.2	236.0	832.2

highest during the rainy season where as the below-ground net productivity (BNP) was found to be higher during winter months as compared to the rainy season possibly due to the active translocation of food reserves to the rhizomes and roots with the advent of unfavorable conditions for shoot growth.

Carbon Stock and Flux in Net Primary Productivity

The carbon content of trees varied considerably due to variation in biomass of tree components and the plant species. The relative contribution of different plant components to total carbon accumulation was in the order: aboveground> belowground> leaves. The biomass carbon storage in tree layer in the three forests was in the order (Mg C ha^{-1}): 39.66 = *Ailanthus excelsa -Cassia fistula* forest, Bhondsi > 23.53 = *Acacia leucophloea-Prosopis cineraria* forest, Gawalpahari > 19.31 = *Anogeissus pendula- Prosopis juliflora* forest, Raisina. Aboveground carbon pool in the three forests during the first year was: 33.58 Mg C ha^{-1} AE-CF forest Bhondsi; 19.77 Mg C ha^{-1} AL-BA forest Gawalpahari; and 22.29 Mg C ha^{-1} AP-AL forest Raisina whereas belowground carbon pool during the same year was: 8.90Mg C ha^{-1} Bhondsi; 5.56 Mg C ha^{-1} Gawalpahari; and 5.59 Mg C ha^{-1} Raisina (Table 9). The carbon pool in the AE-CF forest Bhondsi was contributed mainly by *Azadirachta indica, Albizia lebbeck, Cassia fistula, Derris indica,* and *Kigellia pinnata*; their contribution was about 79% of the total carbon pool. Only 21% of tree biomass carbon pool was contributed by other species (n= 9)

The total carbon pool in different components of shrubs was highest in the AE-CF forest at Bhondsi forest (8.28 Mg C ha^{-1}), followed by Gawalpahari (7.29 Mg C ha^{-1}), and Raisina (4.23 Mg C ha^{-1}) (Table 9). The carbon pool in the herbaceous layer in the three forests (Mg C ha^{-1}) was: 0.270 to 0.391 live shoots; 0.409 to 0.515 standing dead; 0.214 to 0.232 litter: 0.599 to 0.687 roots (Table 9). In the case of herbaceous layer, live shoot biomass carbon attained peak value of 0.391 Mg C ha^{-1} in the AE-CF forest at Bhondsi. Carbon concentrations (%) in different components of shrubs and herbaceous plants are shown in Figures 5A and 5B, respectively.

Carbon flux refers to the input of carbon through net primary productivity into the system and its subsequent transfer to the soil through litter and root turnover. The total carbon input of trees through net primary productivity in forest ecosystems was (Mg C ha^{-1} yr^{-1}): 6.04 in AE-CF forest Bhondsi; 3.25 in AP-AL forest Raisina and 2.68 in AL-BA forest Gawalpahari.

Table 9. Plant biomass carbon and carbon flux in the three forests at Bhondsi, Gawalpahari and Raisina

	AE-CF forest Bhondsi	AL-BA forest Gawalpahari	AP-AL forest Raisina
Carbon pool tree layer (Mg C ha^{-1})			
Aboveground	33.58	19.77	22.29
Belowground	8.90	5.56	5.59
Total	42.48	25.33	27.88
Carbon pool shrub layer (Mg C ha^{-1})			
Aboveground	5.54	4.85	2.81
Belowground	2.74	2.44	1.42
Total	8.28	7.29	4.23
Carbon pool herb layer (Mg C ha^{-1})			
Aboveground	1.14	0.92	0.90
Belowground	0.69	0.63	0.60
Total	1.83	1.55	1.50
Total carbon flux (Mg C $ha^{-1}yr^{-1}$)			
Aboveground Trees+ Shrubs	5.99	3.00	3.48
Belowground Trees+ Shrubs	1.28	0.72	0.75
Total Trees +Shrubs	7.27	3.72	4.23
Carbon return in litter fall (Mg C $ha^{-1}yr^{-1}$)	1.72	0.81	1.04
Carbon Sequestration (Mg C $ha^{-1}yr^{-1}$)	5.55	2.91	3.19

As compared with above ground carbon flux, below ground carbon flux was lower in all the three forests, the value being 0.87, 0.38 and 0.42 Mg C ha^{-1} yr^{-1}, respectively (Table 9). Total carbon flux of shrub layer was (Mg C ha^{-1} yr^{-1}): 1.23 in Bhondsi; 1.04 in Gawal-pahari and 0.98 in Raisina forests (Table 9). The above-ground carbon input through net primary production varied from 85.34 to 86.54%, whereas roots contributed 13.46 to 14.66% carbon input. Carbon sequestration potential of the studied forest ecosystems ranged from 2.91 to 5.55 Mg C ha^{-1} yr^{-1}.

Soil Carbon Storage

Soil organic carbon showed marked decrease with increase in soil depth in all the forests. In the three forests, the soil organic carbon pool (Mg C ha^{-1}) at different soil depths was: 7.383 to 4.923 (0-15cm); 6.693

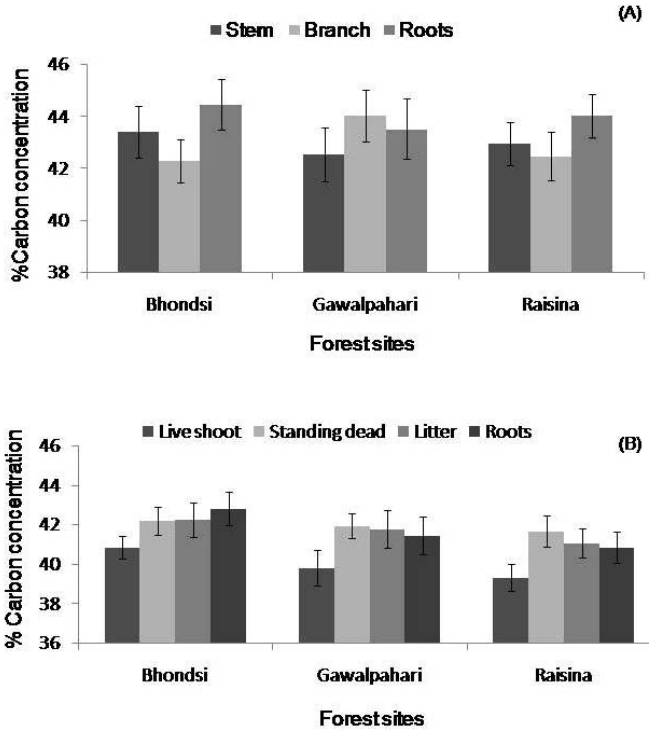

Figure 5. Carbon concentration (%) in different components of (A) shrub species and (B) herbaceous plants in the three forest ecosystems at Bhondsi, Gawalpahari and Raisina.

Table 10. Organic carbon pool in soil in the three forests at Bhondsi, Gawalpahari and Raisina in Gurgaon district

Forest/ Site	Soil depth (cm)	Soil Organic Carbon Pool (Mg ha^{-1})
AE-CF forest, Bhondsi	0-15	7.383^{a} ±0.348
	15-30	6.693^{a} ±0.314
	30-45	4.166^{b} ±0.575
	45-60	3.590^{b} ±0.391
LSD (P<0.05)		1.291
F value		19.713
AL-BA forest Gawalpahari	0-15	4.923^{a} ±0.310
	15-30	4.182^{ab} ±0.241
	30-45	3.948^{ab} ±0.259
	45-60	3.583^{b} ±0.443
LSD (P<0.05)		0.995
F value		3.068
AP-AL forest Raisina	0-15	6.408^{a} ±0.242
	15-30	4.200^{b} ±0.356
	30-45	3.335^{bc} ±0.340
	45-60	2.500^{c} ±0.204
LSD (P<0.05)		0.902
F value		33.014

Different superscript letters indicate a significant difference (P<0.05) by Duncan's multiple range test

to 4.183 (15-30cm); 4.166 to 3.335 (30-45cm); 3.590 to 3.335 (45-60cm) (Table 10). The soil organic carbon pool at 0-30cm soil depth accounted for 54.73% to 64.52 % of the total organic carbon pool up to 60cm soil depth. The total soil organic carbon pool up to 60cm soil depth was greatest in the case of AE-CF forest at Bhondsi (21.832Mg C ha^{-1}), followed by AL-BA forest at Gawalpahari (16.636Mg C ha^{-1}) and AP-AL forest at Raisina (16.443Mg C ha^{-1}) (Table 10). The soil organic carbon (SOC) decreased with increasing soil depths. The higher organic carbon content in the top soil layer may be due to rapid decomposition of ground floor litter due to high microbial activity.

DISCUSSION

Litter constitutes an important component of the soil in all forest ecosystems which plays a significant role in organic matter and nutrient return to the soil. It is also an important indicator of primary production and recycling processes. Litter fall has been found to be influenced by vegetation composition, age of trees, canopy cover, weather conditions and biotic factors (Rawat and Singh 1988, Bargali 1995). In the present study, litterfall in different dry deciduous forest ecosystems ranged from 1.62-3.42 Mg ha^{-1} yr^{-1}. Proctor et al. (1983) reported litter fall in the range of 3-10 Mg ha^{-1} yr^{-1} for a variety of tropical forests. For the forest ecosystems of India, Singh et al. (1992) have reported litter fall of 7.9 Mg ha^{-1} yr^{-1} in *Shorea robusta* forest. An annual litter fall of 0.4 to 6.5 Mg ha^{-1} in 1 to 8 yr old plantations of *Eucalyptus tereticornis* in the tarai belt of Central Himalaya was reported by Bargali et al. (1992). This study showed that leaf litter was 63.08 to 68.77% of total litter fall, which is comparable to several other reports of forest ecosystems (Singh 1984, Sanchez and Sanchez 1995, Sundarpandian and Swamy 1999, Zhou et al. 2007). This study also showed that litter fall deposition on ground floor was highest in winter and lowest in summer months.

The above ground biomass of tropical dry forests of northern India has been reported to range from 38.6 - 239.8 Mg ha^{-1} (Singh and Singh 1981, Gupta and Kumar 2014). For the tropical deciduous forests of Central India, aboveground biomass ranged from 31.8 Mg ha^{-1} to

20.7 Mg ha^{-1} (Salunkhe et al. 2016). In this study, the aboveground biomass of trees in the three forests ranged from 37.93 to 63.73 Mg ha^{-1}.

Total plant biomass in the tree layer of different forest ecosystems in this study ranged from 50.67 Mg ha^{-1} to 84.96 Mg ha^{-1}, which could be related to forest type, species composition, size class of trees, and soil conditions. Net primary production for the forest ecosystems of India has been reported to be 14 to 19 Mg ha^{-1} yr^{-1} (Singh et al. 1992). For the dry deciduous forest ecosystems, net primary productivity varied from 11.3 to 19.2 Mg ha^{-1} yr^{-1} (Singh and Misra 1979). In this study, net primary productivity of tree layer ranged from 6.17 Mg ha^{-1} yr^{-1} to 12.06 Mg ha^{-1} yr^{-1} across the sites.

Shrub biomass is an important component of the total forest biomass. In this study species specific equations were developed for 14 species, the predominant species being *Adhatoda vasica, Capparis sepiaria, Carissa spinarum,* and *Lycium europaeum.* Shrub layer biomass in the studied forest ecosystems varied from 9.79 to 18.91Mg ha^{-1}. The total biomass in different components of shrub was highest (18.91Mg ha^{-1}) in the forest at Bhondsi. Biomass in aboveground component (stem+ branches) of shrubs was found to be double as compared to the root biomass across forest ecosystems. The biomass accumulation in different shrub components followed the order: stems >belowground >foliage. Kumar et al. (2011) reported that shrub biomass ranged from 4.9 ±1.61 to 6.3 ± 1.38 Mg ha^{-1} and the herb biomass fluctuated from 1.7 ± 1.64 to 2.1± 1.81 Mg ha^{-1} in *Butea* forest ecosystems of western Rajasthan. The range of net primary productivity of shrubs in this study was found to vary from 1.07 Mg $ha^{-1}yr^{-1}$ to 2.71 Mg $ha^{-1}yr^{-1}$.

The herbaceous layer is significant to the structure and function of forest ecosystems as it represents less than 1% of the biomass of the forest, yet can contain 90% or more of the plant species of the forest and contribute up to 20% of the foliar litter to the forest floor (Gilliam 2007). Herbaceous vegetation plays an important role for maintaining soil fertility because of their fast turnover. Swamy et al. (2010) studied shrub and herb biomass in tropical wet evergreen forests of Western Ghats in India. The range of net primary productivity of shrubs in this study was found to vary from 1.07 Mg ha^{-1} yr^{-1} to 2.71 Mg ha^{-1} yr^{-1}.

Total plant carbon pool ranged from 33.61 Mg C ha^{-1} to 56.90 Mg C ha^{-1}.Tree species accounted for 74.1% to 82.9% of total plant carbon pool. The above ground carbon pool was observed to almost double than below ground carbon pool. Gairola et al. (2011) reported total carbon stock of 20.6-51.5 Mg C ha^{-1} in *Dalbergia sissoo* plantation on moist temperate valley slopes of the Garhwal Himalaya. Lal and Singh (2000) estimated an average carbon stock of 31.72 Mg C ha^{-1} in Indian forests.

Soil carbon plays a vital role in regulating climate, soil water availability and biodiversity, and providing the ecosystem services that are essential to human well-being. Estimates of SOC stock are required to assess the role of soil in the global carbon cycle (Yang et al. 2007). In this study, soil carbon was assessed up to 60cm soil depth, there were significant variation in total soil carbon due to soil depth and the forest type. The soil organic carbon (SOC) decreased with increasing soil depths. Soil organic matter is also a chief contributor to the carbon stocks of forests (Lal 2005, Kumar et al. 2006), next only to the aboveground biomass (Ravindranath and Ostwald 2008). The soils store both organic carbon (through photosynthesis of plants and then to soils as decomposed plant materials and roots) and inorganic carbon (through the formation of pedogenic calcium carbonates). The predominant source of increased soil organic carbon stock over time appears to be the addition of below-ground carbon in the soils of natural forest. The soils of natural forest showed higher rate of soil organic carbon sequestration in 0 to 30 cm soil depth, because fine roots generally occur in the soil surface layer.

CONCLUSION

Major proportion of plant biomass and productivity was found to be contributed by tree layer in the studied forest ecosystems. Carbon stock in the total plant biomass in the three forests was found to range from 33.61 to 52.59 Mg C ha^{-1}. Carbon flux in primary productivity was estimated to be 3.72 to 7.27 Mg C ha^{-1} yr^{-1} across the sites; out of which 0.81 to 1.72 Mg C ha^{-1} yr^{-1} returned in litterfall. Carbon sequestration potential of the studied forest ecosystems was 2.91 Mg C ha^{-1} yr^{-1} to 5.55 Mg C ha^{-1} yr^{-1}. The soil organic carbon stock in three sites was 16.64 Mg C ha^{-1} to 21.83 Mg C ha^{-1}. Our findings suggest that the tree carbon stocks in the mixed deciduous forests of southern Haryana were influenced by species diversity, soil properties, and micro-environmental conditions. The major difference tree carbon storage between sites could be attributed to tree density and basal area in the three forests. Maintaining the stores and sink of carbon in the natural ecosystems could play

key role to reduce future emission of greenhouses gases. While providing production and natural resource services, the forest ecosystems in arid regions provide ecosystem services of carbon sequestration for climate change mitigation and adaptation.

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