CARBON BUDGET OF INDIAN FOREST ECOSYSTEM

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Abstract

The paper quantifies the role of Indian forests as source or sink of carbon. The model used in the study takes into account the growing stock, additional tree organs, dead biomass, litter layer and soil organic matter, harvesting and harvesting losses, effects of pests, fire etc., allocation of timber to wood products, life span of products including recycling and allocation to landfills. The net carbon balance calculated as the net source or sink of the forest sector was assessed for the year 1993-94. The study is important in view of the obligation placed by the United Nations Framework Convention on Climate Change (UNFCCC) on the signatory nations to provide a periodic update of carbon budget in the atmosphere. For the available data and the underlying assumptions, the results of the carbon budget model indicated that Indian forest sector acted as a source of 12.8 TgC (including accumulation of carbon in the dead biomass) for the year 1994. The results obtained reinforced the notion that an integrated approach is required in order to evaluate the forest sector's influence on the global atmospheric carbon levels. The model used in this study has the advantage that all the factors determining the carbon budget can be integrated and altered to determine their influence. The study also throws light on the issues that stand in the way of preparing through carbon budget for developing countries like India.

Key words: Forests, Carbon, Budget, UNFCCC, Source, Sink, India

1. INTRODUCTION

Forests merit attention due to their important role in the global carbon (C) flux. They store large quantities of carbon in vegetation and soil, exchange carbon with the atmosphere through photosynthesis and respiration, and act as sources of atmospheric carbon if they are disturbed by some human activities (e.g. harvesting, clear cutting for conversion to non-forest purposes, poor harvesting procedures) or natural causes (e.g., wildfires). However, they become atmospheric carbon sinks during land abandonment, regrowth after disturbance and due to afforestation and forest conservation. The net flux of carbon between the forest sector and the atmosphere determines whether forests are net sources or sinks of carbon. Given the role of forests, lot of interest is being shown in forestry related measures to either reduce or offset net emissions of carbon. However, to analyse how much carbon mitigation could be achieved it is necessary to quantify the present role of forests to the greenhouse gas (GHG) budgets. Such an exercise is also important in view of the obligation placed by the United Nations Framework Convention on Climate Change (UNFCCC) on the signatory nations to provide a periodic update of carbon flows and stocks in the atmosphere. The principle objective of this paper is to quantify the role of Indian forests as a source or sink of carbon.

Diverse methodologies varying from static model to detailed dynamic models have been used by various researchers in different countries to account for the amount of carbon sequestered by forests. Examples of global studies are Dixon *et al.* (1994), Nilsson and Schopfhauser (1991), Houghton (1996) on a continental scale, for Europe, Kauppi *et al*., (1992) and for six countries in tropics Makundi and Sathaye (1996). Several studies have been done at the country scale, e.g., in Canada Kurz *et al.* (1992), in Britain Dewar and Cannell (1992), in New Zealand Maclaren and Wakenin (1991), in Germany Burschel *et al.* (1993); in Sweden Eriksson (1991), in Finland Karjalainen and Kellomaki (1993), in Soviet Union Kolchigina and Vinson (1992), in USA Turner *et al.* (1995). The assessments can cover history, portray single years, or give predictions on future dynamics also; the details included in the assessment may vary. The first thorough carbon balance model for a complete forest sector in country was developed by Kurz *et al.* (1992) in order to assess the Canadian forest sector carbon budget. For India Ravindranath *et al.* (1996) has estimated the net emission of carbon from the forest sector for the year 1986 based on the COPATH model developed by Makundi *et al.* (1996) and concluded that Indian forests could sequester around 5 Tg C (1 Tg = Tera gram (10^{12}g)). Another recent study in India by TERI (1998) used the IPCC (1997) methodology in preparing the carbon emissions inventory from forests. Their study found that the net emissions from land use change and forestry sector were 0.4 Tg for the year 1990. The results are not comparable as these studies vary in methodology and assumptions used to calculate the inventories.[2] There is no general consensus on the methods for assessments of carbon budgets, although IPCC (IPCC, 1997) has tried to standardize national GHG inventories in which forest and land-use change carbon budgets are included.

Figure 1 illustrates the framework for reporting greenhouse gas emissions and removals due to landuse change and forestry. As seen from the figure the main emphasis of IPCC framework is on landuse change and forestry and considers the carbon emissions and uptake due to 1) changes in forest and other woody biomass stocks; 2) forest and grassland conversion; 3) abandonment of managed lands. While estimating the changes in forest and other woody biomass stock IPCC framework does not account for the impact of disturbances like stand replacing fires and mortality on the carbon release. The effect of stand-replacing fires can be two fold 1) carbon is released to the atmosphere as CO_2 and other carbon compounds CO and CH_4 and 2) the forest structure is changed as the stand age is reset (Levine, 1991). Similarly, mortality has the same characteristics as stand-replacing fires, except that direct release of carbon to the atmosphere is generally smaller and the transfer of carbon to the forest floor is correspondingly larger. Further, IPCC framework does not consider the fate of harvested wood and assumes that entire wood harvested releases carbon into the atmosphere. The wood products can form a significant pool of carbon in some countries. The IPCC methodology also does not account for the carbon in litter, wood debris, below-ground remains and dry standing stems which can be a significant reservoir in many of the forests (IPCC, 1997).

Accounting for carbon is very complicated and requires a detailed analysis. This is because any disturbance on forests (like harvest for timber, deforestation, fires, mortality etc.) involves flux of carbon between the atmosphere, live biomass, dead biomass, forest soils and forest products. When forests are subjected to various disturbances, some of the carbon remains in the biomass itself, some remains *in situ* and a part of it is transferred to the atmosphere as CO_2, CO and CH_4. Some of the carbon enters the wood products and forms part of the forest product sector. Some of the carbon that has been left on-site forms part of soil carbon pool and rest remains on site. Of the portion of woody slash burnt on site, a small fraction of the carbon remains as charcoal which resists decay for well over 100 years or more and forms part of the top 30 cms soil pool. One can assess whether forests are net sources or sinks of carbon only after taking into account the net flux of carbon between the forest sector and the atmosphere. Hence, the paper uses a thorough methodology to assess the net carbon sequestered in Indian forests by accounting for all the fluxes of carbon between forest biomass (live and dead), soils, forest products and the atmosphere as done by Kurz *et al.* (1992) for Canada. The

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[2] The choice of assumptions seems to have been governed by the availability of data.

specific objectives of the paper are to: a) examine the major factors that influence the carbon budget; b) calculate the annual net forest sector carbon budget of forests in India using a simulation model that takes into account all major pools and fluxes in the forest sector; and c) assess by how much the uncertainties in the estimates affect the carbon budget of the forest sector in India. The paper is organised as follows. The methodology for assessing the carbon fluxes is given in section 2 followed by description of data sources in section 3. The results of the base scenario are given in section 4. The study carries simulation analysis in section 5 and section 6 concludes.

2. MODEL

The study employs a detailed carbon accounting framework using a simulation model similar to the one employed by Kurz et al., (1992) for the Canadian Forest Sector (CBM-CFS I), which includes all the carbon pools and fluxes in forest ecosystems. To start with entire biomass in the forests has been expressed in units of carbon. The model recognises two major carbon pools: forest ecosystem and forest product sector (Figure 2). Forest ecosystem includes three carbon pools: live biomass, dead biomass and mineral soils. The live biomass carbon represents all living tree and plant biomass. The dead biomass pool consists of carbon in detritus, forest floor, standing dead trees and coarse woody debris. The mineral soil pool consists of soil organic matter in the top 30 cms[3]. The forest product sector contains carbon derived from tree biomass harvested in India that may have undergone several conversion processes. In the absence of disturbances, the balance between net photosynthesis and natural decomposition determines the rate of net ecosystem carbon accumulation, which is calculated as the sum of net changes in the biomass (live and dead) and soil carbon pools. The initial point is the stock of carbon present in the live biomass, dead biomass (and litter), top (30-cm) soils and wood products in the beginning of the year. In any given year the stock of carbon may increase due to additions (due to afforestation or regeneration of forests) and decrease due to removals from forest (due to disturbances both natural and man-made). The disturbances in the form of fire[4], insect induced mortality[5], partial cutting (or selective harvesting) and clear cutting along with slash burning removes carbon from biomass out of the forest ecosystem. The amount of carbon transferred out of the forest

[3] Deeper soils also have appreciable carbon stocks but they are generally much less impacted by different disturbances than the topsoil layers.

[4] From the point of view of carbon storage fires may be broadly categorised into two types: non-stand replacing and stand-replacing. The former results in low-intensity but relatively frequent surface fires. These frequent surface fires are set either by accident or as part of silvicultural practices, and may burn young trees and crown cover. The latter is due to occurrence of crown fires or wildfires, which lead to destruction of growing stock and the release of carbon to the atmosphere.

[5] Similarly, the type of disturbances associated with insect induced mortality can be either stand replacing or systemic. Systemic impacts of insect, disease and herbivores may result in direct reduction of net primary productivity (NPP) of forests.

ecosystem depends on the extent of disturbance. Further, not all the carbon that is stored in the biomass is transferred out of the forest ecosystem. Some of the carbon is transferred into the dead biomass and soils and a part of it is transferred to wood products (in the form of timber), some remains in the biomass itself and only the rest is transferred out of the forest ecosystem into the atmosphere.

The proportion of carbon transferred between different biomass and soil carbon pools, the atmosphere (CO_2, CO, CH_4) and the forest products sector at the time of disturbance are quantified by disturbance matrices. These matrices reallocate the carbon in different pools depending upon the specific characteristic of the disturbance. A disturbance may cause fluxes between the biomass (live and dead), and the soil carbon pools without releasing carbon into the atmosphere. For example, partial cutting moves carbon from biomass pools to the forest products sector and to forest floor (as debris), but may not necessarily release carbon directly to the atmosphere at the time of disturbance. However, the increased amount of carbon in the debris results in greater carbon release from decomposition at a later stage.

The carbon transferred to wood products in the form of sawlogs, fuelwood and pulpwood are used to produce different forest products. As the logs and pulpwood are transformed into different products, some of the carbon is released into the atmosphere during different stages of processing (referred as processing efficiency). The minimum is the loss in carbon (in the form of wood products), the higher is the processing efficiency. Once the products are produced, some might remain intact for many years i.e., they decay at a very slow rate. This implies that they might be replaced or abandoned at a slow rate. One such example is construction timber. On the other hand, products like paper may be used and discarded promptly. Depending on the fraction of time the forest products can retain carbon, they can be classified into four lifespan categories: very short, short, medium and long. The proportion of carbon remaining in use from the forest product as it ages can be best explained by the equation given by Row and Phelps (1990)

$$?(t) = ?_d - ?_a / (1 + ?_b e^{-?_r t})$$

where $?_d$, $?_a$ and $?_c$ are dimensionless quantities and $?_r$ is the removal rate from the forest product. This rate varies for very short, short, medium and long life span products.

The carbon that leaves the pool can have three terminal use options (fate of the discarded products). The discarded products can either be recycled into raw materials (or re used) as in the case of paper products and other forms of wood or burnt (as waste or for energy) or set aside in open dumps or landfills to decompose slowly. Both decomposition and burning (for energy or as waste) immediately release carbon into the atmosphere; product recycling is assumed to return carbon to the immediate previous age class of the forest product pool; and transfers to landfills lead to carbon release through gradual decomposition. The amount of carbon stored in wood products in any given time is the sum of carbon in use and carbon in landfills. The transfer of carbon from the various carbon pools to the atmosphere and to the carbon pools varies with ecoclimatic provinces, type of disturbance and also the amount of aboveground standing biomass.

Due to disturbance some of the carbon initially present on forest floor as litter and dead biomass is also transferred into the atmosphere due to decay. The rate of decay is different for different ecoclimatic provinces, with higher decomposition rates in warmer climatic regions. Further, the decomposition transfer from dead biomass and soils also depends on the type of input. Hence, the carbon in dead biomass can be classified into two types designated as fast and medium pool depending on the time the carbon is retained as done in Kurz *et al.* (1992). A fast pool is characterised by half-lives of 3-20 years and consists of detritus material that is less than 10 cm in diameter. In the model it has been assumed that this material is derived primarily from the foliage and other biomass component of the trees (like fine root). A medium pool is characterised by half-lives of 20-100 years and consists of detritus material having diameter greater than 10 cm (assumed to be coming from the stem portion of the biomass). For a given ecoclimatic province, the rate of input is a fixed proportion of the existing biomass carbon pool of these components. The soil carbon pool is characterised by half-lives greater than 100 years and consists of humified soil organic matter in top 30 cms forest soil. In the model it has been assumed that some of the carbon that decomposes from the fast and medium carbon pool forms the input to the soil carbon pool[6]. In the forest ecosystems, some of carbon in forest floor (in litter) and organic matter is initially taken up through plant photosynthesis and then transferred to the soil. Therefore, in the model also, it is assumed that all carbon inputs to the fast and medium carbon pools originate only from the biomass carbon pools and the inputs to the soil, are assumed to be coming from the fast and medium pools. The carbon that decays from the fast and medium pools either enters the soils or released into the atmosphere. In the base scenario, it is assumed that a constant 17% of the carbon leaving the fast and medium soil pools is transferred to the soil pool, and the remaining 83% is released to the atmosphere in the form of $CO_{2.}$[7] The implications of alternate values to this assumption are explored in the sensitivity analysis.

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[6] For instance when the forest is burnt after clear cutting, some of the burned carbon is converted to charcoal which resists decay for 100 years or more and is considered under the soil pool and the rest is released instantaneously into the atmosphere.

[7] In India, there exists no such study describing how much of the carbon is transferred from the fast and medium carbon pool to the soil carbon pool. Thus the present study assumes that the same proportion of transfer as assumed by CBM-CFSI for Canada (Refer Kurz *et al*., 1992).

The three carbon pools (fast, medium and soils) are assigned a carbon retention curve. The carbon retention curves defines the proportion of carbon remaining in the pool as the pool ages. The proportion of carbon remaining in the three pools is obtained using similar set of equations used in determining the fraction of carbon remaining in use in wood products and given by the equation used by Row and Phelps (1990)[8]

$? \ (t) = ?_a / \ (1 + ?_b e^{-?_r t})$

where $^?r$ is the decay rate which is different for different ecoclimatic zones and for different carbon pools and $?_a$ and $?_b$ are scalars. The decomposition rates are lower in the cooler ecoclimatic provinces and doubles for every 10 degrees rise in the mean annual temperature (Kurz *et al.*, 1992). The annual change in the ecosystem carbon is given by the sum of changes in live biomass, dead biomass, wood debris, soil carbon pools and wood products. The total carbon storage (TC) in the forest ecosystems in India and is calculated by summing over all the area and net carbon remaining in each pool.

3. DESCRIPTION OF DATA

The main variables needed to compute the carbon budget of Indian forests are carbon contained in biomass (by different components), soils, accumulation of carbon in the biomass, litterfall, mortality of trees, area subjected to various disturbances, proportion of carbon transferred to various pools after the disturbance, decay rate of soils and wood products and also the terminal use of various wood products. As the information has been collected from different sources, the following paragraphs discuss the various sources of the data used in the model.

3.1. Initial stock of carbon in biomass

The estimates of biomass carbon are a crucial factor in determining the carbon budget. The biomass density can be estimated using destructive sampling, aerial surveys and forest inventories. In India, as estimates of biomass using direct measurement (destructive sampling) and aerial surveys are not available for all forest types in the country, the volume inventory data has been used to estimate the carbon content of the biomass (see Haripriya, 2000a). Such forest volume inventories have provided the basis for several regional and national-level carbon budgets (Kolchigina and Vinson, 1995; Kauppi *et al.*, 1992; Kurz *et al.*, 1992; Turner *et al.*, 1995). For this purpose we used forest inventory

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[8] By definition, we assumed that the fast and medium soil carbon pool gets inputs only due to transfer of carbon in the form of woody biomass, foliage biomass and small twigs. Thus, same equation as assumed in wood product model can be used here also. The purpose of using such an equation is to ensure that the carbon in the pool decreases in an exponential fashion depending on the decay rate parameter. Exponential function is considered as the process occurs throughout the year and is not a one-time process. The decay rate parameter varies for different ecoclimatic provinces and so the proportion of carbon retained also differ. If we take $?_a$ = 120, and $?_b$ = 5, we can see that the proportion of carbon remaining in use in the first year is 100 per cent. As the value of t increases the amount of carbon in the pool decreases in an exponential manner.

data on volumes in various states to estimate the total biomass growing in Indian forests for the year 1993. We also used the information on growing stock and area in Indian forests published by Forest Survey of India (FSI). The overall approach was first to estimate the biomass per hectare of different species in various strata of each inventoried unit using the data on volume of the growing stock (stock tables of the ground inventories) and dry weight density of these species. The individual biomass of species in each inventoried unit is summed to obtain the total stemwood biomass growing in various strata for the inventoried volume. We then calculated mean wood density of various strata as the ratio of stemwood biomass to the stem volume. The mean wood density of the strata from the inventoried area and biomass expansion factors that take into account the non-stem portion of the biomass are combined with the estimate of total growing stock in various strata for the entire country to get the estimate of total above ground biomass for India[9]. Further, it should be noted that the study considers biomass in the trees only and does not consider the biomass in understorey shrubs. More detailed estimates are provided in Haripriya (2000a).

The area and biomass information of different strata is grouped into four main forest types: tropical, subtropical, temperate and alpine[10]for simplicity. The classification into different ecosystems is made according to a set of indices (hardwood, softwood, mixed wood and undefined) derived from the national forest inventory. In order to get an estimate of the timber stock growing in the forest and inputs to fast and medium pools of the dead biomass and soils, it is important to know the biomass distribution in different compartments. Further, for each spatial unit, the proportion of biomass in fine and coarse root (below ground biomass) pools have been computed. The proportion of biomass in fine and coarse roots for the softwood and hardwood species have been taken from the existing studies in literature (see Tewari, 1995a, b c for various studies)[11]. All the biomass data are converted to carbon values by assigning a carbon content of 0.5 Mg C per Mg oven dry biomass. Table 1 gives the biomass distribution in different compartments like stem wood and bark; foliage; and other components of tree biomass (below ground biomass like roots).

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[9] The estimates of biomass are corrected for the stand tables missing in the stand inventories using a method by Gillespie et al. (1994) (discussed in Haripriya, 2000b).

[10] Forests in India are categorised mainly into four major types and have been classified into 16 subtypes by Champion and Seth (1968). The data has been grouped into four major types using the main species classification provided in Champion and Seth (1968).

[11] The estimates are not available for all the forest types/strata in India and hence the figures for some representative species have been taken. For tropical forests the estimates of teak, for temperate and alpine that of conifers and for subtropical an average of teak and conifers are taken. Further as different studies have given different estimates, an average value for teak and conifers is employed.

3.2 Accumulation of Biomass

In addition to the estimates of carbon in biomass, the rate of biomass accumulation in various forest types plays a significant role in the carbon budget. The rate at which carbon is sequestered in forest biomass determines the forest ability to remove carbon from the atmosphere. In India, very little information exists about the rate at which different forest ecosystems sequester carbon. Although, details on annual net carbon uptake of biomass are available for a few specific ecosystems, they are usually carried out for small plots and do not exist for all the forest types in India. In the present study the mean annual increment in volume of different types of species are used to determine the annual net carbon uptake using the method discussed in Haripriya (2000a). This information is used to obtain the amount of carbon sequestered annually in various forest types. Table 1 gives the estimates of accumulation of biomass in different forest types in the country.

3.3.Area subject to Disturbances

The information on area affected annually by various disturbances has been compiled from several data sources. The reference year for all the estimates is 1993-94. Details of the data sources are described in the following text. Table 1 gives the area subject to various disturbances.

1. Fire (F)

Fires can be of two types: surface fires (non-stand replacing) and crown fires (stand replacing). As the surface fires are non-stand replacing fires and does not effect the timber they are not considered in the model. The average area burnt by stand replacing fires fluctuates greatly over the years and also across different estimates. The National Commission on Agriculture (NCA) for the period 1968 to 1973 carried out a study on the incidence of fire. According to NCA, the average number of annual fires was 3,406, affecting an area of 2,576 Km^2 (0.76 km per fire). In 1986, Ministry of Environment and Forests (MOEF) compiled data on fires for the five-year period 1980 to 1985, and found that 17,852 fires occurred in the country burning an area of 5,724 Km^2. This amounts to an average of 3,570 fires affecting 1,145 Km^2 annually (i.e., 0.32 Km^{2}per fire). Based on the data for 1985 to 1988 compiled by MOEF, Forest Survey of India (FSI) estimated that the stand replacing fires affect about 10,000 Km^2 of forest area annually (FSI, 1988). In the present study, the same percentage of area (estimates by FSI, 1988) has been taken as annual area affected by stand-replacing fires for the reference year 1993. The average area burned annually in different states is grouped to the four-ecoclimatic provinces based on the identified forest types in each state[12].

[12] FSI (1995) in the publication ‘Extent, Composition and Density of Growing Stock in Indian Forests’ gives the type of forests present in each and every state in India.

2. Insects (M)

Only insect infestations resulting in loss of biomass are explicitly considered in the study. Recent insect induced mortality data are not available in India and the most latest statistics available at the time of this analysis are the estimates of loss in timber volume due to insects, pests and diseases from Indian Forest Statistics (various years between 1947 to 1972) for various states. The present study assumes the same proportion of insect related volume loss for 1993[13]. These volume estimates are converted into biomass estimates as discussed in Haripriya (2000a). The average area subject to insect infestation in different states and forest types is derived by dividing the biomass lost with mean biomass per hectare. For the year 1993-94 the average area subject to stand replacing insect infestation is estimated at 0.17 M ha[14].

3. Clear-cut logging with slash burning

Area that has been converted for nonforest purposes and the area burnt for shifting cultivation come under this category.[15] Estimates of the area transferred to nonforest purposes in different states are obtained from ICFRE (1995). The area transferred for non-forest purposes (i.e., the area clear cut) varies greatly over different years and hence an average area clear-cut during the three years 1991 to 93 is taken.[16] Using this assumption an average of 424 Km^2 of forest area has been converted for various nonforest purposes (like agriculture, mining, river valley projects, industries etc.).[17] There are varying estimates on actual area subject to shifting cultivation in different states. The area affected by Shifting Cultivation in the northeastern (NE) region was reported to be 3.81 Mha by a task force on shifting cultivation (1983). The task force on shifting cultivation in its report in 1983 estimated that shifting cultivation was practised in 13 states of India and is extensive in northeastern states, Andhra Pradesh and Orissa. Other such estimates are 2.8 M ha by NE council (1975) and 7.4 M ha by FAO (1975). FSI using remote sensing data assesses the reasons for change in forest area including the area under shifting cultivation in different assessment years. The cumulative area affected by shifting cultivation during 1987-97 in the northeastern region (1999) is 1.73 M ha (FSI, 1999), accounting to an annual average of 0.17 M ha. However, this area does not include the natural regeneration in the abandoned areas after shifting cultivation. For instance, in an assessment made by FSI in north-eastern states between 1993 and 1995 reveal that around 1,875 km^2 of forest area was lost because of

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13 Actually five-year average data for more recent years would have been a better analog. Unfortunately, no recent statistics give the extent of volume lost due to mortality in India.

14 Area subject to non-stand replacing mortality is not considered.

15 In fact, the area subject to clear felling and area subject to slash burning have different implications for carbon storage. In India, officially there is a ban on clear-felling forests for logging. The area transferred to non-forest purposes and subjected to shifting cultivation is considered as both clear-felled and slash-burned.

16 Three-year average is used so as to take care of lags in reporting of data.

17 The IPCC default value is 495 km^2 /yr.

shifting cultivation (FSI, 1997). And an additional area of 1,700 km^2 of abandoned shifting cultivation has regenerated which FSI has included them in the area under scrubs or open forests. The net area subject to shifting cultivation (after excluding the regenerated areas) is around 951 km^2 (Haripriya, 2001a).

4. Partial cutting

In India, only the statistics on volume harvested (legally) are available, and there does not exist any estimate of area subject to selective harvesting. Even the volume of timber harvested for timber and fuelwood is highly debated as the estimated consumption exceeds the recorded production (Haripriya, 2001b). The study considers the amount of logging done illegally in Indian forests also (estimated in Haripriya, 2001a). The area subject to partial logging is derived by dividing the total harvested volume (legally and illegally) with the potential above ground biomass per hectare suitable for harvest[18]. This gives the total area harvested. From this the area subject to shifting cultivation and clear felling is subtracted to get the area subject to partial cutting. However, no distinction has been made to account for the variation across the size classes in the harvested timber due to lack of data.

3.4. Disturbance Matrices

The proportion of carbon remaining in live biomass, dead biomass and soils and remaining in live and dead biomass pools and transferred to soils, wood products and atmosphere can be expressed in terms of disturbance matrices. These matrices reallocate the carbon from a pool to other pools depending upon the specific characteristics of the disturbance. The biomass pools are further disaggregated into different components like foliage, stem and other biomass (like roots), dead biomass carbon pool into fast and medium and the soils as soil pool (or slow carbon pool). In this paper, we considered six sources and 10 sinks when simulating the immediate effects of disturbances (Tables 2a-2d). The six sources in the disturbance matrix include the three biomass carbon pools (stem wood, foliage and other biomass components), two dead biomass carbon pools (fast, medium) and a (slow) soil carbon pool. The ten sinks describe three forms of gaseous release into the atmosphere (CO_2, CO and CH_4), the forest product sector release, and the six source carbon pools. Each entry in the disturbance matrix contains a coefficient that quantifies the proportion of the carbon moved from source to the sink. The sum of each row adds up to unity, thus ensuring conservation of carbon. As not all combinations of possible carbon fluxes can occur in reality, there is a zero entered in the matrix. For example, none of the disturbances move carbon from the fast, medium and soil carbon pools to the foliage biomass components. Sometimes, a disturbance may cause fluxes between the biomass and fast and medium pools without releasing carbon into the atmosphere. For example, partial cutting moves carbon from biomass pools to the forest products sector and to the debris, but may not necessarily release carbon

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[18] I.e., the stem portion of the biomass.

directly to the atmosphere at the time of disturbance. In such cases the coefficients are given a zero value. The increased amount of carbon in the debris (fast and medium pools) and soils result in greater carbon release from decomposition to the atmosphere, which is accounted separately.

In order to arrive at the proportion of carbon transferred to different sinks, an estimate of the proportion of carbon left on site, when a forest is subject to disturbance should be available. Unfortunately, in India there are no studies that report the amount of carbon left on site, in the biomass and transferred to atmosphere when forests are subject to various disturbances. For instance, when forests are subject to wildfires, there is no information on how much carbon is left on site and how much is released to the atmosphere. Thus, we used the coefficients provided in Kurz *et al*. (1992) with some variations[19]. The variations are done based on the distribution of biomass in different components like stem, foliage, roots etc. For instance, in the matrix corresponding to partial cutting the amount of carbon transferred to forest products are taken as 85% of the total biomass as some earlier studies done on Indian forest utilisation specify that 10-15% of the timber is left on the site after harvest (FRI, 1970) (10% remains on the stump itself and 5% can be taken as logging damage). Similarly 10% of the foliage is left behind in the original form and the rest of the woody component of foliage enters the fast carbon pool. Other coefficients are also changed accordingly depending on the distribution of biomass in different components. Though there should be one disturbance matrix for each ecoclimatic zone and each disturbance type, the unavailability of information at such a disaggregated level forced us to use only one matrix for each disturbance. The final amount of carbon in different sinks depends also on other factors like half-lives and decay rate of various carbon pools. Hence, the amount of carbon redistributed in different ecoclimatic zones during disturbance differs as the carbon pool sizes differ between and within ecoclimatic zones.

The disturbance matrix can be interpreted as follows (see Tables 2a-2d). In the matrix 2d for instance, the first row indicates the proportion of carbon transferred from stem biomass to different sinks out of every 1 ton of carbon in biomass. The entries indicate that when a one hectare of forest is subject to partial cutting, of the carbon in the stem wood component of biomass, 5% forms part of the medium carbon pool and 85% is transferred to wood products and 10% remains in the stump itself (as not the entire tree is felled till the roots)[20]. Similarly, the second row indicates the proportion of carbon

[19] The proportions are changed based on the biomass distribution in different components. For instance, the biomass distribution in stems, branches, twigs and leaves may be different for boreal and tropical forests. This variation has been captured in the study. Local coefficients would have given better precision for the results, unfortunately I could not find any such study, which gives such coefficients for tropical forests apart from the IPCC, which uses different framework.

[20] See Haripriya (2001a).

transferred from foliage biomass to different sinks. The entries in 2nd row indicate that 10% of the foliage remains as foliage when tree is subject to partial cutting, 90% is transferred to the forest floor as fast carbon pool, which decays after certain time. Zeros in various columns indicate that no such transfer is possible. For instance, no transfer of carbon is possible from stem biomass to foliage biomass or other component of the biomass like roots. One can note that the sum of all the rows add up to unity to ensure conservation of carbon (i.e. carbon can neither be created nor destroyed but can be transferred from one form to another). Further, the carbon that has been transferred to wood products can be again released into the atmosphere, which was simulated in the model.

3.5. Decomposition rate of carbon in wood products and soils

To get an estimate of the carbon release profile from wood products, it is important to know the proportion of harvest in very short, short, medium and long life span categories, the carbon retention profile and the terminal use of the wood products. In India, the average carbon entering the harvested timber is around 68,880 Gg C, representing 62,323 Gg C in fuelwood and the rest 6,570 Gg C in sawnwood, pulpwood and other industrial round wood (discussed in detail in Haripriya, 2001b). Of the 6,570 Gg C (excluding fuelwood which does not enter production process and can be dealt separately as there does not involve loss of process energy), around 1.5% is in very short, 10.5% in short, 68% in medium and 20% in long lifespan categories[21] (see Table 3). The proportion of carbon remaining in different product pools depends on their half-lives, which vary from product to product. In this study, we used half-life estimates as 30 years for long lifespan, 12 years for medium, three years for short lifespan products and it is assumed that all the carbon stored in very short lifespan products is released within an year (see Table 4). The parameters describing the rate of release of carbon from different products can be derived from the half-life periods through simulation (discussed in Haripriya 2001b) and given in Table 4. The amount of carbon released from wood products also depends on the terminal use of carbon. The assumptions based on detailed analysis in Haripriya (2000b) are given in Table 4.

The soil carbon pool at the beginning of the simulation period is computed using the soil carbon data for different forest types compiled in Ravindranath *et al.* (1996) (see Table 5). Additional data, which describes the inputs and outputs of the fast and medium pools, are also needed for the model. An important input to the fast and medium carbon pool is the data on litterfall. This data on litterfall for different ecosystems has been taken from Dadhwal (1995). The amount of carbon present in different

[21] Fuelwood and matchwood are categorised as 'very short lifespan' products, 'short lifespan' products include newsprint, some packing paper, paperboard and printing and writing paper. Under 'medium lifespan' the products considered are other packing paper, paperboard, printing and writing paper, sports goods, bullock carts, agricultural implements, rural constructions and other miscellaneous products. The 'long lifespan' products include railway sleepers, furniture and panelling, housing constructions, fibreboard, particle and chipboard.

pools at the start of the model is given in Table 6. The half-lives of different pools are assumed to depend on the mean annual temperature[22] for various ecosystems and have been taken from Lal (1991). Table 7 gives the mean annual temperature, half-lives of various carbon pools and the decay rate parameters. In the model, three decay rate parameters are considered for each of the three carbon pools.

4 RESULTS OF THE BASE SCENARIO

From Table 9, it can be seen that the total carbon stock in biomass and mineral soils at the beginning of the period is 2,934 Tg C and 5,109 Tg C respectively. The average biomass carbon of the forest ecosystems in India for the year 1994 is 46 Mg C ha^{-1}, of which nearly 76% is in aboveground biomass and the rest is in fine and coarse root biomass (Table 1). High average biomass carbon is found in temperate forests dominated by softwood species. The average mineral soil carbon in Indian forests at the beginning of the year is found to be 80 Mg C ha^{-1}. High soil carbon is found in those eco-climatic provinces that have low mean annual temperatures (alpine and temperate zones).

Prior to accounting for disturbances, the biomass carbon pools sequestered an estimated 49 Tg C (1 Tg = 1000 Gg) due to the mean annual increment. This increment of approximately 1.2 Mg C $ha^{-1}yr^{-1}$. is roughly equivalent to a net volume increment of 1.8 m^3 $ha^{-1}yr^{-1}$, with carbon uptake rates differing across ecoclimatic provinces, forest types, and the distribution of trees in various age groups. The carbon increases due to natural regeneration is assumed to be offset by loss in carbon due to surface fires and grazing. Apart from this around 20 Tg C is accumulated in the forest floor as debris due to detritus litter fall. Actually all the carbon that is transferred to the forest floor from litterfall is ultimately released back into the atmosphere resulting in zero balance. However, the exact time span when the entire carbon is decomposed back into the atmosphere is not known. In the ideal case, the emissions carried forward from the past will be the sum of all emissions expected to be released at time t from each of those preceding years. As the data on historical emissions are not available, an approximation is required to carry forward the emissions from the past. Hence, in the present study the emissions of future 20 years have been assumed to be carried forward from the past.[23] Under this assumption, the forest floor in India (due to litterfall) is accumulating carbon at the rate of 0.3 Mg C $ha^{-1}yr^{-1}$ before disturbance.

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[22] Also depends on humidity but the amount of carbon in soils in different forest types is determined by the humified organic matter.

[23] The IPCC (1997) worksheet on the framework for accounting the greenhouse gases assumed that the carbon in the year t-20 released carbon in the year t.

Every year a small proportion of forests in India is disturbed by fires, insects or harvesting. The results show that during the year 1993-94, disturbances released 11.5 Tg C of the carbon sequestered in the biomass, directly into the atmosphere (of which fires account for 10.8 Tg C, 0.02 Tg C due to mortality and 0.7 Tg C due to clear cut and slash burning). Due to partial cut and clear-cut around 69 Tg C has been transferred directly from biomass to the forest product sector. Disturbances also transfer around 31 Tg C to the fast, medium and slow carbon pool (of which fires accounted for 15.6 Tg C, 0.5 Tg C due to insect infestation, 0.4 Tg C due to clear cut and 14.5 Tg C due to partial cut) from which carbon will be released through future decomposition. Of the carbon transferred to fast and medium carbon pool around 5.2 Tg C is released directly into the atmosphere due to decomposition. Fires accounted for 5.1 Tg C of that release and the rest is released by other disturbances. After accounting for disturbance releases to the atmosphere and carbon transfers to the soils and forest product pools, the biomass pool decreased by 1 Mg C ha^{-1} (62 Tg C). The net carbon content of the fast, medium and slow carbon pools at the end of 1993 after accounting for transfers from biomass and disturbances increased to 45 Tg C. Of the carbon transferred to the forest products, around 91% of the carbon is instantaneously released in the first year due to burning of products like fuelwood and matchwood and due to processing energy and losses (discussed in details in Haripriya, 2001b). After taking into account the oxidation of forest products originating from biomass harvested during the previous 20 years[24], the total carbon released back into the atmosphere from wood products is around 95%. As a result, the forest product pools show a net accumulation of 5 Tg C at the end of the year 1993.

The estimate of average carbon content (in the biomass and forest soil) in Indian forests is 126 Mg C/ha of which 36% (45.8 Mg C ha^{-1}) is in biomass and 64% (79.8 Mg C ha^{-1}) in forest soils. The results of the base scenario show that Indian forests and forest sector activities in 1994 are a 'source' of 12.8 Tg C. The net change of carbon pools on an area basis averaged 0.2 Mg C $ha^{-1}yr^{-1}$ for all the forest ecosystems in India. The highest per-hectare carbon releases is observed in the temperate forest types (i.e., 0.58 Mg C $ha^{-1}yr^{-1}$) On the other hand subtropical and alpine forest types acted as sinks of carbon at the rate of 0.09 and 0.19 Mg C $ha^{-1}yr^{-1}$. However, the estimate of net carbon flux does not take into account the carbon release by the combustion of fossil fuels used in the forest management activities or in the manufacturing of forest products. If the accumulation of carbon in wood debris, litter, dead trees and wood products is not considered, the forests are source of 62 Tg C. This shows the need to include all the carbon stocks and flows in the forest ecosystem while accounting for carbon.

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[24] The reason for this assumption is same as mentioned for soil carbon pool.

5 RESULTS FROM THE SENSITIVITY ANALYSIS

There are some uncertainties in the estimates of biomass, soil carbon, the parameters defining the decomposition rates, the initial values assigned to the soil carbon pools and in the estimates of disturbance transfers and releases between various sources and sinks. Thus, it is important to examine how these uncertainties influence the carbon budget in various pools. In order to test the robustness of the model to the changes in various parameters, the study carries out a sensitivity analysis by changing different parameters and assumptions. The results of the sensitivity analysis are also useful in analyzing the key factors that play an important role in altering the carbon budget. Table 10 shows the results of the sensitivity analysis. Table 11 gives the percentage change in various estimates from the base run scenario. The results of different scenarios are discussed at length in the ensuing text.

5.1 High Biomass

In this scenario, the biomass estimates have been increased by 34% from the estimates used in the base run. The motivation for this 34% increase has come from the study by Ravindranath *et al.* (1996), where they extrapolated the data on destructive sampling for some of the forest types given in the literature for the entire country, and estimated the biomass of Indian forests as 126 Mg/ha. The carbon estimates obtained in this scenario provide an upper bound of the carbon balance in Indian forests as the carbon flux calculated from the estimates based on destructive sampling of biomass gives an upper bound (Houghton, 1991). The increased biomass resulted in a high litterfall input to the forest floor, causing 34% increase in net detritus inputs before disturbance and a 25% increase in the carbon in fast and medium pools and soils, which leads to a greater amount of carbon release during disturbances. The disturbance release of carbon into the atmosphere from biomass increases by 30%, from biomass to the fast, medium pools and soils increase by 15% while the releases to the atmosphere from fast, medium pools and soils increases only by 0.9%. As expected, the total biomass carbon inventory and uptake of carbon increased by 34%. Results of this run are consistent with the given model structure and the relationships between various carbon pools and fluxes. Thus increase in biomass estimates by 34% increases the carbon sink capacity by 1.6 times resulting in a net carbon sink of 7.2 Tg C. The results although are in tune with the study of Ravindranath *et al.* (1996), cannot be compared. The difference in methodology adapted, the use of different rates of change in the use of forestlands, rates of reforestation, growing stock and mean annual increment, soil carbon flux, rates of use of forest products etc. refrains to compare the two studies. The sensitivity analysis, however, indicated that if a systematic bias were present in the biomass data, it would be directly reflected in carbon pool size and its releases to the atmosphere.

5.2 High Fire

As the area burned annually in India is highly dependent on the prevailing annual climatic conditions and varies greatly across years, it is pertinent to explore with a different estimate of area burned annually. To test the sensitivity of the affect of any alteration in the area affected by fire, all fire statistics are increased by a factor of two, i.e., the area burned annually is increased from one million ha to two million ha annually. However, the proportion of the area burned in each ecoclimatic province is not altered. The results show that the increased fire regime on the net carbon flux is consistent with the expected behaviour of the carbon budget model, i.e. the associated transfers to dead biomass and soil pools and the atmosphere increased by 100%. The resulting net change in the biomass carbon pool and the carbon in different dead biomass pools and soils are –88.4 Tg C and 56.5 Tg C, respectively and forests act as a source of 28 Tg C.

5.3 Low Half-life of fast, medium and soil carbon pools

In the base scenario, the two dead biomass carbon pools (fast and medium) and soil carbon pools are distinguished based on their half-lives. In order to examine the effect of decrease in the half-life of the three carbon pools (fast, medium and soils) on the carbon budget, the half-lives of the carbon pools are decreased by 25%. The decomposition parameters of the three carbon pools change accordingly and are tabulated in Table 8. The result show that the half-life affects only the carbon decaying from the carbon pools (Table 10). As a result of faster decay from the carbon pools, the carbon source from forest sector increases to 14.4 Tg (i.e., an increase of 13.3%). Hence, the half-lives of carbon pools are an important factor in determining whether forests act as a source or sink of carbon.

5.4 Changes in Carbon Transfer to the Soil Carbon Pool

The carbon input to the soil carbon pool has been assumed originating from the fast and medium carbon pools of the dead biomass. In the alternate scenario, instead of 17% of the carbon entering the soil carbon pool earlier, it is assumed that only five percent enters the soil carbon pool. The results of these changes show that the net carbon uptake decreases by 22% and the carbon releases increase to 15.5 Tg C. This increase in emissions of carbon is due to lesser inputs to the soil carbon pool (reduction of 71% from the base scenario) and a higher release to the atmosphere from the fast and medium carbon pool. As expected there is no effect on the net biomass carbon existing in the ecosystem. This necessitates an immediate attention to explore the dynamics of the dead biomass and soil carbon.

5.5 Extending the Life-Span of the Forest Products

In the base scenario of the forest product model, it has been assumed that 90% of the products are distributed in very-short life span products and the rest in other life-span categories. In order to examine by how much the carbon budget of the forest ecosystem would be affected with increase in lifespan, the proportion of carbon in very short life span products is decreased by 10% and used as short life span products. As a result, the sink capacity of the forest ecosystem increases by around 15%. Thus, the results indicate that the carbon budget of the forest ecosystem is influenced by the distribution of carbon in various forest products.

6 CONCLUSIONS

The present paper quantifies the carbon stock in the forest ecosystem and forest products using a simulation model, which takes into account the growing stock, additional tree organs, litter layer and soil organic matter, harvesting and harvesting losses, effects of pests, fire etc., allocation of timber to wood products, life span of products including recycling and allocation to landfills. The carbon budget of the forest sector was assessed for the year 1993-94. For the available data and the underlying assumptions, the results of the carbon budget model indicated that Indian forest sector acted as a source of 12.8 Tg C (including accumulation of carbon in the forest floor and soils) during 1993-94. The results obtained reinforced the notion that an integrated approach is required in order to evaluate the forest sector's influence on the global atmospheric carbon levels. The model used in this study has the advantage that all the factors determining the carbon budget can be integrated and altered to determine their influence. Further, the model can also be easily subjected to alternate scenarios and options.

As the model results are dependent on certain assumptions and parameters, a sensitivity analysis was carried out to explore how the results would be affected if any of these parameters were changed. The sensitivity analysis can also help in highlighting those areas, which are important for the purpose of carbon budget, and also in quantifying how much do the improvements in data collection affects the flows and stocks of carbon. The results suggest that 10% increase in biomass estimates will result in 50% increase in the carbon sink capacity of the forests keeping all other things constant. Similarly 10% increase in the area subject to forest fires can increase the carbon emissions by 12%. A 10% decrease in the half-life of soils results in 5% increase of carbon emissions from forest sector. A 10% decrease in the proportion of carbon transferred to soils from decaying carbon from dead biomass result in 20% increase in carbon emissions. By lengthening the life span of wood products by 10% the carbon retained by forest products will increase thus reducing the emissions by 15%. This suggests that the effect of altering any one of these parameters is not linear and can result in greater increase/decrease of emissions depending on the amplitude of change.

Though the study demonstrates that such an integrated approach is needed to estimate the carbon budget, several issues stood in the way of preparing carbon budget for India using the model discussed in the study. Latest estimates on the extent of area subject to forest fires, mortality, clear-cut and partial cut and the volume of timber affected due to these disturbances is not available. Further, in the study did not distinguish young forests from mature forests. Young forests tend to accumulate more carbon than the mature forests but the study had to assume the average values due to paucity of data thereby introducing some bias in the results. Similarly, the coarse and fine-root components of forest biomass need to be fully represented in the carbon budget model. The study borrowed the Canadian coefficients and modified some of them to the local conditions in order to estimate the proportion of living biomass remaining on site, transferred as litter and released to atmosphere following a disturbance, as the data is not available for India or for any other tropical country. Similarly, there are some uncertainties in the half-life of various wood products, terminal use of wood products after they are removed from use, the decay rate of wood products dumped in landfills. There is also some uncertainty about the half-life of carbon in soils and the rate at which carbon decays from forest soils. More accurate data on biomass, disturbances and soil dynamics would substantially improve the understanding of carbon dynamics of the forest ecosystems. An area of future research is to develop proper data set that is required for a more detailed analysis. The estimates obtained in the paper can be easily revised once proper data set is made available at the accuracy and scale necessary for the analysis at the entire country.

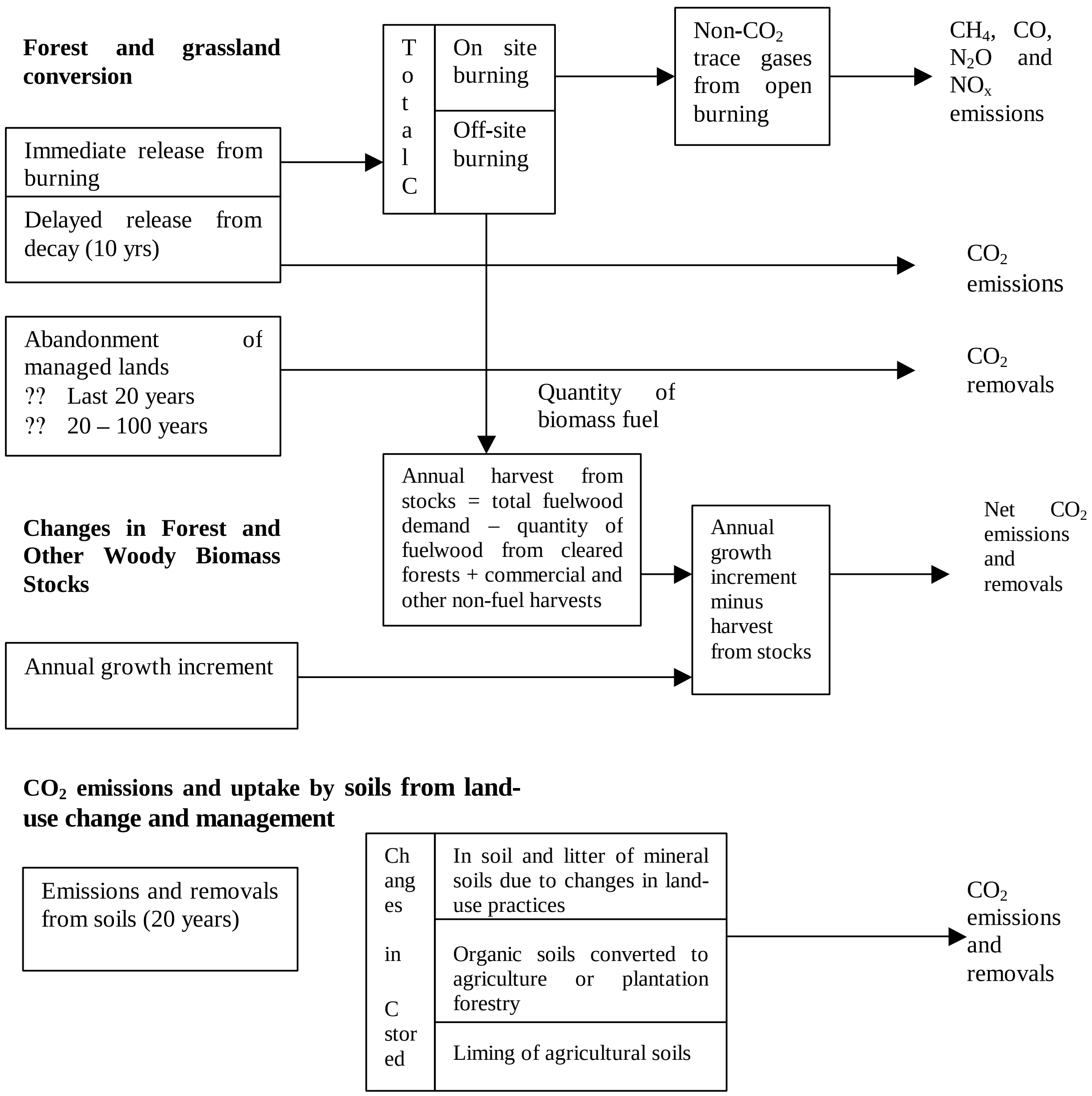

Figure 1. IPCC framework for accounting emissions from Landuse Change and Forestry

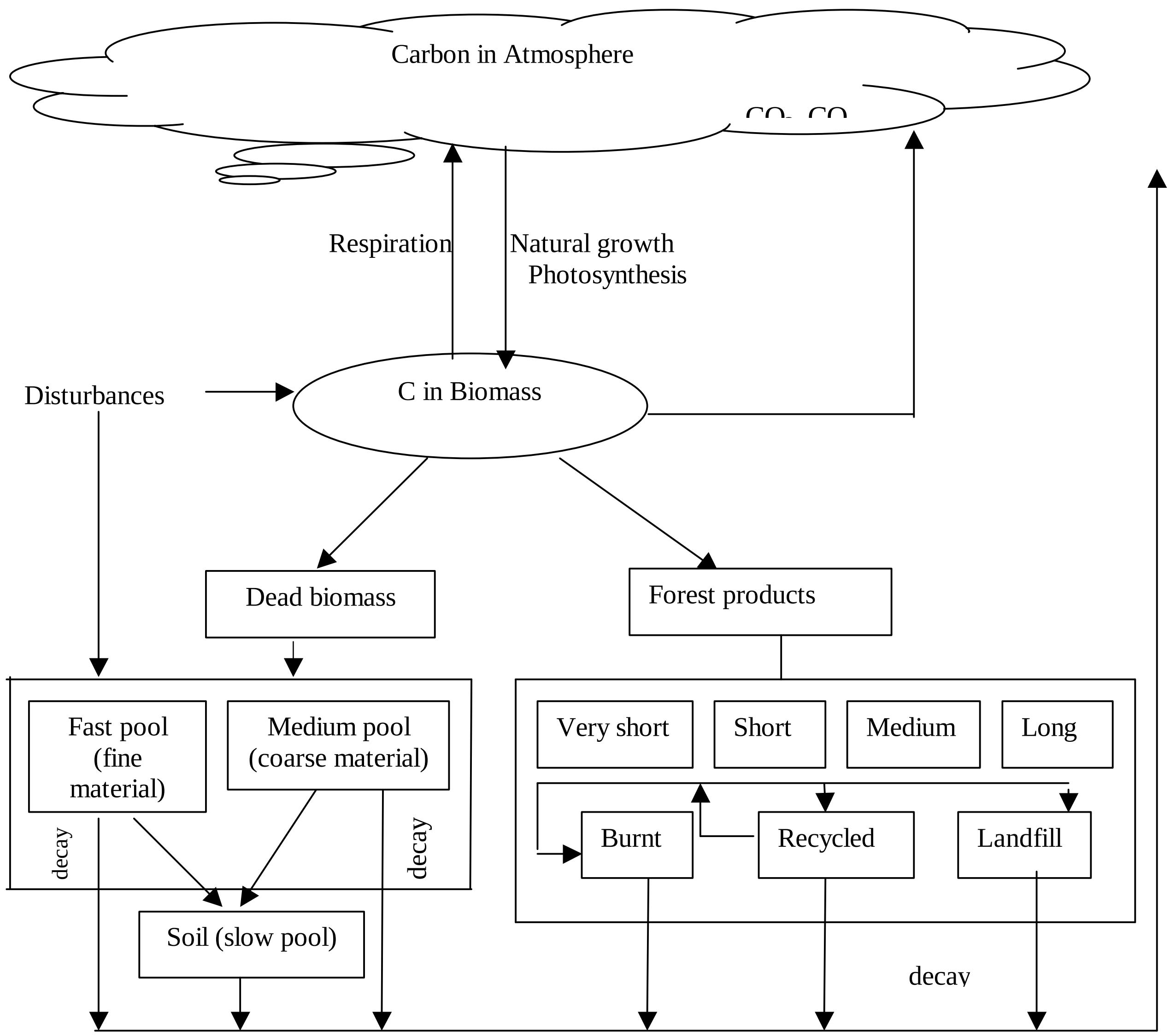

FIGURE 2. Representation of the carbon flow from forest ecosystem

TABLE 1. Carbon in Biomass and Mean Annual Increment in Various Ecoclimatic Provinces of India

	Tropical	Temperate	Subtropical	Alpine	Total
Area (in sq. km)	540778	35838	35838	27519	639974
Area subjected to disturbances (in ha)					
Forest fires	968705	7354	8145	27842	1012046
Insect Mortality	14341	656	1260	519	16776
Clear cutting	123783	2508	3894	7390	137575
Partial cutting	2121138	153312	163519	90965	2528934
Stem wood biomass (Tg)	3017	352	187	165	3721
Total biomass C (Tg)	2398	266	145	125	2934
Biomass C/ha by component (Mg C/ha)					
Stem	27.9	49.0	26.0	30	29.1
Foliage	1.1	2.9	1.3	1.8	1.3
Others	4.5	9.3	4.6	5.7	4.8
Root	10.9	12.8	8.5	7.8	10.7
Biomass carbon/ ha (Mg C/ha)	44.3	74.2	40.5	45.3	45.8
Mean annual increment of biomass (Mg C/ha)	1.2	1.4	1.1	1.2	1.2
Carbon in different pools (Tg C)					
Soils	3502	556	341	710	5109
Medium	27.8	1.8	2.3	1.7	33.6
Fast	103.0	8.1	10.5	8.1	129.7

Source: Haripriya (2000b)

TABLE 2a. Disturbance Matrix: Wildfire

	Sink / *Source*	Stem biomass (1)	Foliage biomass (2)	Other biomass (3)	Fast pool (4)	Medium pool (5)	Soils (6)	CO_2 (7)	CO (8)	CH_4 (9)	Forest products (10)
1	Stem biomass	0.197	0	0	0.099	0.346	0.047	0.278	0.03	0.003	0
2	Foliage biomass	0	0.185	0	0.094	0	0	0.62	0.1	0.01	0
3	Other biomass	0	0	0.19	0.097	0.194	0	0.464	0.05	0.005	0
4	Fast pool	0	0	0	0.52	0.087	0.087	0.275	0.028	0.003	0
5	Medium pool	0	0	0	0	0.752	0.094	0.138	0.014	0.002	0
6	Soils	0	0	0	0	0	0.918	0.06	0.02	0.002	0

Note: Each coefficient gives proportion of carbon transferred from source to sink

TABLE 2b. Disturbance Matrix: Stand Mortality

	Sink / **Source**	Stem biomass	Foliage biomass	Other biomass	Fast pool	Medium pool	Soils	CO_2	CO	CH_4	Forest products
1	Stem Biomass	0.2	0	0	0.1	0.7	0	0	0	0	0
2	Foliage Biomass	0	0.2	0	0.6	0.1	0	0.1	0	0	0
3	Other Biomass	0	0	0.2	0.1	0.7	0	0	0	0	0
4	Fast pool	0	0	0	1	0	0	0	0	0	0
5	Medium pool	0	0	0	0	1	0	0	0	0	0
6	Soils	0	0	0	0	0	1	0	0	0	0

Note: Each coefficient gives proportion of carbon transferred from source to sink

TABLE 2c. Disturbance Matrix: Clear-cut Logging With Slash Burning

	Sink / Source	Stem biomass	Foliage biomass	Other biomass	Fast pool	Medium pool	Soils	CO_2	CO	CH_4	Forest products
1	Stem biomass	0.02	0	0	0.04	0.02	0.01	0.10	0.01	0.001	0.8
2	Foliage biomass	0	0.17	0	0.33	0.03	0.016	0.41	0.04	0.004	0
3	Other biomass	0	0	0.17	0.33	0.03	0.016	0.41	0.04	0.004	0
4	Fast pool	0	0	0	0.71	0	0	0.26	0.026	0.004	0
5	Medium pool	0	0	0	0	0.855	0	0.13	0.013	0.002	0
6	Soils	0	0	0	0	0	1	0	0	0	0

Note: Each coefficient gives proportion of carbon transferred from source to sink

TABLE 2d. Disturbance Matrix: Partial Cutting

	Sink / Source	Stem biomass	Foliage biomass	Other biomass	Fast pool	Medium pool	Soils	CO_2	CO	CH_4	Forest products
1	Stem biomass	0.1	0	0	0	0.05	0	0	0	0	0.85
2	Foliage biomass	0	0.1	0	0.9	0	0	0	0	0	0
3	Other biomass	0	0	0.1	0	0.25	0	0	0	0	0.65
4	Fast pool	0	0	0	1	0	0	0	0	0	0
5	Medium pool	0	0	0	0	1	0	0	0	0	0
6	Soils	0	0	0	0	0	1	0	0	0	0

Source: For all tables 2a-2d Kurz *et al.* (1992) with some modifications.
Note: Each coefficient gives proportion of carbon transferred from source to sink

TABLE 3. Distribution of Carbon in Various Categories of Products

Lifespan of the Product	Amount of Carbon (Gg C)	Distribution of Carbon (%)	? a	? b	? d	? r
Very short	62,429	90.7				
Short	704	1	120	5	120	0.64
Medium	4,435	6.4	120	5	120	0.16
Long	1313	1.9	120	5	120	0.065
Total	68,880	100				

Source: Haripriya 2000(b)

Table 4. Terminal Use, Half-lives and Decomposition Rates of wood products used in the model

	Proportion of carbon sent to various terminal uses			**Land Fill**	**Half-lives of various categories of products (years)**		
Scenario	Recycle	Landfill	Energy	Decay rate (%/yr)	Short	Medium	Long
Short	0.38	0.52	0.10	0.1%	3	12	30
Medium	0.60	0.30	0.10	0.1%	3	12	30
Long	0.85	0.10	0.05	0.1%	3	12	30

Source: Haripriya 2000(b)

TABLE 5. Soil Carbon in different forest types

Forest type	Mean Soil carbon in top 30 cm (Mg/ha)
Tropical wet evergreen	132.8
Tropical semi evergreen	171.7
Tropical moist deciduous	57.1
Littoral and Swamp	34.9
Tropical dry deciduous	58.0
Tropical thorn	44.0
Tropical dryevergreen	33.0
Subtropical broad-leaved hill	108.7
Subtropical pine	90.4
Subtropical dryevergreen	33
Montane wet temperate	188.3
Himalayan moist temperate	140.4
Himalayan dry temperate	74.7
Subalpine and alpine	258.1

Source: From various references quoted in Ravindranath *et al.* (1996)

TABLE 6. Initial Values of Different C Pools for Various Ecoclimatic Provinces

Carbon pool / Ecosystem	Soils (Tg C)	Medium pool (Coarse litter) (Tg C)	Fast pool (Fine litter) (Tg C)
Tropical	3501.6	27.8	103.0
Temperate	556.1	1.8	8.1
Subtropical	341.3	2.3	10.5
Alpine	710.3	1.7	8.1
Total	5109.3	33.6	129.7

TABLE 7. Parameters Used in computing Decomposition rates from Various Soil Carbon pools

Major forest type / Parameter	Tropical	Temperate	Subtropical	Alpine
Mean annual temperature	over 24 ^{o} C	17 to 24^{o} C	7 to 17^{o} C	under 7 ^{o} C
Half-life period				
Fast carbon pool	4	8	16	20
Medium carbon pool	25	50	75	100
Soils	120	140	160	180
Half-life parameters (?$_r$)				
Fast pool	0.52	0.26	0.13	0.1
Medium pool	0.084	0.04	0.025	0.02
Soils carbon pool	0.006	0.005	0.004	0.003

Notes: ?$_a$?$_b$ are scalars equal to 120 and 5 respectively (derived from simulation based on half lives) (as in Haripriya 2000a)

TABLE 8. Half-Lives and Decay Rate Parameters of Various Soil C Pools (Low Half-life Scenario)

Ecosystem / Variable	Tropical	Temperate	Subtropical	Alpine
Half-life period				
Fast pool	3	12	6	16
medium pool	20	60	40	80
soils	80	120	100	140
Half-life parameters				
Fast pool	0.64	0.16	0.32	0.12
Medium pool	0.1	0.032	0.05	0.024
Soils	0.009	0.006	0.007	0.005

TABLE 9. Carbon flow accounts (in Gg C) for the Indian Forest Sector (for 1993-94)

Ecosystem Variable	Tropical	Temperate	Subtropical	Alpine	Total
Forest biomass					
Net growth before disturbance	41,779	2,955	2,567	2,038	49,339
Disturbance releases to the atmosphere					
Wildfire	-10,213	-146	-83	-338	-10,780
Insect	-1.6	-0.2	-0.2	-0.1	-2
Clear-cut and slash burn	-628	-25	-19	-45	-717
Partial cut	0	0	0	0	0
Subtotal disturbance releases	-10,842	-171	-103	-383	-11,499
Disturbance transfer as dead biomass					
Wildfire	-14,843	-203	-118	-468	-15,632
Insects	-382	-32	-32	-15	-461
Clear-cut and slashburn	-338	-13	-10	-24	-386
Partial cut	-11,349	-1661	-879	-602	-14,491
Subtotal disturbance transfer	-26,913	-1,909	-1039	-1,110	-30,970
Transfer to forest products	-55,4009	-6,920	-3907	-2,658	-68,885
Net change	**-51,376**	**-6,045**	**-2,481**	**-2,112**	**-62,015**
Forest floor, dead biomass and soil					
Net detritus inputs before disturbance					
Fast pool	13,192	1,350	1,554	1,367	17,396
Medium pool	18,489	1,264	1,527	1,171	22,451
Soils	3,475	167	295	127	4,065
Decay from fast pool	-13,122	-868	-1,489	-665	-16,145
Decay from medium pool	-7,321	-116	-243	-83.8	-7,765
Sub total (detritus inputs)	14,647	1,796	1,642	1,916	20,002
Disturbance transfer from biomass	26,913	1,909	1,039	1,110	30,970
Dist. releases to atmosphere from litter, dead biomass and soils					
Wildfire	-4517	-81	-56	-509	-5,163
Insects	0	0	0	0	0
Clear-cut and slashburn	-15	-0	-1	-1	-17
Partial cut	0	0	0	0	0
Subtotal disturbance releases	-4,531	-82	-57	-511	-5,181
Net change	**37,029**	**3,623**	**2,625**	**2,515**	**45,792**
Forest products					
Transfer from biomass	55,4009	6,920	3,907	2,658	68,885
Releases to atmosphere	52,519	6,560	3,703	2,520	65,303
Net change	2,881	360	203	138	3,582
Total net accumulation of carbon	**-11,521**	**-2,071**	**336**	**534**	**-12,723**
Carbon inventory					
Biomass C	23,98,28	2,65,760	1,44,960	1,24,770	29,33,770
Carbon in forest soils	35,01,56	5,56,140	3,41,290	7,10,340	51,09,330
Forest products sector	2,881	360	203	138	3,582

Notes: +ve sign indicates sequestration/increase of carbon and – (minus) sign indicates emission of carbon/decrease in stock of carbon.

TABLE 10. Results of the Sensitivity Analysis (Alternate Scenarios) of the Carbon Budget Model for the Year 1993 - 94 (in Gg C)

Simulation run / Variable	Base run	High biomass	Extended life of forest products	High fire	Low half-life of soil	Slow transfer to soil C
Forest biomass						
Net growth before disturbance	49,339	66,115	54,273	49,339	49,339	49,339
Disturbance releases to						
Wildfire	-10,780	-14,030	-11,875	-21,561	-10,780	-10,780
Insect	-2	-3	-2	-2	-2	-2
Clear-cut and slash burn	-717	-939	-790	-717	-717	-717
Partial cut	0	0	0	0	0	0
Subtotal disturbance releases	-11,500	-14,972	-12,667	-22,280	-11,500	-11,500
Disturbance transfer to soil						
Wildfire	-15,632	-20,340	-17,220	-31,264	-15,632	-15,632
Insects	-461	-609	-508	-461	-461	-461
Clear-cut and slashburn	-386	-505	-425	-386	-386	-386
Partial cut	-14,491	-14,287	-14,460	-14,491	-14,491	-8,297
Subtotal disturbance transfer	-30,970	-35,741	-32,613	-46,602	-30,970	-24,776
Transfer to forest products	-68,885	-68,882	-68,879	-68,885	-68,885	-68,879
Net change	**-62,015**	**-53,480**	**-59,886**	**-88,428**	**-62,015**	**-55,815**
Forest floor, dead biomass and soil						
Net detritus inputs before disturbance						
Fast pool	17,396	23,079	19,161	17,396	17,510	17,396
Medium pool	22,451	29,595	24,729	22,451	22,451	22,451
Soil pool	4,065	5,340	4,477	4,065	4,451	1,195
Decay from fast pool	-16,145	-21,297	-17,783	-16,145	-16,610	-16,145
Decay from medium pool	-7,765	-10,115	-8,553	-7,765	-9,573	-7,765
Sub total (detritus inputs)	20,002	26,601	22,031	20,002	18,230	17,133
Disturbance transfer from biomass	30,970	35,741	32,613	46,602	30,970	24,776
Disturbance releases to atmosphere from litter, dead biomass and soils						
Wildfire	-5,163	-5,203	-5,177	-10,002	-5,164	-5,160
Insects	0	0	0	0	0	0
Clear-cut and slash burn	-17	-23	-19	-17	-17	-17
Partial cut	0	0	0	0	0	0
Subtotal disturbance releases	-5,181	-5,226	-5,196	-10,019	-5,181	-5,177
Net change	**45,792**	**57,117**	**49,448**	**56,585**	**4,40,198**	**36,733**
Forest products						
Transfer from biomass	68,885	68,882	68,879	68,885	68,885	68,879
Releases to atmosphere	65,303	65,300	63,374	65,303	65,303	65,297
Net change	3,582	3,582	5,511	3,582	3,582	3,582
Total (net sink)	**-12,723**	**7,218**	**-10,794**	**-28,260**	**-14,415**	**-15,501**

Notes: +ve sign indicates sequestration/increase of carbon and – (minus) sign indicates emission of carbon/decrease in stock of carbon.

TABLE 11. Percentage increase in the Estimates of Different Parameters (Alternate Scenarios)

Variable / Simulation run	High biomass	Extended life of forest products	High fire	Low half-life of soil	Slow transfer to soil C
Forest biomass					
Net growth before disturbance	34	10	0	0	0
Disturbance releases to atmosphere					
Wildfire	30	10	100	0	0
Insect	34	10	0	0	0
Clear-cut and slash burn	31	10	0	0	0
Partial cut	0	0	0	0	0
Subtotal disturbance releases	30	10	94	0	0
Disturbance transfer to soil					
Wildfire	30	10	100	0	0
Insects	32	10	0	0	0
Clear-cut and slashburn	31	10	0	0	0
Partial cut	-1	0	0	0	-43
Subtotal disturbance transfer	15	5	50	0	-20
Transfer to forest products	0	0	0	0	0
Net change	**-14**	**-3**	**43**	**0**	**-10**
Litter, dead biomass and mineral soils					
Net detritus inputs before disturbance					
Fast pool	33	10	0	0.7	0
Medium pool	32	10	0	0	0
Soil pool	31	10	0	9.5	-71
Decay from fast pool	32	10	0	2.9	0
Decay from medium pool	30	10	0	23.3	0
Sub total (detritus inputs)	33	10	0	-8.9	-14
Disturbance transfer from biomass	15	5	50	0	-20
Disturbance releases to atmosphere					
Wildfire	1	0	94	0	0
Insects	0	0	0	0	0
Clear-cut and slashburn	31	10	0	0.5	-2
Partial cut					
Subtotal disturbance releases	0.9	0	93	0	0
Net change	**25**	**8**	**24**	**-3.9**	**-20**
Forest products					
Transfer from biomass	0	0	0	0	0
Releases to atmosphere	0	-3	0	0	0
Net change	0	54	0	0	0
Total (net sink)	**-157**	**-15**	**122**	**13.3**	**22**
Carbon inventory					
Biomass carbon	34	100	0	0	0
Carbon in forest soils	0	0	0	0	0
Forest products sector	0	54	0	0	0

Notes: +ve sign indicates sequestration/increase of carbon and – (minus) sign indicates emission of carbon/decrease in stock of carbon.

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