Variation in carbon storage among tree species in the planted forest of Kathmandu, Central Nepal

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Carbon stock variation among trees of planted forest, was estimated in a 41-year old Coronation garden of Kathmandu, Central Nepal. Forty-one square quadrates of 20 m × 20 m were selected by applying stratified systematic sampling method in three horizontal strata of the forest. The biomass of trees was estimated using an allometric equation which was later converted to the carbon stock by using carbon fraction. The study site stored 196.4 Mg C ha^{-1} (carbon sequestration rate: 4.78 Mg ha^{-1} yr^{-1}) equivalent to 720.7 Mg CO$_2$ ha^{-1} (CO$_2$ assimilation rate: 17.58 Mg ha^{-1} yr^{-1}). *Eucalyptus citriodora* had the highest carbon storage (54.6 Mg ha^{-1}, 27.8%) and sequestration rate (1.33 Mg ha^{-1} yr^{-1}). *Cinnamomum camphora* and *Salix babylonica* were the dominant tree species, while *Salicaceae* and *Lauraceae* were the dominant families growing in the forest. Myrtaceae was the dominant family in terms of carbon storage and carbon sequestration rate. The study suggests that *E. citriodora*, *C. camphora*, *S. babylonica* and *P. roxburghii* would be the best species to select for forest plantation which would yield large impacts on landscape-level carbon stocks and could also mitigate climate change.

Keywords: Allometric equation, carbon sequestration rate, Coronation garden, importance value index, species-specific.

GLOBAL warming and climate change are the most widespread, well-known and pressing global issues. They primarily result from a rise in greenhouse gases (GHGs) levels due to anthropogenic activities like excessive use of fossil fuel, industrialization and land use change. Deforestation contributes about 20% to global GHG emission which is more than the contribution of the entire transportation system[1]. Of the GHGs, carbon dioxide (CO$_2$) is on top, accounting for 76% of total anthropogenic GHG emissions[2]. Therefore, the importance of various activities to reduce CO$_2$ emissions is being realized in connection with global warming[3]. To reduce GHG emissions and partly offset deforestation, the Kyoto protocol explicitly considered afforestation, reforestation and regeneration of forests for carbon sequestration (CS) accounting[4]. Thus, the forest has a major role in mitigation and adaptation to the climate change[5]. The recognition of forests in mitigating climate change has led countries to study their forest carbon (C) budgets and initiate the assessment of enhancing and maintaining CS of their forest resource[6]. Plantation forestry has an important role in mitigation of GHGs, and there is a pressing need to monitor, preserve and enhance terrestrial carbon stock (C-stock)[7]. In addition, plantation forests products may also relieve pressure on timber extraction from natural forests, thus contributing to forest conservation.

In Nepal, forest and other wooded land together represent 44.74% of the total area of the country. The total C-stock in these forests has been estimated as 1,054.97 million tonnes (176.95 Mg ha^{-1})[8]. The present state of forest C-stock was only due to the introduction of community forestry in Nepal which started in the late 1970s, and has reversed the deforestation and forest degradation rates[9,10]. Such forests act as a major source of C sink storing about 20% of the total C-stock[11]. Forest management regimes in Nepal include eleven different types such as community forests (CFs), leasehold forests, private forests, government forests, religious forests, plantation, etc.[12]. Plantation forest is one among them and Coronation garden of the present study is an example of a plantation forest. History of plantation in Nepal dates back to 1980s when large-scale plantations were done in degraded hills to maximize biomass production[13]. Though there are different forest management regimes in Nepal, C-stock estimation was mainly restricted to CFs (whether planted[14–16] or unplanted[17–20] CFs) with few exceptions[12,21–26]. C-stock estimation is strongly desirable in both mixed stand and monoculture plantations and warrants promotion by the community forestry programme of Nepal[14]. Thus, it is important to study C-stock in Coronation garden.

Forest C estimates help understand the forest contribution to the global C cycle[27]. Growing stock and C storage are important parameters, because they indicate forest degradation and the extent to which they mitigate climate

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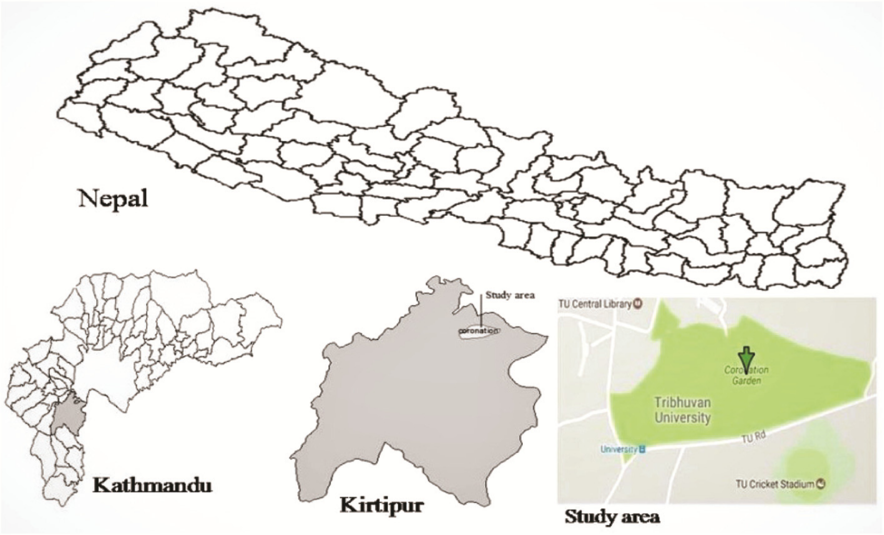

Figure 1. Map of the study site.

change[28]. In addition, estimates of CS could be important for natural resource management and planning mitigation strategies for climate change[18]. Therefore, we decided to study the tree carbon stock and to assess the variation in carbon stock among trees of a planted forest (Coronation garden) of Kathmandu, Central Nepal.

Materials and methods

Study site

The study was conducted in Coronation garden of Kirtipur, Kathmandu, Central Nepal (Figure 1) which lies within the area of Tribhuvan University. The study area covers 2.7 ha and expands from 27°67′911″–27°68′106″N and 85°28′49″–85°29′176″E. The altitude ranges from 1283 to 1322 m above sea level. The study area is located in the subtropical monsoonal climatic zone. The average annual temperature becomes maximum (31.9°C) during June and minimum during December (2°C). The average annual rainfall exceeds more than 1480.4 mm (ref. 29).

The forest was planted in the Coronation ceremony of the then-king of Nepal, late Birendra, in February 1975 AD (Falgun 2031 B.S) and named Shree fifth Birendra Coronation garden (Shree Paach Birendra Rajyabhysek Udhyan) now called the Coronation garden. Plantation programme was carried out jointly by the Palace, Ministry of Education and Tribhuvan University with participation from Ambassadors of 28 countries. The planted species were mainly, *Cinnamomum camphora* (L.) J. Presl, *Salix babylonica* L., *Pinus roxburghii* Sarg., *Grevillea robusta* A. Cunn. ex R. Br., *Eucalyptus* sp., *Populus euramericana* (Dode) Guinier, *Jacaranda mimosifolia* D. Don, *Celtis australis* L., *Alnus nepalensis* D. Don, *Lagerstroemia indica* L., etc. Before plantation, the area was like a stream. There was little vegetation and during rainy season water mixed with sediments and mud from Nayabazar of Kirtipur drains were brought to the site. After plantation, it has now become a mixed forest. Tribhuvan University central office has given its management responsibility to the Central Department of Botany, Tribhuvan University, Kirtipur (data obtained from TU central office, Kirtipur in March 2017). The management activities mainly include clearance of bushes and climbers once every 1–2 years and checking the collection of firewood and fodder.

Sampling and measurements

The study was carried out in April 2016. The stratified systematic sampling method was used for vegetation sampling. Square quadrates of 20 m × 20 m were located in three horizontal strata of forest and distance between one stratum to other was 30 m. The horizontal distance between successive quadrates was 20 m. Forty-one quadrats were sampled in the forest.

Geographic location (latitude, longitude and elevation) of each plot (20 m × 20 m) was recorded using global positioning system (GPS, Garmin etrex) from the centre of the plot. Canopy cover (%) for each plot was estimated visually from the centre of the plot. Tree height ($H > 137$ cm) and diameter at breast height (DBH, 137 cm, ≥ 5 cm) of all individuals of tree species were measured using clinometer and DBH tape respectively. These tree measurements were used to estimate biomass using allometric equation (see eq. 1).

The plant specimens were identified with the help of standard literature[30] and by tallying with the specimens of Tribhuvan University Central Herbarium. Annotated checklist of the flowering plants of Nepal was followed for specimen nomenclature[31].

Estimation of biomass and carbon stock

The allometric model developed for the tropical 'moist forest' (annual precipitation 1,500–3,500 mm) was applied for estimation of the above-ground biomass (AGB) of the tree layer[32]

$$\text{AGB (kg)} = 0.0509 \times \rho D^2 H, \tag{1}$$

where ρ is wood density (g m^{-3}), D the DBH of the tree (cm) and H is the height of the tree (m). The global database was used for the dry wood density[33]. The below-ground biomass (the root of tree layers) was estimated by assuming that it constitutes 26% of the above-ground biomass[34].

The total dry biomass (only living) is the sum of the above and below-ground biomass of the trees. The living C-stock was calculated by multiplying the sum of the dry living biomass with the default carbon fraction of 0.47 (ref. 34). C-stock of individual tree species in a forest was determined by adding the C-stock values of that particular species in all plots of that forest. Percentage contribution of C-stock of each species in a forest was calculated by the equation

$$\text{Carbon stock (\%)} = \text{Carbon stock of a particular tree species/the sum of carbon stock of all tree species} \times 100. \tag{2}$$

Estimated C-stocks were converted into CO_2 equivalents (quantity of C × 44/12) for calculating CO_2 assimilation by biomass of trees[35,36]. The mean annual carbon increment [hereafter referred as, carbon sequestration rate (CSR)] was estimated as the sum of C-stock of tree species to the age of the forest[23]. The difference of time of plantation (1975 AD) and study (2016 AD) was considered as the age of forest (age of plantation) (2016–1975 = 41 years).

Analysis of community structure

The field data were used to calculate frequency, density, basal area and importance value index (IVI) following the method described earlier[37]. The maturity index of the forest community was calculated by Pichi-Sermolli's[38] method which is the ratio of the sum of frequencies of all species in the stand to the total number of species in the stand. The total number of plants of all species recorded in all plots was divided into different size classes based on DBH of 5 cm intervals. The size class diagram of plants was then prepared to analyse the distribution pattern of individuals in DBH classes.

Data analysis

Data (mean, total and standard deviation) was calculated using Microsoft Excel 2007.

Results and discussion

Properties of forest stand

A total of 46 species (with 1 unidentified sp.) in 28 families were recorded for the study site (Table 1). Of the 46 species, *Cinnamomum camphora* and *Salix babylonica* have high importance value index (IVI), accounting for 49.7% and 44.3% respectively (Table 1). High IVI of these species indicates that these were the dominant species in the studied forest[39]. Thus, they play an important role in regulating the forest structure and species like *Dalbergia* sp., *Myrica esculenta*, *Sapindus mukorossi*, *Sambucus javanica*, *Mimosa* sp. and *Murraya koenigii* have very low IVI (Table 1) and are the rare and sensitive species. Any disturbance can lead to their permanent removal from the study site. Species preference, management activities, overutilization and removal of other species from a mixed forest stand to create a monoculture in the forest[40]. Similarly, the dominance of any species depends on age, available resources, associated species, disturbance regime and successional changes[41].

Salicaceae and Lauraceae were the dominant families, accounting for 53.2% and 52.6% IVI (Table 2). Similarly, Pinaceae, Myrtaceae and Proteaceae were also the common families, but, Platanaceae, Sapindaceae, Juglandaceae, Boraginaceae, Myricaceae and Sambucaceae were rare (Table 2).

The number of species per plot (referred as, species richness) ranged from 1 to 15 (Table 3). Mean canopy cover was 60% (range: 35–90%) and maturity index of the study site was 9.97 (Table 3). The maturity index of the present study site was lower compared to maturity index calculated in the two sacred groves of Kathmandu valley, Nepal (29.4–80)[12]. A more developed plant community has a higher maturity index[38]. So, in this regard the studied forest is a less developed plant community than the sacred groves of Kathmandu valley.

The DBH-size class distribution curve of the study area shows a reverse J shaped structure due to higher density of the trees with smaller girth size (Figure 2). This indicates the regenerating nature of the forest. A higher density of trees with smaller girth size than of trees with a larger girth size indicates a good regeneration state[42]. This is mainly due to proper management of the forest with low disturbance intensity which ensures high density and enhanced regeneration of socio-economically important tree species[43].

Forest carbon stock

Biomass of the studied site was 418.2 Mg ha^{-1} with 86.3 Mg ha^{-1} below-ground and 331.9 Mg ha^{-1} above-ground (range: 0.02–116.1) (Figure 3 *a* and Table 4). C-stock of 196.4 Mg ha^{-1} (range: 0.007–54.57) with

Table 1. Frequency (F), relative frequency (RF), density (D), relative density (RD), basal area (BA), relative basal area (RBA) and importance value index (IVI) of tree species in the mixed plantation forest in Kathmandu, Central Nepal. List according to IVI (from high to low)

Species	F	RF (%)	D (pl ha^{-1})	RD (%)	BA (m^2 ha^{-1})	RBA (%)	IVI (%)
Cinnamomum camphora	58.5	12.8	71.95	16.1	9.724	20.83	49.7
Salix babylonica	36.6	7.98	86.59	19.4	7.923	16.97	44.3
Pinus roxburghii	21.9	4.79	54.88	12.3	5.455	11.69	28.8
Grevillea robusta	34.1	7.45	37.20	8.32	2.705	5.795	21.6
Celtis australis	48.8	10.6	29.88	6.69	1.487	3.184	20.5
Eucalyptus citriodora	17.1	3.72	24.39	5.46	4.566	9.781	18.9
Alnus nepalensis	14.6	3.19	21.95	4.91	1.599	3.425	11.5
Lagerstroemia indica	12.2	2.66	22.56	5.05	1.534	3.285	10.9
Populus euramericana	14.6	3.19	5.49	1.23	2.068	4.430	8.85
Jacaranda mimosifolia	14.6	3.19	9.15	2.05	1.402	3.004	8.24
Diospyros sp.	4.87	1.06	3.05	0.68	3.011	6.449	8.19
Cupressus torulosa	7.32	1.60	10.98	2.46	1.441	3.088	7.14
Callistemon citrinus	12.2	2.66	6.71	1.50	0.221	0.473	4.63
Morus alba	14.6	3.19	4.27	0.96	0.110	0.236	4.38
Eucalyptus sp.	9.76	2.13	2.44	0.55	0.577	1.237	3.91
Prunus cerasoides	12.2	2.66	3.05	0.68	0.063	0.136	3.48
Casuarina equisetifolia	4.9	1.06	6.71	1.50	0.420	0.900	3.46
Alangium chinense	9.76	2.13	4.27	0.96	0.097	0.208	3.29
Unidentified sp.	7.32	1.60	4.88	1.09	0.150	0.321	3.01
Melia sp.	9.76	2.13	2.44	0.55	0.147	0.315	2.98
Thuja orientalis	4.88	1.06	4.88	1.09	0.374	0.802	2.96
Litsea sp.	9.76	2.13	3.05	0.68	0.040	0.085	2.89
Zizyphus incurva	7.32	1.60	1.83	0.41	0.052	0.112	2.12
Quercus lanata	4.88	1.06	1.83	0.41	0.235	0.504	1.98
Bauhinia purpurea	4.88	1.06	3.05	0.68	0.073	0.155	1.90
Michelia champaca	4.88	1.06	1.22	0.27	0.117	0.251	1.59
Sequoia sempervirens	4.88	1.06	1.22	0.27	0.063	0.135	1.47
Pyrus pashia	4.88	1.06	1.22	0.27	0.024	0.051	1.39
Citrus maxima	4.88	1.06	1.22	0.27	0.013	0.029	1.37
Tamarindus indica	2.44	0.53	1.83	0.41	0.155	0.333	1.27
Clerodendrum indicum	2.44	0.53	0.61	0.14	0.190	0.407	1.08
Leucaena leucocephala	2.44	0.53	1.83	0.41	0.056	0.120	1.06
Juniperus sp.	2.44	0.53	1.83	0.41	0.023	0.048	0.90
Ficus lacor	2.44	0.53	0.61	0.14	0.140	0.300	0.97
Platanus orientalis	2.44	0.53	0.61	0.14	0.127	0.272	0.94
Cedrus deodara	2.44	0.53	0.61	0.14	0.101	0.217	0.89
Cordia dichotoma	2.44	0.53	1.22	0.27	0.018	0.039	0.84
Sapindus mukorossi	2.44	0.53	0.61	0.14	0.062	0.133	0.80
Juglans regia	2.44	0.53	0.61	0.14	0.039	0.084	0.75
Ficus elastica	2.44	0.53	0.61	0.14	0.037	0.080	0.75
Dalbergia sp.	2.44	0.53	0.61	0.14	0.009	0.020	0.69
Ficus auriculata	2.44	0.53	0.61	0.14	0.009	0.020	0.69
Myrica esculenta	2.44	0.53	0.61	0.14	0.009	0.020	0.69
Sambucus javanica	2.44	0.53	0.61	0.14	0.007	0.014	0.68
Mimosa sp.	2.44	0.53	0.61	0.14	0.005	0.012	0.68
Murraya koenigii	2.44	0.53	0.61	0.14	0.004	0.008	0.68
Total	459	100	447	100	46.686	100	300

40.4 Mg ha^{-1} below-ground and 156 Mg ha^{-1} above-ground was estimated from the present study. Similarly, study site assimilated 720.7 Mg CO_2 ha^{-1} (range: 0.03–200.08), 148.8 Mg CO_2 ha^{-1} below-ground and 571.9 Mg CO_2 ha^{-1} above-ground (Figure 3 *a* and Table 4). Thus, study site stored and sequestered 322.1 Mg C and 1180.9 Mg CO_2 respectively (Figure 3 *b*). The CSR and CO_2 assimilation rate (CAR) were 4.78 and 17.58 Mg ha^{-1} yr^{-1} respectively (Table 4).

Species-specific biomass, C-stock, CO_2 assimilation, CSR and CAR varied with species. Generally, all of these values were found highest in *E. citriodora*, while it was lowest in *S. javanica* (Table 4). Similarly, species like *C. camphora*, *S. babylonica*, *P. roxburghii*, *G. robusta*, *Diospyros* sp. and *P. euramericana* also have a high value of C-stock, CO_2 assimilation, CSR and CAR. Some species particularly, *M. koenigii*, *Mimosa* sp., *F. auriculata*, *F. lacor*, *C. maxima* and *Dalbergia* sp. have

Table 2. Importance value index (IVI), carbon stock (CS), CO_2 assimilation (CA), carbon sequestration rate (CSR, Mg ha^{-1} yr^{-1}) and CO_2 assimilation rate (CAR, Mg ha^{-1} yr^{-1}) of plant families in the mixed plantation forest of Kathmandu, Central Nepal

					CSR	CAR
Family	IVI (%)	CS (Mg ha^{-1})	CS (%)	CA (Mg ha^{-1})	Mg ha^{-1} yr^{-1}	
Myrtaceae	27.51	58.53	29.80	214.61	1.43	5.23
Lauraceae	52.59	33.69	17.15	123.53	0.82	3.01
Salicaceae	53.17	32.30	16.45	118.43	0.79	2.89
Pinaceae	29.64	17.83	9.08	65.38	0.44	1.59
Proteaceae	21.56	11.76	5.99	43.12	0.29	1.05
Ebenaceae	8.19	9.82	5.00	36.01	0.24	0.88
Cupressaceae	12.56	5.98	3.05	21.93	0.15	0.54
Ulmaceae	20.51	5.91	3.01	21.67	0.14	0.53
Betulaceae	11.53	4.65	2.37	17.05	0.11	0.42
Bignoniaceae	8.24	3.32	1.69	12.17	0.081	0.297
Lythraceae	10.99	3.23	1.65	11.84	0.079	0.289
Casuarinaceae	3.46	2.59	1.32	9.497	0.063	0.232
Fabaceae	5.60	1.65	0.84	6.05	0.04	0.148
Fagaceae	1.98	1.64	0.84	6.01	0.04	0.143
Platanaceae	0.94	0.58	0.29	2.13	0.014	0.052
Verbenaceae	1.08	0.47	0.24	1.72	0.012	0.042
Meliaceae	2.99	0.45	0.23	1.65	0.011	0.040
Magnoliaceae	1.59	0.38	0.19	1.39	0.0093	0.034
Moraceae	6.79	0.37	0.19	1.36	0.009	0.033
Sapindaceae	0.80	0.23	0.12	0.84	0.0056	0.021
Unidentified sp.	3.01	0.23	0.12	0.84	0.0056	0.021
Rosaceae	4.87	0.21	0.11	0.77	0.005	0.019
Alangiaceae	3.29	0.20	0.10	0.73	0.0049	0.0179
Rhamnaceae	2.12	0.14	0.07	0.51	0.0034	0.0125
Juglandaceae	0.75	0.12	0.06	0.44	0.0029	0.0107
Rutaceae	2.04	0.04	0.02	0.14	0.0009	0.0034
Boraginaceae	0.84	0.03	0.02	0.11	0.0007	0.0027
Myricaceae	0.69	0.03	0.02	0.11	0.0007	0.0027
Sambucaceae	0.68	0.007	0.004	0.03	0.0002	0.0006
Total	300	196.39	99.99	720.66	4.78	17.58

Table 3. Species richness, canopy cover and maturity index in mixed plantation forest of Kathmandu, Central Nepal

Study site	Number of species	Canopy cover (%)	Maturity index
Coronation garden	46 (range: 1–15 sp/plot)	60 (range: 35–90%/plot)	9.968

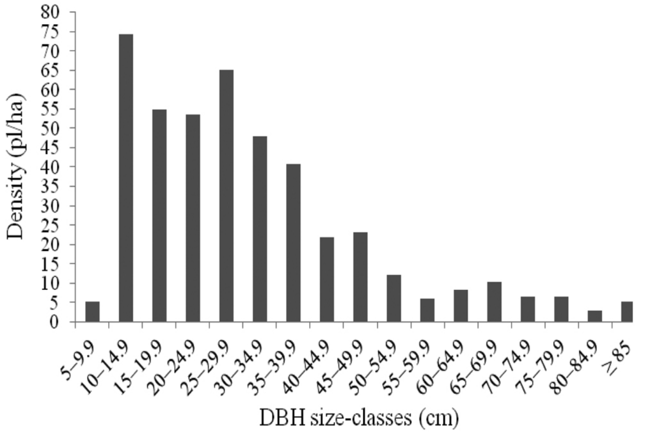

Figure 2. DBH size-class distribution curve of the mixed plantation forest of Kathmandu, Central Nepal.

low value for these parameters (Table 4). Myrtaceae was the family with highest C-stock, CO_2 assimilation, CSR, and CAR which was followed by Lauraceae, Salicaceae, Pinaceae and so on, while Sambucaceae had the lowest value for all these attributes (Table 2). All the sampled trees were not planted at the same time, some trees had regenerated afterwards. But we calculated CSR considering a single plantation time. The C-stock and CSR vary with the species and the reason for this may be the variation in the actual age of the species (we considered the same age for all species and sampled trees during calculation), the density of tree and habit of the species. Species containing high C-stock do not necessarily have a high CSR[35], but species with a high growth rate have high CSR[6]. So, another reason for CSR variation may be the varied growth rate of different species.

Table 4. Mean height (HT), mean diameter at breast height (DBH), biomass, carbon stock (CS), CO_2 assimilation (CA), carbon sequestration rate (CSR) and CO_2 assimilation rate (CAR) of the tree species in mixed plantation forest of Kathmandu, Central Nepal. List according to carbon stock (from high to low)

Species	HT (m)	DBH (cm)	Biomass (Mg ha^{-1})	CS (Mg ha^{-1})	CS (%)	CA (Mg ha^{-1})	CSR	CAR
							Mg ha^{-1} yr^{-1}	
Eucalyptus citriodora	29.6	44.9	116.10	54.57	27.79	200.08	1.33	4.88
Cinnamomum camphora	16.5	35.9	71.54	33.62	17.12	123.28	0.82	3.01
Salix babylonica	16.7	31.6	49.61	23.32	11.87	85.50	0.57	2.09
Pinus roxburghii	23.4	33.01	36.89	17.34	8.83	63.58	0.42	1.55
Grevillea robusta	15.2	25.7	25.01	11.76	5.99	43.12	0.29	1.05
Diospyros sp.	11.8	99.4	20.90	9.82	5.00	36.02	0.24	0.88
Populus euramericana	30.9	67.7	19.10	8.98	4.57	32.92	0.22	0.80
Celtis australis	11.8	20.1	12.57	5.91	3.01	21.66	0.14	0.53
Alnus nepalensis	18.5	29.2	9.88	4.65	2.37	17.03	0.11	0.42
Cupressus torulosa	15.6	36.5	9.13	4.23	2.15	15.73	0.10	0.38
Eucalyptus sp.	20.0	53.2	7.12	3.34	1.70	12.26	0.08	0.298
Jacaranda mimosifolia	13.0	39.3	7.06	3.32	1.69	12.17	0.08	0.296
Lagerstroemia indica	8.8	26.1	6.88	3.23	1.65	11.86	0.08	0.288
Casuarina equisetifolia	13.2	22.5	5.52	2.59	1.32	9.51	0.06	0.231
Quercus lanata	15.0	33.3	3.49	1.64	0.84	6.01	0.04	0.146
Thuja orientalis	16.6	28.4	3.40	1.60	0.82	5.86	0.04	0.143
Tamarindus indica	12.3	31.2	2.45	1.15	0.59	4.22	0.03	0.103
Callistemon citrinus	8.8	18.9	1.31	0.62	0.32	2.26	0.02	0.055
Platanus orientalis	25.0	51.4	1.24	0.58	0.30	2.14	0.01	0.052
Cedrus deodara	27.0	46.0	1.05	0.49	0.25	1.81	0.01	0.044
Clerodendrum indicum	12.0	62.9	1.00	0.47	0.24	1.73	0.01	0.042
Melia sp.	13.0	23.6	0.95	0.45	0.23	1.63	0.01	0.040
Michelia champaca	14.0	34.5	0.78	0.38	0.19	1.38	0.009	0.034
Morus alba	9.6	17.5	0.51	0.24	0.12	0.88	0.006	0.022
Sapindus mukorossi	14.0	36.0	0.50	0.23	0.12	0.86	0.006	0.021
Leucaena leucocephala	14.0	18.7	0.49	0.23	0.12	0.85	0.006	0.021
Bauhinia purpurea	10.6	16.7	0.48	0.23	0.12	0.83	0.006	0.021
Unidentified	5.25	17.0	0.48	0.23	0.12	0.83	0.006	0.021
Sequoia sempervirens	21.5	25.6	0.43	0.20	0.10	0.74	0.005	0.018
Alangium chinense	12.4	16.4	0.43	0.12	0.06	0.73	0.003	0.011
Prunus cerasoides	10.2	15.5	0.35	0.17	0.09	0.61	0.004	0.015
Zizyphus incurva	9.3	18.0	0.31	0.14	0.07	0.53	0.003	0.013
Juglans regia	15.0	28.5	0.27	0.12	0.06	0.46	0.003	0.011
Ficus elastica	12.0	27.8	0.21	0.09	0.05	0.37	0.002	0.008
Litsea sp.	9.6	12.1	0.15	0.07	0.04	0.27	0.002	0.006
Pyrus pashia	6.5	15.0	0.09	0.04	0.02	0.16	0.001	0.004
Juniperus sp.	8.0	12.5	0.07	0.03	0.02	0.12	0.0007	0.003
Cordia dichotoma	9.0	13.8	0.07	0.03	0.02	0.12	0.0007	0.003
Myrica esculenta	10.0	14.0	0.06	0.03	0.02	0.11	0.0007	0.003
Dalbergia sp.	10.0	14.0	0.06	0.03	0.02	0.10	0.0007	0.003
Citrus maxima	6.5	11.7	0.06	0.03	0.02	0.09	0.0007	0.003
Ficus lacor	10.0	17.0	0.04	0.02	0.01	0.07	0.0005	0.002
Ficus auriculata	9.0	14.0	0.03	0.02	0.01	0.06	0.0005	0.002
Mimosa sp.	8.0	10.5	0.03	0.01	0.01	0.05	0.0002	0.001
Murraya koenigii	8.0	8.5	0.02	0.008	0.004	0.03	0.0002	0.001
Sambucus javanica	6.0	12.0	0.02	0.007	0.004	0.03	0.0002	0.001
Total			418.15	196.39	99.99	720.66	4.78	17.58

Similar kind of study conducted by various researchers estimated the different amount of C-stock and CSR in either a single species plantation forest or a mixed species plantation forest in different parts of the world (Table 5). The C-stock of 196.4 Mg ha^{-1} estimated in the present study was higher than C-stock of other studies conducted in single species (monoculture) plantation forests of Nepal and the world (Table 5). The values were also higher than those obtained for mixed-culture plantation forests of Sri Lanka[44] and global mean biomass C-stock for plantation forests[45] estimated using meta-analysis approach. But, our result was witin the range of values obtained for a mixed plantation forest along the roadside of Bangladesh[46].

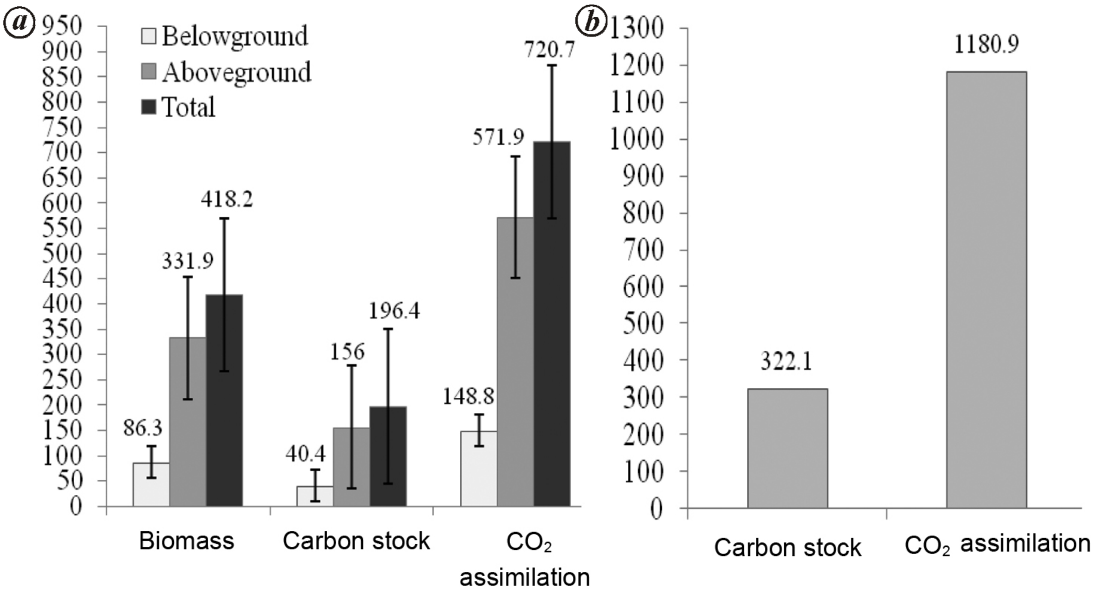

Figure 3. ***a***, Estimated biomass, C-stock and CO_2 assimilation (Mg ha^{-1}) in different pools and stand densities; ***b***, total carbon stock and CO_2 assimilation (Mg) in the present study site (Note: here 'total' referred as the whole area of the present study site, i.e. 41 plots of 400 m^2 = 1.64 ha; for detail see supplemental material; bar in the figure '***a***' indicates the standard error).

Table 5. Comparison of carbon stock (CS) and carbon sequestration rate (CSR) in a plantation forest

Forest type/species	Location	Age (year)	CS (Mg ha^{-1})	CSR (Mg ha^{-1} yr^{-1})	References
Mixed plantation	Kathmandu, Nepal	41	196.39	4.78	Present study
Pinus patula	Kavrepalanchok, Nepal	25–35	134.07 and 142.03	7.2	15
Pinus roxburghii	Myagdi and Sindhupalchowk, Nepal	15–32	41.5–101.9	2.09–3.9	16
Alnus nepalensis	Two sacred groves of Kathmandu, Nepal	NA	0.34	NA	12
Celtis australis			0.54 and 2.02		
Myrica esculenta			1.75 and 23.6		
Pyrus pashia			2.24 and 22		
Quercus glauca			2.3, 38.6 and 321.5		
Ziziphus incurva			0.22		
Eucalyptus camaldulensis	Mahottary, Nepal	8–10	30.3–148.9	3.4–10.2	23
Populus deltoides	Haryana, India	7	74.3	8.3–11.5	36
Mixed plantation	Southwestern, Bangladesh	11	192.8	NA	46
Populus deltoides	Uttarakhand, India	11	55.07	6.15	47
Populus deltoides	Uttarakhand, India	8	28.7 and 4.5	0.43–2.8	35
Eucalyptus tereticornis		10	10.5	0.84	
Dalbergia sissoo		10	43.4	2.73	
Prunus salicina		5	8.05	1.28	
Mixed-cultures plantation	Covers 17 forest divisions of Sri Lanka	<50	114.5	NA	44
Monoculture plantation			73.3		
Eucalyptus citridora			86.8		
Casuarina sp.			27.4		
Eucalyptus tereticornis	Terai region, India	9	41	6	6
Populus deltoides		9	55	8	
Mean biomass C-stock	Globally	4–55	101.4	NA	45

NA = Not available.

The species-specific C-stock for forest types of two sacred groves of Kathmandu valley calculated earlier found that the same species contained different amounts of carbon when grown at a different study site[12]. Similarly, several other studies[16,20,35,36,47–51] also found a variation of C-stock with the age of forest, stand condition, species composition, climatic condition, physiography and degree of disturbance. Thus, the difference found in carbon stocks between these studies and our results may be due to the difference in any one of the following factors: physiographic region, species composition, the age of the forest, stand condition, forest type and allometric equation applied.

Influence of stand properties on carbon stock

Though, we did not analyse the relationship between stand properties and carbon stock, we reviewed the published literature to some extent, and on that basis we have discussed this topic. The previous study showed that C-stock was not significantly affected by maturity index[12]. While species richness significantly affected the C-stock in the two sacred groves of Kathmandu valley[12] and three collaborative forests of Mahottari district of Nepal[22], it did not affect the C-stock of community managed sal forest of central Nepal[20]. Similarly, the previous study failed to observe a clear relationship between species richness and C-stock[50]. The previous study found that old mature forest with large girth size and taller trees are larger carbon pools[24,52].

Other researchers[48,49,51] have a common opinion that the potential for carbon sequestration depends on a single or multiple factors like, forest type, the age of the forest, the density of trees, size of trees, stand condition, biomass decomposition, climatic condition, the degree of disturbance and allometric equation used.

Conclusion

The present study reveals the variation in carbon stock and carbon sequestration rate among the trees. At the study sites, most of the carbon was stored by three species, with a high carbon sequestration rate *Eucalyptus citriodora, Cinnamomum camphora* and *Salix babylonica*. Similarly, the study area stored (196.4 Mg C ha^{-1}) and sequestered (4.8 Mg $\text{ha}^{-1}\,\text{yr}^{-1}$) a high amount of carbon and atmospheric CO_2 (720.7 Mg $CO_2\,\text{ha}^{-1}$). Thus, the study suggests that until species-specific growth rates are available, forest managers or forest practitioners might decide to use this information to select species (*Eucalyptus citriodora*, *Cinnamomum camphora*, *Salix babylonica*, *Pinus roxburghii*, *Grevillea robusta* and *Populus euramericana*) for long-term reforestation projects which would have the greatest impacts on landscape-level carbon stocks and potential to mitigate climate change.

The scope of research should be extended by establishing permanent sample plots and continuous measurements. Further studies can determine the soil organic carbon and other soil parameters like nitrogen, potassium, phosphorus, etc. and their variation with carbon stock. Until species-specific growth rates are available, species cannot be recommended for long-term restoration or plantation projects so that species-specific growth rates can be calculated to find the appropriate species for plantation (reforestation) projects.

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ACKNOWLEDGEMENTS. We thank Central Department of Botany, Tribhuvan University, Kirtipur for the necessary survey equipment and the Tribhuvan University Central Office, Kirtipur for information related to the study site.

Received 24 August 2017; revised accepted 6 April 2018

doi: 10.18520/cs/v115/i2/274-282