Chapter 3

Estimation of carbon stock under different management regimes of tropical forest in the Terai Arc Landscape, Nepal

Abstract

Carbon (C) stocks in the forests of Reducing Emissions from Deforestation and Forest Degradation (REDD+) participating countries have to be estimated and monitored to determine accurate financial incentives and compensation. The research estimated the distribution of C stock across the different pools and management regimes of tropical *Sal* forest in the Terai Arc Landscape of Nepal. It applied a field measurement-based forest inventory method combined with the best predictive allometric model available, to increase accuracy and precision. Shrub and litter C were estimated by destructive method and soil organic carbon (SOC) up to a depth of 30 cm. Biomass data and samples were collected from 113 plots distributed throughout four different management regimes on 1.1 million ha of forest in the landscape. The estimated average C stock in aboveground biomass, belowground biomass, shrub, litter, SOC and total were 105.58±17.05, 24.92±4.15, 0.23±0.06, 1.49±0.25, 96.53±8.76 and 228.76±19.61 Mg ha^{-1} respectively. The mass of total C stock varied from 291.55±42.51 Mg ha^{-1} in Protected Areas to 237.15±32.54 Mg ha^{-1} in Community forests to 189.16±26.46 Mg ha^{-1} in Government-managed forests and to 126.76±56.36 Mg ha^{-1} in other forests. These estimates of carbon stocks differed from all earlier estimates based on biome-average datasets. They are consistent with those from similar forest type and site- specific earlier studies, indicating the importance of field measurement-based, site-species- specific studies to achieve precise and reliable estimates of C stock. Evidence of strong association of C stock with management regime provides valuable information for policy makers to make informed choice of management regime for the landscape.

Keywords: Carbon Stock, Management regime, REDD+, Tropical *Sal* Forest, Terai Arc Landscape

3.1 Introduction

Tropical forests have received much attention in recent years thanks to global concern over climate change and potential roles of these forests as both source and sink of carbon (C). As a source, high rates of tropical deforestation are a major concern in international efforts to mitigate climate change. Deforestation in the tropics is estimated to have released 0.9 Pg C (DeFries, Houghton, Hansen, Field, & Townshend, 2002), 1.7 Pg C (IPCC, 2001), 1-2 Pg C (Houghton, 2005) between 1.4 to 3.0 Pg C (House, Prentice, Ramankutty, Houghton, & Heimann, 2003) per year during the 1990s in the context of net anthropogenic emissions of 6.3 Pg C from fossil fuel combustion (IPCC, 2001). These forests are also large carbon sinks because of the high carbon uptake during fast growth of their highly productive plants. Data from long-term forest plot monitoring indicates that these forests are capable of capturing up to 1.2 Pg C year^{-1}(Lewis, 2006) by increasing biomass.

Reducing Emissions from Deforestation and Forest Degradation (REDD+) which includes the roles of conservation, sustainable management of forest and enhancement of C stocks, is proposed as an incentive mechanism for developing countries, in the post-Kyoto climate regime, to reduce C emissions from forested land and to achieve low-carbon sustainable growth. C stocks in the forests of participating countries have to be estimated and monitored to determine accurate financial incentives and compensation under this mechanism. However, the foremost challenge is to quantify each country's C emissions from deforestation and forest degradation, which requires information on C stocks and deforestation rates (Gibbs et al., 2007).

Global estimates of C stocks (DeFries et al., 2002; Gibbs et al., 2007; Houghton, 1999; IPCC, 2006; Saatchi et al., 2011) and some estimates specific to Asian tropical forests (Ajtay, 1979; Brown & Lugo, 1982; Houghton, 2005) provide generic approximations of C stocks in tropical forests. These estimates of C stocks are based on the biomass estimates from ecological studies and have shown wide variations. Most of the estimates of tropical forest C stock and emissions are uncertain and are erroneous for many ecosystems (IPCC, 2000). Uncertainties and lack of consensus in all these estimates are due to the use of divergent estimates of forest carbon stocks per unit area (Lewis, 2006). This arises because forests in the tropics have different spatial distribution of biomass and inventory of the entire tropical forest is rarely done (Baker et al., 2004; Malhi & Grace, 2000).

Measurement-based inventories of C stocks have been increasingly important in recent years to evaluate the magnitude of carbon fluxes between forest ecosystems and the atmosphere (Grace, 2004). Estimates disaggregated at sub-national level (Tier 3), with higher levels of accuracy, can potentially lead to higher financial return under the proposed REDD+ mechanism (IPCC, 2006). Sporadic inventory-based attempts have been made in some similar forest type (Boonpragob, 1998; Haripriya, 2000; Manhas, Negi, Kumar, & Chauhan, 2006; Ogawa, Yoda, Ogino, & Kira, 1965; Sharma, Baduni, Gairola, Ghildiyal, & Suyal, 2010) of the region. However, C stocks even in comparable forest types, varies from place to place, region to region as these are influenced by natural succession; management activities like silviculture, harvesting, and degradation and natural impacts by wildfire and climate change (Brown & FAO, 1997). Those similar forest-types studies are designed to represent specific sites; therefore, they may not necessarily reflect the anthropogenic and environmental conditions of Nepal.

Analysis of forest biomass provides estimates of C stored in the various pools; viz. aboveground and belowground biomass, necro-mass including litters, twigs and woody debris, soil organic matter and harvested wood products (Malhi, Meir, & Brown, 2002). Selection of C pools to estimate C stock, emissions and removal will depend on the significance of the pool, model availability, as well as resources and capacity to collect and analyse additional information (IPCC, 2006). Therefore, the IPCC guidelines suggest identifying key carbon pools that make the greatest contribution to total C stock in order to make the most efficient use of available resources. Since there are no studies that have covered the C pools of litter, shrub and soil organic carbon (SOC) in similar forest types of the region, it is imperative to understand the contribution of these pools to the total C stock.

This paper aims to (a) estimate C stock in the Tropical Sal (*Shorea robusta*) and associated species forest of Terai region of Nepal, (b) estimate contributions of key C pools to total C stock of the forest, (c) to estimate the distribution of C stock across management regimes and, (d) to estimate the emissions reduction potential of the forests of the landscape.

3.2 Materials and Methods

3.2.1 Site description

The Terai Arc Landscape (TAL) is a trans-boundary conservation endeavour spread over 49,500 square km, linking 11 trans-boundary protected areas in Nepal and India. In Nepal, it covers 23,129 square km, stretching from Rautahat district in the east to Kanchanpur in the west covering 15 districts including part of Arghkhanchi district of Southern Nepal (Figure 3.1). The study was conducted in Nepal's part of the landscape of 1,102,300 ha (out of a total 10,872 square km including grass lands and forest with less than 10 % canopy class) of forest which includes five protected areas including the recently declared Banke National Park. The study area is one of the world's biodiversity hotspots and supports the world's most spectacular biodiversity that includes 86 mammal species, 47 reptiles and amphibian species, 556 bird species and more than 2100 species of flowering plants (HMG/N, 2004).

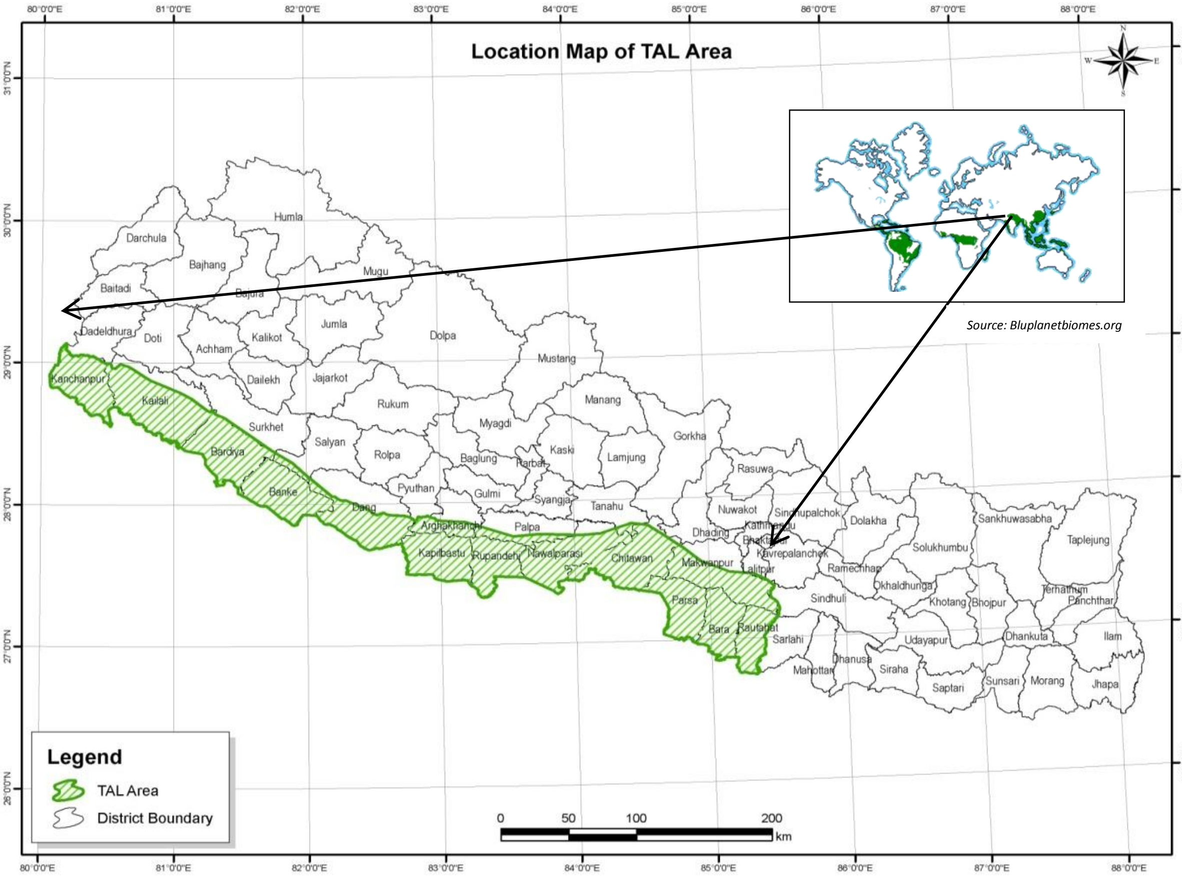

Figure 3.1 Location map of Terai Arc Landscape, Nepal

Climatic conditions, altitude, geographical location, soil composition and biotic factors are the determinants of vegetation distribution in Nepal (Jackson, 1994). The TAL lies between elevations of 200-1000 m, has a hot climate of annual average temperature 18.5-26.1^{0}C and heavy monsoon rain with mean precipitation between 1056-2929 mm/year. The land in the TAL is composed of flat and highly fertile alluvium deposits. Forests of TAL contribute 75% of the total forests of the *Terai* (HMG/N, 2004).

Forest of the landscape has enormous commercial as well as subsistence importance (Webb & Sah, 2003). Under heavy pressure from anthropogenic activities, these forests have been depleted in the last few decades resulting in degradation and fragmentation of historically contiguous landscapes and posing threats to both biodiversity conservation and to local livelihoods (Timilsina et al., 2007) . According to the latest forest inventory data, the annual deforestation rate was 1.25 % during 1978-1991 with large sub-regional variations. Rupendehi district which is located almost in the middle of the landscape had the highest annual deforestation rate of 3.8 % while Kailali district in the western part had the largest deforestation (HMG/N & FINNIDA, 1994) in absolute area of 16,000 ha during the period (FAO, 1999).

3.2.2 Forest type and management regime

On the basis of ecology and vegetation, Stainton (1972) and later on Jackson (1994) have classified the forests of Terai region of Nepal as tropical forest. Based on FAO's ecological zoning, the forests of the study area largely belong to tropical moist deciduous forest with some parts of tropical rain forest and tropical dry forest (FAO, 1999, 2001). *Shorea robusta* Gaertn. F., locally known as *Sal,* dominates the forest of the Terai region (FAO, 1999) constituting 43% of total standing volume of Terai forest of Nepal (FSISP, 1993). The species is accompanied by *Adina cordifolia, Lagerstroemia parviflora, Anogeissus latifolia,* and *Terminalia tomentosa* (HMG/N, 1988; Jackson, 1994; Sharma et al., 2010) making up the forest type.

Sal forest is one of the most important forest types among 35 different forest types found in Nepal (MFSC, 2009). The formation of this forest type is distributed across the Indian Sub-continent covering 11 million ha in India, Nepal and Bangladesh (Gautam & Devoe, 2006). The *Dipterocarpaceae* family is considered to be the most valuable tree species found in the forests of the sub-continent. Timber is used for construction and carpentry purposes; branches for fuel wood, and leaves are used for fodder and disposable plates in the southern plains of Nepal (Jackson, 1994; Rautiainen & Suoheimo, 1997).

On the basis of ownership of the forest land, the forests of Nepal are broadly classified as "private forest" and "national forest". National forests are further disaggregated into five categories; protection forest, community forest, leasehold forest, religious forest and government-managed forest. The landscape has five protected areas, including the recently established Banke National Park, managed under protection forest covering a total area of 3.2 million hectares that includes forest, shrub land, grassland and other land uses. 189,000 hectares of forests are managed under community forest by more than 1300 user groups. Except for negligible areas of private, religious and collaborative forests, the rest of the forest areas are managed as government-managed forest under the control of District Forest Offices. National forest policy introduced in 1989 promotes gradual conversion of government managed national forest into forest managed by local users to eliminate current uncontrolled use of national forest (FAO, 1999).

3.2.3 Measurement of carbon stocks

Though direct measurement by destructive harvesting of above and belowground biomass provides an accurate estimate of C stock, this method is not practically feasible at national, sub-national or landscape scales. Efforts (IPCC, 2006) have been made to develop models based on proxies measured in the field for quantification at national and sub-national or site level. The Inter-governmental Panel on Climate Change (IPCC, 2006) has suggested a three-tier approach to estimate C stock; use of biome average values in tier I rough approximation, country specific values for tier II and measurement-based forest inventory combined with predictive relationships in tier III for higher levels of accuracy. More accurate estimation of C stock means potentially higher financial returns under the proposed mechanism because buyers are more confident and willingness to pay higher price (IPCC, 2006).

Gibbs et al. (2007) have enumerated benefits, limitations and levels of uncertainty of available methods to estimate C stock. They argued that biome average and optical remote sensors are highly uncertain because of their fairly generalized nature, lack of properly sampled data sources, and saturation of spectral indices at relatively low C stocks. Very high resolution optical, radar and laser remote sensing methods have low to medium levels of uncertainty but they are expensive and technically demanding. They require extensive field data for calibration, and have decreased accuracy in complex canopies and mountainous terrain (Gibbs et al., 2007), making them infeasible for this study. Instead, we adopted the forest inventory method for the study because of its capability to estimate C stocks to known levels of accuracy and precision and because of its relatively inexpensive, low-tech nature (Brown, 2008; Gibbs et al., 2007; IPCC, 2006).

3.2.4 Sampling design

A pilot inventory was carried out to determine the sample size for field measurement. Aboveground biomass (AGB) is assumed to be the largest carbon pool that is most susceptible to human activities. Hence, only AGB was considered for the variance analysis, since the largest pools carry the largest variance. A total of 113 sample plots that include 28 sample plots in protected area forest, 40 each in community and government managed forest and five sample plots in other forests were randomly established for field inventory on the basis of variance analysis. Co-ordinates of these plots were uploaded to GPS devices which were later used to locate the plots on ground. Inventory crew members were trained on field measurement and equipment was calibrated prior to the field work.

Circular plots of various radiuses for different purposes were established because they are relatively trouble free to establish. 500 m^2 plots were established to record diameter at breast height (dbh; 1.3 m above the ground), height and other morphological characteristics of each individual tree having ≥ 5 cm dbh as this size of plot is the minimal size for biomass estimation (Chave et al., 2005) suitable for moderately sparse vegetation (MacDicken, 1997) having dominant trees of 20-50 cm dbh (Pearson, Brown, & Birdsey, 2007). Shrub and tree regeneration samples were collected using destructive methods from each 25 m^2 intermediate sub-plot nested inside the same tree plot. Additionally, four nested small sub-plots of one m^2 were established in four corners of the tree sample plot to record litter biomass. The samples collected from these plots were oven dried in the laboratory to estimate biomass.

Soil samples were collected from a depth of 30 cm as recommended by IPCC (2006). Samples collected from five different pits in a W-shape inside the one m^2 sub-plots were well-mixed in different phases and 500 gm out of them was taken for laboratory analysis. A core sampler was used to collect soil core for bulk density analysis. These samples were marked with sample plot numbers and later analysed at National Agricultural Research Council (NARC) laboratory in Kathmandu. Soil Organic Carbon (SOC) and soil bulk density (BD) were tested to determine total SOC in the forest using equation prescribed by Pearson (Pearson, Walker, & Brown, 2005).

3.2.5 Data analysis

Tree Aboveground Biomass (AGB)

Tree allometry provides quantitative relationships between tree biomass, hence, carbon stock, and other tree dimensions; i.e.; tree diameter, height etc. These dimensions are easy to measure. Allometric models enable aboveground biomass (AGB, in kg) of a tree to be estimated from the size of the tree; e.g. diameter (D). It is based on the allometric scaling theory that explains a power-law relationship between tree biomass and tree diameter. But this relationship has been questioned by Niklas (1995) and Chave *et al*. (2005) because of mechanical and physiological limits to an increase in tree height at large diameters leads to over-estimation of biomass for large trees. In some recent studies, incorporating additional variables of tree size viz; height (*H*) and wood specific gravity (ρ, oven dry wood over green volume) in the generic model has provided biomass estimates with better precision (Brown, Gillespie, & Lugo, 1989; Chave et al., 2005; Djomo, Ibrahima, Saborowski, & Gravenhorst, 2010).

Though *Sal* is a dominant species, forests of the landscape generally contain several associate species even within a 500 m^2 sample plot. As a result, one cannot use species-specific allometric equations for these forests. Therefore, a region-specific mixed species tree biomass regression model is normally required because tree form and allometric relationships are expected to be different from region to region with the changes in the environmental factors (e.g. soil and climate), genetic (wood density, crown architecture) and other biotic factors (Vieilledent et al., 2012). As the region specific model was not available, the study used Chave's model, which has been widely used and gave accurate tree biomass estimates for Madagascar (Vieilledent et al., 2012) including diameter, height and wood specific gravity as explicative variables to estimate aboveground biomass from plot inventories.

Following is the best predictive model for moist forest stands (Chave *et al*. (2005), irrespective of tree species and of the stand location, used to estimate AGB;

$$\ln AGB = \alpha + \beta \ln (D^2 H \rho) \qquad \text{(I)}$$

The following parameter values were used for moist tropical forest;

$$\ln AGB = -3.080 + 1.007 \ln (D^2 H \rho) \quad \text{(II)}$$

This model uses $D^2H\rho$ as a single predictor. For the model, diameter (D) was measured in centimetre, tree height (H) in meter, wood density (ρ) in grams per cubic meter representing oven dry mass divided by green volume, and the resulting aboveground biomass (AGB) estimates is in kilograms. Stand level average wood density for Sal forest and *Acacia-Dalbergia* species of HMG/N (HMG/N, 1988) was used as suggested by Baker et al. (Baker et al., 2004).

Belowground biomass (BGB)

The plot inventory done for this study doesn't directly provide BGB. However, use of AGB data as a predictor by using root: shoot ratio has become core method for estimating root biomass. To estimate BGB and carbon stocks for greenhouse gas inventory purposes, multiplying the AGB by the root: shoot ratio applicable to that forest type is the recommended method (IPCC, 2006; Snowdon et al., 2000) because AGB alone accounts for 83% of variation in BGB (Cairns, Brown, Helmer, & Baumgardner, 1997). Mokany *et al.*(2006) has found vegetation specific root; shoot ratios to be a more accurate method for predicting belowground biomass. After an extensive review of the literature, IPCC (2006) recommended two root: shoot ratios for the tropical moist deciduous forest;

Table 3.1 Ratio of belowground biomass to aboveground biomass

AGB stock	Ratio	range
AGB <125 tonnes ha^{-1}	0.20	(0.09-0.25)
AGB >125 tonnes ha^{-1}	0.24	(0.22-0.33)

Source: Mokany et al. (2006)

Both of these ratios in table 3.1 were used to estimate BGB and carbon stock.

Shrub Biomass

In contrast to availability of tree allometric models to estimate AGB, shrub allometric equations for the vegetation types of the region are evidently missing. Therefore, the study applied the destructive method recommended by Pearson *et al.* (2005) to estimate biomass in the shrub carbon pool. Gibbs *et al.*(2007) reinforced the use of the destructive method to improve accuracy in the quantification of forest carbon stocks. After harvesting all shrubs within the sample plot, total green weights were recorded. Then, well mixed sample of 500 gm were oven dried to determine the factors of oven dry weight and green weight. Those were used to extrapolate the total dry biomass inside the plots.

Litter

The litter pool represents all forest floor biomass lying above the soil surface consisting of dead leaves, twigs, branches, grasses and small downed dead wood. In the landscape, this pool is prone to frequent events of forest disturbances, like forest fires. IPCC's tier 1 level of estimation assumes that the carbon in the non-merchantable components is to be released entirely to the atmosphere due to disturbances. However, inventory of this pool helps to identify whether this pool of C is a key category for monitoring and reporting purposes and it provides changes through subsequent inventories, if required. Evenly mixed 500 gm sample litter were brought to the lab to determine oven dry mass. Factors of over dry mass and sample mass were used to estimate total dry mass in the litter sample sub-plots, hence, to extrapolate in the entire pool.

Carbon Fraction

Accurate knowledge of carbon concentration in wood and other parts of plants is essential to quantify carbon stock in a forest. A generic value of 50 % carbon fraction in dry biomass was widely used and reinforced by empirical reviews (Brown & FAO, 1997; Matthews, 1993). However, recent literature argues that C concentration is highly variable among tree parts (Bert & Danjon, 2006; Laiho & Laine, 1997; Lamlom & Savidge, 2003) and tree species (Martin & Thomas, 2011; Thomas & Malczewski, 2007). In the absence of values specific to the forest types of the region, we used the value of 0.47 (IPCC, 2006)to convert dry biomass into carbon in order to cover all three parts.

Soil Organic Carbon (SOC)

Soil is the largest terrestrial store of C which is nearly three times that in AGB and approximately double that in the atmosphere (Eswaran, Van Den Berg, & Reich, 1993; Jobbagy & Jackson, 2000). This pool is an important component of forest C pools (Tremblay, Ouimet, & Houle, 2002). It may prove to represent a more stable and longer lasting solution than C stored in standing tree biomass (Batjes, 1998) since biomass C stocks are more vulnerable to natural and human-induced disturbances (Jandl et al., 2007).

Total carbon stock in forest soil was calculated as per Pearson et al. (2005):

$$\text{SOC (t/ha)} = (\text{Soil Bulk Density (gm/cm}^3) \times \text{Soil depth (cm)} \times C) \times 100 \qquad \text{(III)}$$

Where;

C is the carbon fraction of the sample expressed in decimal format.

The composite soil samples collected from the prescribed depth of 30 cm were analysed to estimate carbon content. Core samples were used to determine soil bulk density. Soil bulk density was estimated by core method; soil samples were dried at $110^0\pm1^0$C and weighted for the oven dry mass divided by the volume of the cylindrical core sampler. Carbon concentration was analysed using colorimetric method with external heating.

Total carbon stock and uncertainty estimate

The total carbon stocks per hectare were calculated by summing up C stock in the AGB, BGB, Shrub, Litter and SOC pools C extrapolated into Mg ha^{-1} from the plot level data. Total C stock of each management regime was estimated by aggregating the mean C stock in all plots falling into the regime. Uncertainties were estimated at 95% confidence intervals.

3.3 Results

Numbers of sample plots established across the management regimes and samples analysed are illustrated in table 3.2.Protected area forest covers the largest percentage (68 percent) of total forest area with more homogenous forest biomass density, hence the lesser number of sample plots. Community forest and government managed forest cover approximately 10 percent and 21 percent of total forest area respectively. These forests, however, includes a wide ranges of C densities because of variations in forest biomass densities. The other forest areas contribute an insignificant portion (less than one percent) of total forest area of the landscape.

Table 3.2 Numbers of sample plots across the managament regimes and carbon pools

Management regime	Numbers of Sample plots AGB	Shrub	Litter	SOC
Protected area	28	28	112	112
Community Forest	40	40	160	160
Government-managed Forest	40	40	160	160
Other Forest	5	5	20	20

3.3.1 Aboveground biomass (AGB)

In the forest of TAL, average carbon stock in AGB was estimated as 105.58±17.05 Mg ha^{-1}. The lowest value was 0.29 and the highest 439.83 Mg ha^{-1} with a standard deviation of 92.46 Mg ha^{-1}. Large variations in carbon stored in AGB were observed within each particular management regime (Fig. 2). Forests of the protected areas have the highest AGB stocks of carbon, 161.47±38.68 Mg ha^{-1}, and the other forests store the least (8.73±8.6 Mg ha^{-1}). Community forest and government-managed forest had 101.07±27.09 and 83.08±22.69 Mg ha^{-1} of carbon respectively.

AGB carbon stocks in the forests of the landscape were determined by the management regime applied. The AGB pool had statistically strong association with the forest management regime at the 0.05 level of significance. The result shows that the more restrictions on timber harvesting from forest, as enforced in the protected areas, the more stock of C in the AGB pool.

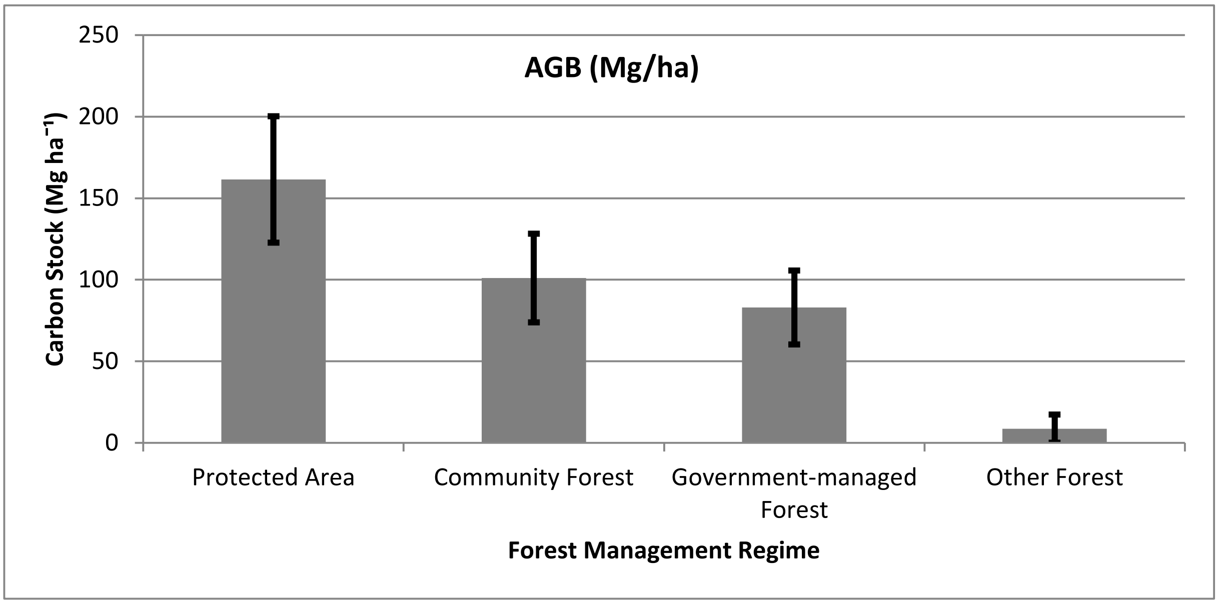

Figure 3.2 Distribution of Aboveground Biomass in different management regimes

3.3.2 Belowground biomass

Mean C stock in the belowground C pool in the forests of the TAL was 24.92±4.15 Mg ha^{-1}. In this study, we used the root: shoot ratio to estimate belowground biomass, hence, wide ranges of variations of C stock in belowground biomass were observed within and among management regimes. Similar to AGB C stock, forests of protected areas had the highest mean stocking of C in BGB pool followed by Community forest, government-managed forest and other forest respectively. This pool of carbon represents 8.14 % of total carbon stock. Uncertainty is higher in the 'other' forest regime because of the extreme values of AGB observed within this regime.

Table 3.3 Estimates of carbon stock in belowground biomass, in mg ha^{-1}

Forest Management Regime	Mean	95% CI	Range
Protected Area	38.59	9.36	3.03-105.56
Community Forest	23.81	6.61	1.57-84.64
Government-managed Forest	19.37	5.56	0.38-73.87
Other Forest	1.75	1.72	0.06-4.83

3.3.3 Shrub and Litter pool

The shrub pool contributed the lowest amount (0.23±0.06 Mg ha^{-1}) to total carbon stock. Estimates ranged from 0.00 to 1.62 Mg ha^{-1}. Not much variability on carbon stock was found in this pool between the management regimes. Estimated C stock in the litter pool (1.49±0.25Mg ha^{-1}) was greater than those of the shrub pool. Distribution of C in the litter pool ranged from 0.66 Mg ha^{-1} in other forest to 1.92 Mg ha^{-1} in protected area. Community forest and government-managed forest have 1.59±0.45 and 1.20±0.26 Mg ha^{-1} of C respectively.

3.3.4 Soil organic carbon (SOC)

SOC contains the second largest portion of total average C stock. Average C stock at a depth of 30 cm was found to be 96.53 Mg ha^{-1}. SOC has shown no statistical relationship with management regime at 95 % significance level.

Table 3.4 Estimates of Soil Organic Carbon, in Mg ha^{-1}

Forest Management Regime	Mean	95 % CI	Range
Protected Area	89.39	14.92	22.47-160.98
Community Forest	110.43	16.76	32.04-214.72
Government-managed Forest	85.26	12.43	26.09-197.13
Other Forest	115.56	55.66	61.86-217.93

3.3.5 Total Carbon Stock

Total C stock across the region was estimated at 228.76±19.61 Mg ha^{-1}. AGB is the largest C pool contributing 46 % share of total C stock, followed by SOC (42%), and BGB (11%).The litter and shrub pools contribute merely one percent to total average C stock in the forest of the TAL (Figure 3.4).

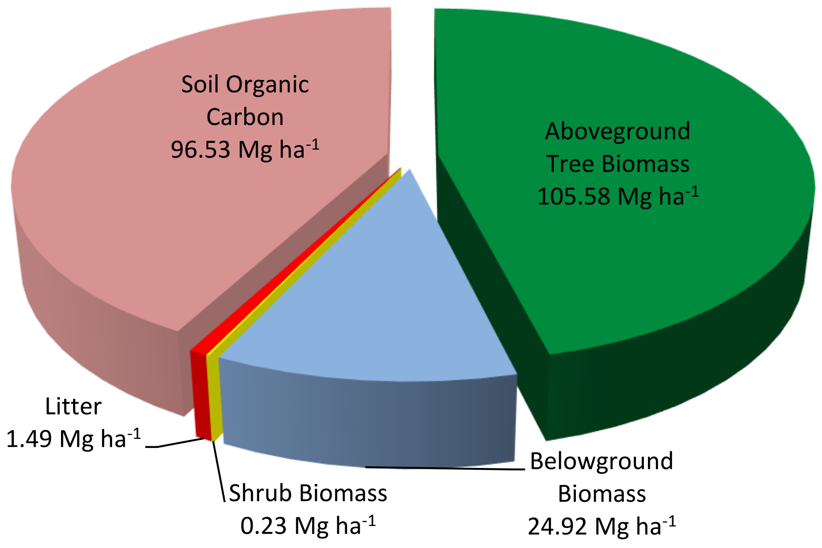

Figure 3.3 Distribution of carbon stock in different carbon pools

However, percentages share of different C pools vary according to management regimes, as do the total C stocks. The results showed statistically significant variations in total C stocks between the management regimes. Forests of protected areas had the highest level of C stock along with community forest, government-managed forest and other forest regimes in decreasing order.

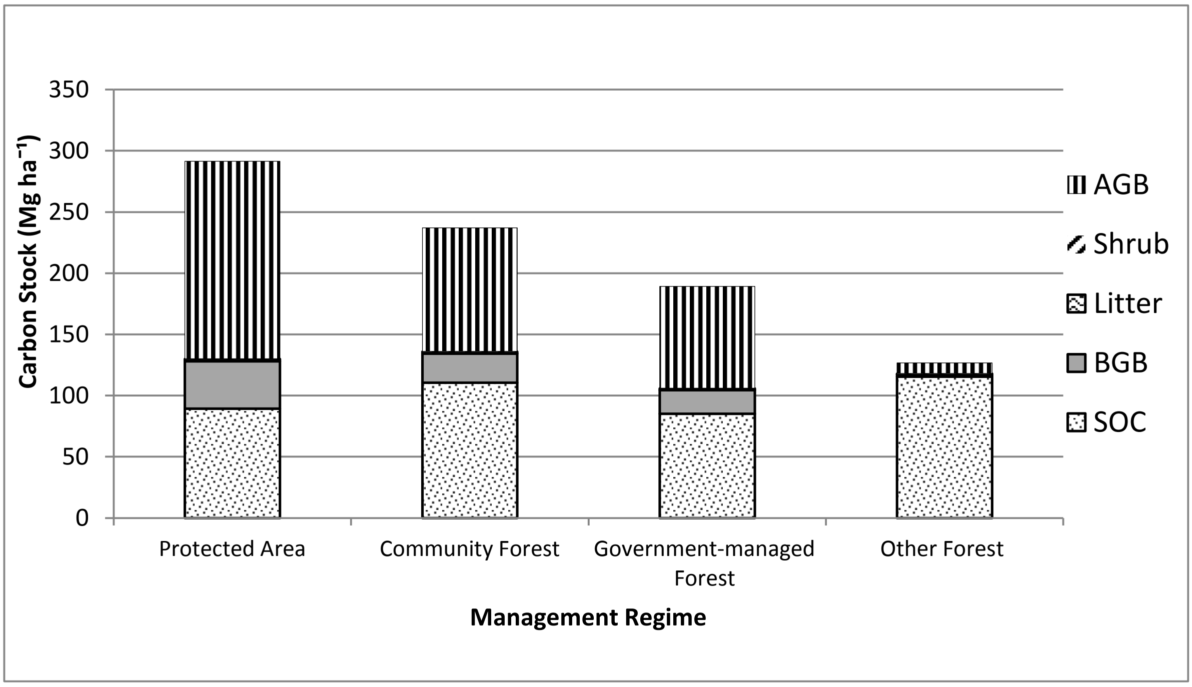

Figure 3.4 Distribution of carbon Stock (Mg ha^{-1}) across various forest management regimes

AGB remained the largest C pool in the forests of protected areas. Percentages share of this pool in total C stock decreased from 55 percent in protected areas to 7 percent in other forest. SOC dominated the share (91%) of total C stock in other forests. SOC pool was relatively stable across the management regimes (85-115 Mg ha^{-1}) and found no significant impact of management choice over the C stock in this pool. The result reinforced that AGB pool is the most susceptible pool due to anthropogenic activities in the forests. The stocking of the C in this pool is highly correlated with degree of enforcement of forest protection activities.

3.3.6 Changes in C stocks and emission reduction potential

The entire 1,102,300 ha forest at 2009 (Gurung & Kokh, 2011) stored 252,000±22,000 Gg C at 95 % confidence interval. According to HMG/N and FINNIDA's (1994) estimate of 1.25% annual deforestation rate, the entire region was losing approximately 13,000 ha of forest each year. More recent landscape focused research by Winrock/WWF estimated that the TAL had faced absolute deforestation of 40,000 hectares during the period 1990-2009 at an annual deforestation rate of 0.18% (Gurung & Kokh, 2011). The deforested lands were converted into agriculture, scrub and other land uses. Assuming no change in SOC after deforestation, loss of biomasses alone contributed emissions of 4,223±682Gg C during the period 1990-09. Switch of these forests to other land uses caused emissions of 15,499±2,503 Gg CO_2e to the atmosphere, which would have been avoided if those forests were conserved.

Community forest stored 48 Mg ha^{-1}, considerably more C than in government managed forest (176.14 CO2e Mg ha^{-1}). Forests in the protected areas reserved 102.40 Mg ha^{-1} more C than did government managed forest. If government managed forest was considered as degraded forest, forest of the landscape had potential of sequestering 375.79 Mg ha^{-1} CO_2e through avoided forest degradation. The difference in carbon stocks between average for TAL forest and other forests which included agro-forest was found to be 102 Mg C ha^{-1} (374.32 Mg $ha^{-1}CO_2e$). Converting current forests into other land use; agro-forestry land use for the most conservative estimate, for example; would emit 374.32 Mg $ha^{-1}CO_2e$ into the atmosphere. In other word, the forest of TAL has potential to reduce 374.32 Mg $ha^{-1}CO_2e$ emissions through avoiding deforestation.

3.4 Discussion

No study of a similar forest type was available to compare each of the comprehensive forest C pools considered in this study. Sporadic efforts have been made to estimate the C stock in AGB Pool for similar forests of Asia. Our estimate of AGB is consistent with128.63 Mg ha^{-1} (Carbon fraction 46%) for adjoining Moist Bhabar *Sal* forest of Garhwal Himalaya of India reported by Sharma *et al.* (2010). Our mean value of C stock in AGB (105.58±17.05Mg ha^{-1}) is higher than the mean values reported by Haripriya (2000) and Chaturvedi *et al.* (2011). They reported C stock of 34.10 Mg ha^{-1} (Carbon fraction 50%), and 87 Mg ha^{-1}in *Sal* forests of India respectively. The forests of the TAL largely belong to tropical moist deciduous forest*,* hence, our AGB estimate is higher than those estimates of 62 and 63 Mg ha^{-1} for dry *Dipterocarp* forest of Thailand reported by Boonpragob (1998) and Ogawa *et al.* (1965) respectively.

The C stock estimates in forest biomass differs markedly from the value of 250 Mg ha^{-1} (Carbon fraction 50%) for Asian Moist forests (Ajtay, 1979; Brown & Lugo, 1982) and 264 Mg ha^{-1} for Asian natural forest reported by Houghton (2005) estimated using secondary data. Compared to IPCC (2006) default value of 84.6 (47% of 180 tonnes dry matter ha^{-1}) for tier I estimate, the result gives a higher estimate of C stock in the tropical moist deciduous forest of the region. Our combined value of AGB and BGB of 130.50 Mg ha^{-1} is lower than those estimates of 150 Mg ha^{-1} (DeFries et al., 2002; Houghton, 1999), 142 Mg ha^{-1} (Gibbs et al., 2007), but higher than 105 Mg ha^{-1} (IPCC, 2006) for moist deciduous forest and 103 Mg ha^{-1} (Saatchi et al., 2011) for forest of Nepal. Most of these earlier estimates were based on biome-average datasets with some country level estimates using forest inventory data. This sub-national estimate is, however, closer to the country level estimate of Saatchi et al. (Saatchi et al., 2011) because per hectare growing stock in the Terai forest, according to FAO (2009) was estimated to be about one and half times more than the national average.

As we used root: shoot ratio to estimate BGB, and hence C stock, variations among the estimates of AGB had obvious implications on estimates of C stock in BGB pool. Estimated C stock in belowground biomass (24.92±4.15 Mg ha^{-1}) was higher than those reported (17.55 Mg ha^{-1}) by Moser *et al.* (2011) for similar climatic condition tropical forest of Ecuador, but within the range of 12.82 - 46.46 Mg ha^{-1} in the forest of an adjacent region of India reported by Sharma *et al.* (2010). However, we did not find any evidence of direct measurement of BGB carbon in similar forest types to compare to our results. Because of the substantial percentage share of this pool in total carbon stock, BGB carbon warrants greater research attention.

None of the studies reviewed in this paper reported shrub and litter pools. Studies on SOC content in similar forest types were patchy. Seikh *et al*. (2009) and Singh *et al.* (2011) reported 124.8 to 141.6 Mg ha^{-1} (0-60 cm), 62 Mg ha^{-1} (0-30 cm) respectively in sub-tropical forests of a contiguous region. The estimated mean value of the SOC stock found in this study falls within the range of those estimates. Compared to those global estimates, our estimate was slightly higher than those reported for tropical deciduous forest (88.48 Mg ha^{-1}, 0-40 cm depth, 56% of 158 Mg ha^{-1} at one meter depth) by Jobbagy and Jackson (2000) but consistent with 96.60±2.47 Mg ha^{-1} (0-30cm) in primary forest of the Porce region, Columbia (Sierra et al., 2007). Evidence suggests that our estimated values are closer to those site specific studies in similar forest types than those of generic values derived from global data-sets.

This study showed that AGB and SOC are the two most important C pools. Less than one per cent of total C stocks are in shrub and litter pools, demonstrating that these are not significant pools to measure and report. Considering the time and resource-demanding nature of the work involved for field measurement, sample collection and laboratory analysis, it is not recommended to include these two pools in future Monitoring, Reporting and Verification (MRV) systems to be established under the REDD mechanism. However, for these pools, information on C stock of the litter pool provides sufficient information to approximate the emissions from recurring incidents of forest fire in the landscape.

Prior to this study, limited evidence was provided about the impact of management regimes on C stock or density. Jandl *et al.* (2007) argued that old growth forest had high C density compared to young stands. Prolonging the harvesting period of the natural forest may allow a progressive accumulation of C, hence increased C density (Canadell & Raupach, 2008; Hudiburg et al., 2009; Hyvönen et al., 2007; Krankina & Harmon, 2006). The increasing gradient of C stock from the other forest category to protected area, as shown in figures 3.2 and 3.4 confirm this argument. The variations among the management regime reflected the degree of use restrictions of forest products, mainly timber harvesting. Timber harvesting is strictly prohibited within protected areas as conservation is the prime objective of management, whereas, timber production is one of the major objectives of community forest and government-managed forests. Forestry is not the principal objective of the other forest regime. Significant variations of carbon stock across the management regimes support the argument of Canadell and Raupach (2008) that the overall potential of management activities to increase carbon stock can be substantial and comparable to that of reforestation. Higher stocking of AGB C in protected areas also highlights the ‘role of conservation’ that has been included in the plus (+) part of REDD+.

Higher density of C in community forest than in government-managed forest could be due to effective enforcement mechanisms in place in CF to protect forest. Government-managed forests in the *Terai* have proved to be unsatisfactory (Chakraborty, 2001) and it has not been possible to prevent the illegal extraction of forest products (Shrestha & Budhathoki, 1993; Talbott & Khadka, 1994). On the other hand, protection of forest under the control of local communities as Community Forests has worked because of established systems of authority in the villages that include monitoring and enforcement mechanisms. However, many villagers resort to exploiting forests managed by the government instead (Chakraborty, 2001). Logging activity may have shifted from community forests to government-managed forests causing leakage-effect within the landscape. The impact of other management activities (i.e.; prevention of forest fire, silvicultural activities, and other biotic factors) practiced within any of the management regimes on C stock should also not be overlooked and need further research on their roles on stocking of carbon.

3.5 Conclusion

Accurate and reliable estimates of C stock in forests is the key challenge to quantify the C emissions from deforestation and forest degradation that are necessary to secure incentives from the REDD mechanism. This study focussed on quantifying C stock in the tropical forest of the Terai Arc Landscape of Nepal. The results demonstrated that our estimates of carbon stocks are lower and differ from all those earlier estimates based on biome-average datasets. They also differ from some country level estimates with inadequate representative sampling, including default values mentioned in the IPCC methodology for tier I estimates. The consistency of our estimates with those from similar site and forest type of specific earlier studies supports the importance of field-focused, site-forest type- specific studies to achieve precise and reliable estimates of C stock.

The study also highlighted the important C pools in the forests of the Terai Arc Landscape. AGB, SOC and BGB contribute 99 percent of total C stock in the forest. BGB can be calculated using root: shoot ratio and SOC was more or less stable over the different management regimes. The single most important C pool of the forest to measure is AGB. This information is particularly relevant while devising monitoring, reporting and verification (MRV) framework under REDD+ framework. The study recommends not including the litter and shrub pools in the future MRV framework mainly because of their negligible share in total C stock and the time and resource-demanding nature of the work involved for field measurement.

Our study indicated the strong association of C stock with management regime. Higher stocking of C was found in the protected areas where strict restriction on exploitation of forest products is enforced, rather than in community, government-managed and other forests where timber harvesting is recurrent. Though the sink capacities of forests under these different management regimes and impact of management practices on C stock warrant further research, this result highlights the 'role of conservation' to preserve C stock and reduce emissions that have been included in the plus ($^{+}$) part of REDD. The findings are valuable for policy makers who need to make informed choices of management regime for the landscape, to achieve C benefits among others.

The forest of TAL has a huge C reservoir. Because of biomass loss due to high rates of deforestation in the landscape, much C previously stored in this reservoir has been emitted into the atmosphere. There is huge potential to reduce future emissions through retarding deforestation on TAL. In the TAL forest, a huge amount of C emissions from forest degradation, particularly from the government-managed forest, has also been observed. Avoiding forest degradation has equal significance for reducing C emissions in future from the TAL forests. Incorporating activities in future REDD+ design framework that address forest degradation along with deforestation may be vital in achieving net C emissions reductions.