CARBON BUDGETS AND CARBON SEQUESTATION POTENTIAL OF INDIAN FORESTS

KOOLSTOFBUDGETTEN EN KOOLSTOFOPSLAG POTENTIEEL VAN INDIASE BOSSEN

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CARBON BUDGETS AND CARBON SEQUESTRATION POTENTIAL OF INDIAN FORESTS

Meenakshi Kaul

Thesis

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This thesis is dedicated to my husband

ABSTRACT

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Global climate change is a widespread and growing concern that has led to extensive international discussions and negotiations. Responses to this concern have focused on reducing emissions of greenhouse gases, especially carbon dioxide, and on measuring carbon absorbed by and stored in forests and soils. Forests are a significant part of the global carbon cycle. The amount of carbon stored, however, changes over time as forests grow and mature. Land use changes, especially afforestation and deforestation may have major impacts on carbon storage. An option for mitigating the accumulation of CO_2 in the atmosphere is the enhanced sequestration of carbon by the biosphere through massive reforestation or sustainable afforestation programs. Reducing the rate of deforestation reduces carbon losses from the biosphere. Establishing plantations on former agricultural land may have less of an impact on increasing carbon sequestration than restoring natural forests. The focus of this study was to estimate the carbon budgets and carbon sequestration potential of Indian forests, assessing the possible impacts of land-use changes and climate change on carbon stocks of Indian forests, and the mitigation potential of using forest-based bioenergy for fossil fuel substitution. The results from this study show that over a 10-year period from 1992-2002, Indian forests have acted as a small carbon sink. Thus, India with high population density, low forest cover per capita, high dependence of a large part of human population on forests, and a predominantly agrarian economy, has been able to reduce deforestation rate and increase its forest cover and associated carbon sink in the terrestrial biosphere. Due to fast growth rate and adaptability to a range of environments, short rotation plantations, in addition to carbon storage, rapidly produce biomass for energy and contribute to reduced greenhouse gas emissions. India has the potential to create additional carbon sinks using marginal lands, while at the same time balancing economic development and environmental concerns.

Keywords: Carbon uptake, Forest biomass, Bioenergy, Land use change, Indian forests, Deforestation, Afforestation, Rotation length, Trees outside forests.

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Chapter 1

General introduction

1.1 Background

The concern for likely impact of climate change, need to control the green house gas (GHG) emissions, protecting the ozone layer and similar issues related to sustainability have become globally important. It is now well established fact that anthropogenic greenhouse gas increases caused most of the observed increase in global average temperatures since the mid-twentieth century. The total temperature increase from 1850-1899 to 2001-2005 is 0.76°C ± 0.19°C (IPCC, 2007). The rate of warming averaged over the last 50 years (0.13°C ± 0.03°C per decade) is nearly twice that for the last 100 years (IPCC, 2007). The years 2005 and 1998 were the warmest two years in the instrumental global surface air temperature record since 1850. Since the Third Assessment Reports (TAR) of Intergovernmental Panel on Climate Change (IPCC) there have been many important advances in the science of climate change projections. Knowledge of the climate system together with model simulations confirm that past changes in greenhouse gas concentrations will lead to a committed warming and future climate change. Evidence suggests that a rise in the atmospheric carbon dioxide (CO_2) level and temperature is likely to have adverse impacts on natural ecosystems such as forests and human systems such as food production.

Carbon dioxide is the most important green house gas responsible for global warming. The concentration of atmospheric CO_2 has increased from a pre-industrial value of about 280 parts per million (ppm) to 379 ppm in 2005 (IPCC, 2007). Annual emissions of CO_2 from fossil fuel burning, cement production and gas flaring increased from a mean of 6.4 ± 0.4 Pg C yr^{-1} in the 1990s to 7.2 ± 0.3 Pg C yr^{-1} for 2000 to 2005. Emissions from the combustion of fossil fuel and land use change reached 10 billion Mg of carbon in 2007. World carbon dioxide emissions are expected to increase by 1.8 percent annually between 2004 and 2030 (International Energy outlook, 2007, EIA). Much of the increase in these emissions is expected to occur in the developing world, such as China and India, with fossil fuel based economic development. Despite the increasing international sense of urgency, the growth rate of emissions continues to increase, bringing the atmospheric carbon dioxide concentration to 383 parts per million (ppm) in 2007. Natural CO_2 sinks are growing but slower than the atmospheric CO_2 growth, which has been increasing at

2 ppm since 2000 or 33% faster than the previous 20 years. Countries contribute different amounts of heat trapping gases to the atmosphere. Figure 1.1 shows the carbon dioxide emissions from the consumption and flaring of fossil fuels for top ten countries for the year 2006.

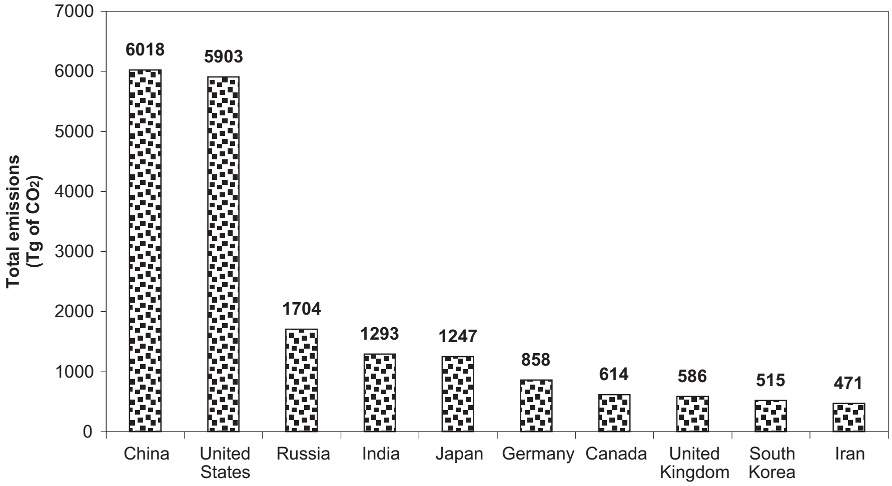

FIGURE 1.1 **CO_2 emissions from the consumption and flaring of fossil fuels for top ten countries for the year 2006.**

Source: International Energy outlook, 2006, EIA

India holds over 1 billion people, i.e. over 16% of global population. Endowed with coal, India's energy system has evolved around coal. The contribution of India to the cumulative global CO_2 emissions from 1980 to 2003 is only 3 per cent (Sathaye *et al*. 2006). Thus historically, and at present, India's share in the carbon stock in the atmosphere is relatively very small in terms of per capita emissions. India's per capita carbon emissions average one-twentieth of those of the United States and one-tenth of most countries in Western Europe and Japan. Based on sector-wise distribution, 743.8 Tg of CO_2 equivalent emissions were emitted from energy sector (61 per cent); 344 Tg of CO_2 equivalent emissions came from the agriculture sector (28%); 102.7 Tg of CO_2 equivalent were contributed by the industrial processes

(8%); 23 Tg from waste disposal (2%) activities and 14 Tg were generated from land use, land use change and forestry (LULUCF) sector (1%) (NATCOM, 2004). Figure 1.2, shows the percentage contribution to the total GHG emissions from various sectors by sources and removals by sinks for India for the base year 1994. In response to the growing concern and the mounting evidence of global climate change, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted at the United Nations Conference on Environment and development at Rio in 1992.

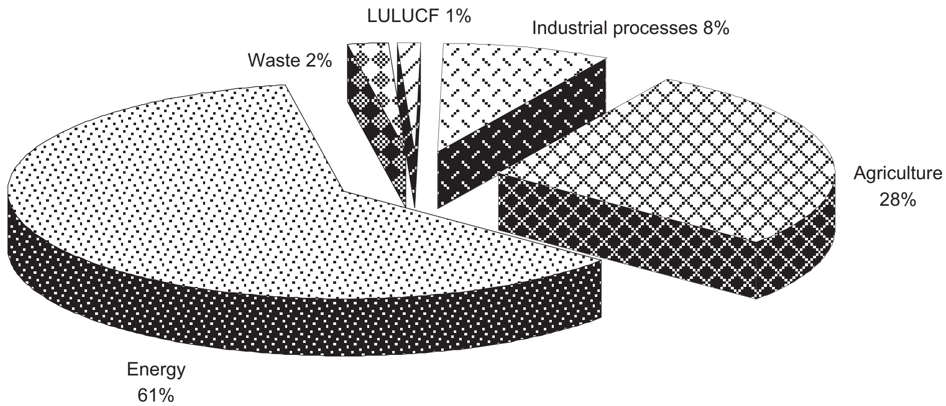

FIGURE 1.2 **Percentage contribution of different sectors to the total GHG emissions for the base year 1994**

Source: NATCOM, 2004

It is well known fact now that forests are important component of global carbon (C) cycle. Tropical forests clearly dominate the role of forests in the global carbon cycle based both on C flux, and the volume of carbon stored. Deforestation and forest degradation in the tropics currently account for about 20% of the GHG emissions and constitute the majority of emissions from developing countries (IPCC, 2007; Gullison *et al*. 2007). Recognizing the importance of tropical forests and the value of developing countries participation in the global climate change mitigation efforts, Reduced Emissions from Deforestation and Degradation (known as REDD) is under discussion and an important part of the future international climate agreement. REDD is an instrument to maintain carbon pools, support sustainable development and mechanism to reward countries with carbon credits for preserving their forest cover.

As reported above, India is the fourth largest emitter of CO_2 emissions. Being a major tropical forest ecosystem constituting nearly 67.71 million hectares (Mha), which is 20.6% of the geographical area of country (FSI, 2005), Indian forests therefore are focal point for an analysis of forest carbon sequestration potentials. In order to contribute significantly to the reduction of the atmospheric CO_2, two things must happen: tropical deforestation should be slowed down and enhancement of carbon sinks through proper forestry management practices like forest protection, afforestation and reforestation must be pursued.

1.2 India – General profile and land use pattern

The Republic of India, in Southern Asia, is the seventh largest country in the world, covering an area of 329 Mha (Mha = 10^6 ha). India occupies only 2.4 percent of the world's geographical area, supports about 16.2 percent of the global human population. India also has only 0.5% of the world's grazing area but supports 18% of the world's cattle population. India is endowed with a variety of soils, climate, biodiversity and ecological regions. The mainland extends between latitudes 8° 04′ and 37° 06′ North and longitudes 68° 07′ and 97° 25′ east and measures 3200 km from north to south between the extreme latitudes and about 2950 km from east to west between the extreme longitudes. Agriculture is the major sector of growth of the Indian economy. A large percentage of the population is still dependent on agriculture for its sustenance. Of the total cultivated area of 142 Mha, over 97 Mha (68% of the net cultivated area) is rain fed agricultural land.

India's mainland comprises four broad geographical areas: the Northern Mountains which has the great Himalayas, the vast Indo-Gangetic plains, the Southern (Deccan) Peninsula bounded by the Western and Eastern Ghats, and fourthly, the coastal plains and islands.

(i) Northern Mountains: Corresponding with the Himalayan Zone, along with country's northern boundaries including the Jammu and Kashmir (J&K), Himachal Pradesh (H.P.), north-west Uttar Pradesh (U.P.), Sikkim, part of Assam, and the North-eastern States of Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura and Meghalaya. The Himalayas comprise of mountain ranges that form an indomitable physical barrier as the world's biggest and largest mountain range. The Himalayas also contain the cold arid deserts and fertile valleys.

(ii) The Great Plains: Also known as the Indo-Gangetic plain is formed by the basin of three distinct river systems - the Indus, the Ganga and the Brahmaputra. The Plains extend from Rajasthan in the West to Brahmaputra valley in the East. This region covers the entire States of Punjab, Haryana, and the Union Territory of Chandigarh and Delhi and major parts of U.P., Bihar, West Bengal, and parts of Assam. The desert region, which contains the Great Thar desert, extends from the edge of Rann of Kutch to larger parts of Rajasthan (Western) and lower regions of Punjab and Haryana.

(iii) The Deccan Peninsula: This zone covers the whole of south India which includes the states of Tamil Nadu, Karnataka, Andhra Pradesh and Kerala. The Region also covers the State of Madhya Pradesh, and parts of Bihar, Orissa, and Puriliya district of West Bengal. The Indo-Gangetic plains and the peninsular plateau are separated by mountain and hill ranges known as the Aravali, Vindhya, Satpura, Ajanta and Maikala ranges.

(iv) The Coastal Plains and Islands: The peninsula is flanked on either side by the Eastern Ghats and the Western Ghats. On either side of the Ghats outward to the sea lies a coastal strip. The western coastal plains lie between the Western Ghats and the Arabian Sea in the west, whereas the eastern Coastal Plains face the Bay of Bengal in the east.

India has mainly four seasons: (i) Winter (December-February), (ii) Summer (March-June), (iii) South-west monsoon season (June-September), and (iv) Post monsoon season (October-November). During the post monsoon season, commonly known as winter monsoon, monsoon rains begin over north India and pass over the Bay of Bengal before reaching the Andaman and the south-east coast. However, the south-west or the summer monsoon is the main source of rainfall in the country providing 80% of the precipitation.

TABLE 1.1 **Land use pattern in India**

Sl. No	Classification	Area (Mha)	% of total geographical area
1	Total Geographical Area	329	
2	Area under forests	68.86	22.60
3	Area not available for cultivation		
	(i) Area under non-agriculture use	22.53	7.40
	(ii) Barren and unculturable land	19.03	6.20
4	Other Uncultivated land (exclusive fallows)		
	(i) Permanent pasture or other grazing land	10.91	3.60
	(ii) Land under miscellaneous tree crops and groves not included in net area under cultivation	3.57	1.20
	(iii) Culturable waste	13.88	4.50
5	Fallow land		
	(i) Other than current fallows	9.76	3.20
	(ii) Current fallows	14.36	4.70
6	Net area sown (Agriculture)	142.02	46.60
7	Total reporting area	304.92	100
8	Area for which no records exist	23.81	-

Source: Forests & Wildlife Statistics of India, (2004)

Of the total geographical area of 329 Mha, land use statistics are available for approximately 305 Mha contributing 93% of the total. Table 1.1 shows the land use classification in India (see Appendix I for definitions). In India, an estimated 146.82 Mha area suffers from various forms of land degradation due to water and wind erosion and other complex problems such as alkalinity/salinity and soil acidity due to water logging (Figure 1.3). Loss of vegetation occurs as a result of deforestation, unsustainable fuel wood and fodder extraction, shifting cultivation, encroachment

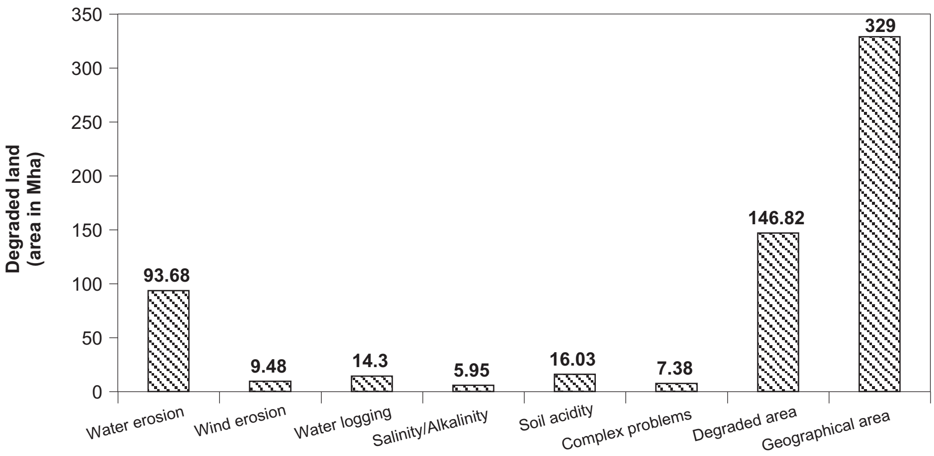

FIGURE 1.3 **Extent of various kinds of Land degradation in India.**

Source: State of Environment Report India-2009

into forest lands, forest fires and over-grazing, all of which subject the land to degradation forces. A change in land use pattern implies variation in the proportion of area under different land use categories at a point in two or more time periods. Over the past fifty years, while India's total population increased by about three times, the total area of land under cultivation increased by only 20.2 per cent (from 118.75 Mha in 1951 to 142 Mha in 2005-2006). Most of this expansion has taken place at the expense of forest and grazing land. Despite fast expansion of the area under cultivation, less agricultural land is available on per capita basis.

1.3 Status of Indian forests

Forests are not just trees, but part of an ecosystem that underpins life, economies and societies. Forests provide a wide range of services, which include prevention of soil erosion, floods, landslides, maintenance of soil fertility, and fixing carbon from the atmosphere as biomass and soil organic carbon. Indian forests show greatest variation and range depending upon rainfall, soil topography and climatic factors. Forests are both a resource and a habitat for a rich flora and fauna found in

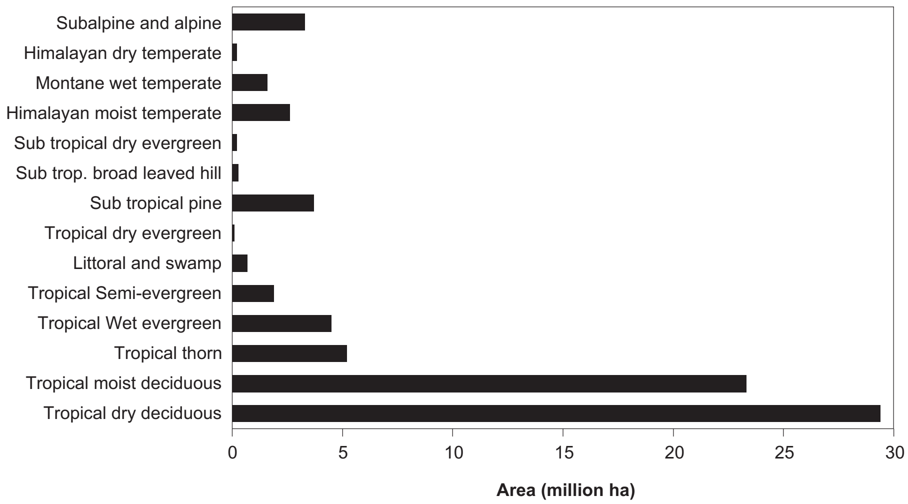

FIGURE 1.4 **Forest area in different forest types in India (Mha)**

Source: FSI, 1987

the country. Indian forests are classified into four major forest groups based on climatic factors. These major groups are further classified into 16 forest types based on temperature and moisture contents. More than half of the forest area in India is tropical-moist and dry-deciduous (Figure 1.4). The tropical deciduous forests in India form the major forest type accounting for 38.2% of the total forest area. Other predominant forest type is the moist deciduous covering 30.3% of the forest area of the country.

The forest types vary from tropical rainforest in north-eastern India, to desert and thorn forests in Gujarat and Rajasthan; rich mangrove forests in West Bengal, Orissa and other coastal areas; and dry alpine forests in the western Himalaya. The main areas of tropical forest are found in the Andaman and Nicobar Islands, the Western Ghats, which fringe the Arabian Sea coastline of peninsular India and the greater Assam region in the North-East. Small remnants of rain forest are found in Orissa state. The tropical vegetation of North-East India (which includes the states of Assam, Nagaland, Manipur, Mizoram, Tripura and Meghalaya as well as the plain regions of Arunachal Pradesh) typically occurs at elevations up to 900 m. India is a mega-biodiversity country where forests are extremely diverse and heterogeneous in nature with "Miscellaneous forest" category (with no dominant species) occupying the highest (63%) proportion of forest area under all the forest types.

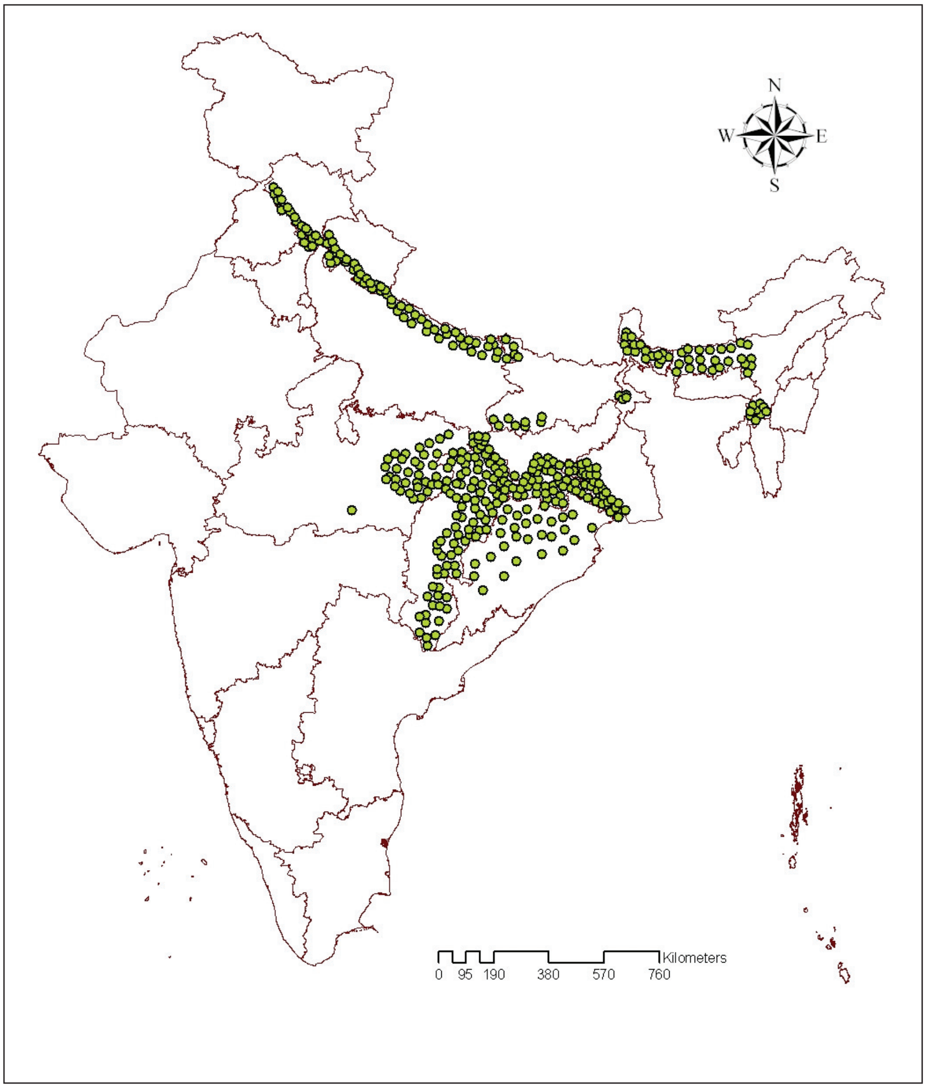

FIGURE 1.5a **Map showing distribution of sal forests in India.**

Source: Tewari (1995a)

The other two dominant types are *Shorea robusta* Gaertn. f. or sal (12%) in the eastern part of Central India (Figure 1.5a) and *Tectona Grandis* Linn. f. or teak (9.5%), spread across Central India and the Western Ghats in southern India (Figure 1.5b). There is large variation in the amount of rainfall received in different parts of the country. Average rainfall is less than 13 cm in the Thar dessert, while at

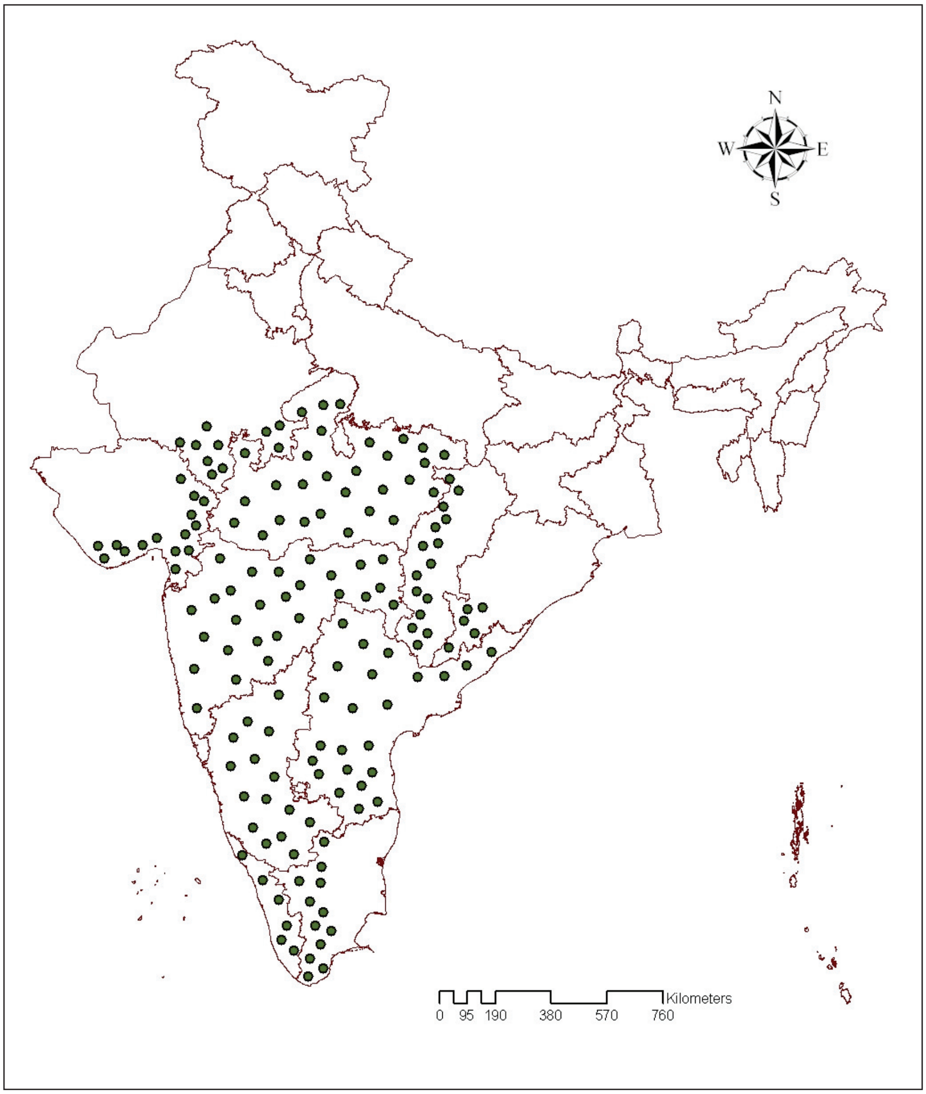

FIGURE 1.5b **Map showing distribution of teak forests in India**
Source: Tewari (1995b)

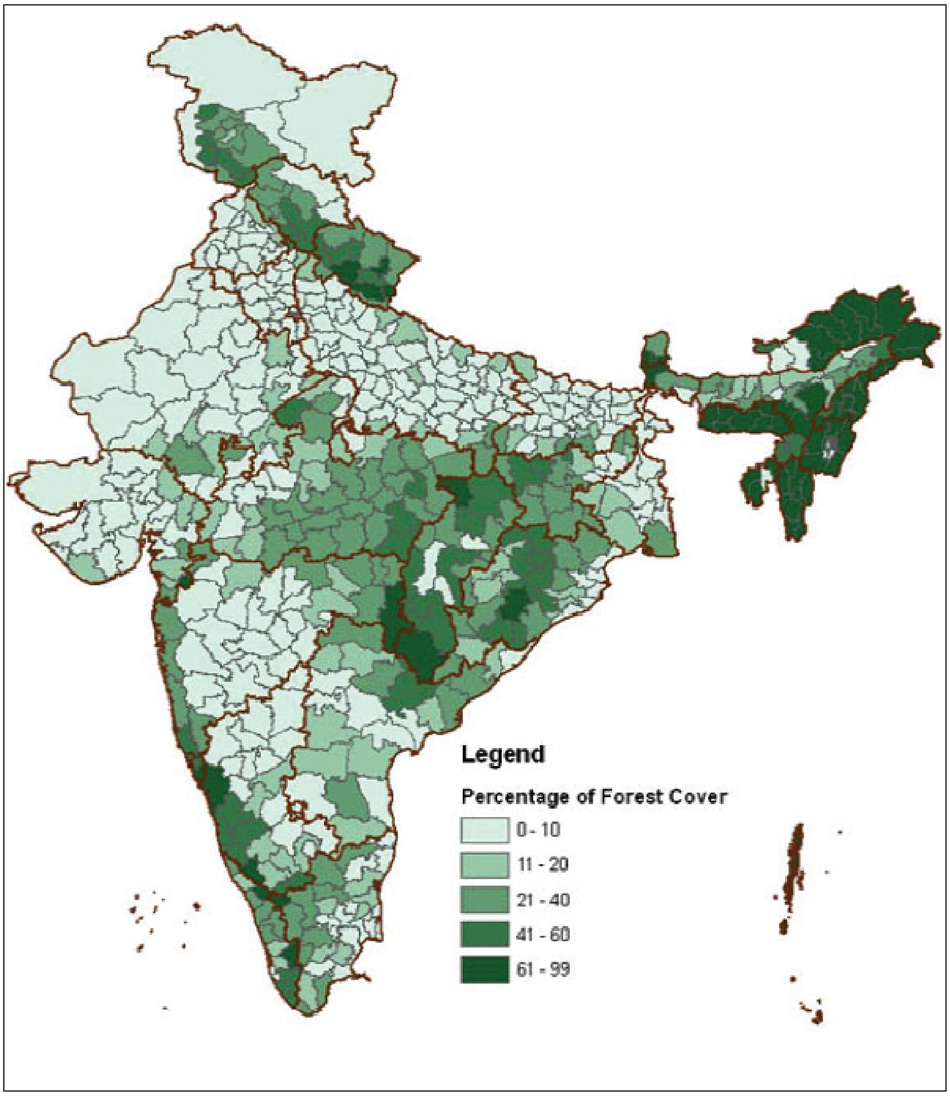

FIGURE 1.6 **District wise status of forest cover in India**

Source: FSI (2003)

Cherrapunji in the North-East it is as high as 1080 cm. The most important feature of Indian climate is the season of concentrates rain called "the monsoon".

Presently 23.4% of the total land area is under the forest and tree cover, while 44% is the net sown area (FSI, 2005). According to the Forest Survey of India, the total forest cover in the year 2004 was 67.71 Mha, which is 20.6% of its geographical area (FSI, 2005). Of this, 5.46 Mha (1.66%) is very dense forest, 33.26 Mha (10.12%) is moderately dense and the rest 28.99 Mha (8.82%) is open including 0.44 Mha mangroves. Figure 1.6 shows the district wise status of forest cover in India for the year 2003 (FSI, 2003).

The estimated tree cover is 9.17 Mha, which constitutes about 2.8% of the geographic area of the country. Thus, the total forest and tree cover of the country so estimated comes out to be 76.88 Mha constituting 23.4% of its geographical area (FSI, 2005). The total growing stock of wood in the country is estimated to be 6.22 billion m^3 (including 1.61 billion m^3 growing stock for trees outside forests) which gives an average growing stock of 80.9 m^3 per ha in 76.88 Mha of forest and tree cover (FSI, 2005).

1.4 Carbon studies and mitigation options in India

India is a party to the UNFCCC and attaches great importance to climate change issues. To meet its obligations under the UNFCCC and to best understand the interactions between the national concerns and global environmental problems, India carried out a national inventory of its anthropogenic emissions of greenhouse gases.

A comprehensive inventory of the GHG emissions from all the sectors was submitted to the UNFCCC on 22 June 2004 for the base year 1994 using IPCC guidelines. The first available estimates for forest carbon stocks (biomass and soil) for the year 1986 are in the range of 8.58 to 9.57 Pg (Pg = 10^{15}g) C (Ravindranath *et al*. 1997; Haripriya, 2003; Chhabra and Dadhwal, 2004). According to Food and Agriculture Organization (FAO) estimates, the total forest carbon stocks in India have increased over a period of 20 years (1986–2005) and amount to 10.01 Pg C (FAO, 2005). However, there is wide variation in the estimated carbon pools and fluxes because of methodological differences, different sources of data, estimates for different years, as well as paucity of reliable countrywide statistics and use of detailed global parameters for biomass estimation. The carbon stock projection for the period 2006–2030 is projected to increase from 8.79 Pg C to 9.75 Pg C (IISc, 2006) with forest cover becoming more or less stable, and new forest carbon accretions coming from the current initiatives of afforestation and reforestation programme (Ravindranath *et al*. 2008). With the knowledge and information that is now emerging, the role of forest and plantations in mitigation is becoming more and more important. Over the past decades, national policies of India aimed at conservation and sustainable management of forests have transformed India's forests into a net sink of CO_2.

Trees outside forests play multifunctional roles by providing a wide range of goods and services, particularly to rural India and to wood-based industries. However, because of poor accounting, their contribution to the local and the national economy is largely unknown. The recorded production of round wood from Indian's forests was of the order of 12–14 million m^3 annually during the 1970s (National Commission of Agriculture, 1976), but this has gradually declined to about 2.5–3 million m^3 at present (ICFRE, 2003). This has happened mainly because of the increasing emphasis on the conservation of forests and severe restriction on felling of trees from natural forests. About 2.5 million m^3 of timber is being imported to fill the gap. Though consumption and sources of round wood supply have not been studied reliably at the national level, it has been estimated that, of total timber production in India, about 80 percent is being produced from non-forest areas under private ownership (Rai and Charkrabarty, 1996).

Wood fuel is the principal source of energy for cooking and heating in rural India. It was estimated by the Forest Survey of India (FSI) that total wood fuel consumption for the whole country was 201 Tg (Tg = 10^{12}g) in 1996, of which 51 percent came from forests and 49 percent from non-forest areas (Rai and Charkrabarty, 1996). There are other estimates which state that the bulk of wood fuel (more than 75 percent) in India is accounted for by non-forest areas (Saxena, 1997; Natarajan, 1996; Agarwal, 1998). Some local studies have confirmed that where the forest area is small, most of the wood fuel is from non-forest areas, whereas in areas with rich forests, the reverse is true (Bhattacharya and Joshi, 1999, Prasad *et al.* 1999).

To encourage conservation and expansion of forests world-wide, India internationally supported compensation for nations in return for the carbon services they are, and will be, providing by conserving, stabilizing and/or increasing their forest cover. The policy approach advocated by India in the context of the agenda item of "Reducing emissions from deforestation and degradation in developing countries" of the UNFCCC, also known as REDD or REDD-plus was named "compensated conservation" (Kishwan, 2007). However, any future agreement on REDD/REDD-plus would require assessment and monitoring of forest carbon stocks of a country at regular intervals through application of scientifically acceptable methodologies.

1.5 Scope and objectives of the thesis

The main aim of the thesis was to estimate the carbon budgets and carbon sequestration potential of Indian forests, assessing the possible impacts of land-use changes and disturbance on carbon stocks of Indian forests, and further the potential of bio fuel to substitute for fossil fuel (e.g., coal). The knowledge obtained from this thesis should be helpful to improve consistency and completeness in the estimation and reporting of carbon dioxide emissions and removals by natural and plantation forestry.

To fulfil the main aim of this PhD, the study focused on the following research questions:

(i) What forest types exist in India and how much area each type covers?

(ii) What is the present carbon budget in Indian forests?

(iii) What is the carbon sequestration potential of Indian Forests?

(iv) What are the management options for sustainable increase of carbon sequestration in Indian forests?

(v) What changes occur in the total carbon stock as a result of land-use change, disturbance and climate changes? and

(vi) What is the current status of Indian biomass energy programme and its potential to substitute for fossil fuel to reduce emissions?

1.6 Data availability and data use

The data used in this study are obtained from various sources e.g., the Ministry of Environment and Forests (MoEF), the State Forest departments (SFD) and the forest inventories carried by the Forest Survey of India (FSI). In addition, data from regional soil survey departments, from the Indian Institute of Tropical Meteorology, and from reports such as published by FAO have been used. As the data has been collected from various sources, accuracy and precision is variable.

The National Forest Policy (1988) in India aims at maintaining a minimum of 33 percent of country's geographical area under forest and tree cover. This requires periodic monitoring of the forest cover of the country for effective planning and sustainable development. The Forest Survey of India, an organization under the Ministry of Environment and Forests (Government of India) has been carrying out these assessments of forest cover using satellite-based remote sensing data. The FSI publishes its findings in the State of Forest Report (SFR) every two years. The assessment of forest cover of India is based on interpretation of satellite data, whereas estimation of tree cover and growing stock is done by field inventory using a sampling approach. Accuracy assessment is an essential part of remote sensing based mapping, and accuracy of forest cover mapping, precision of tree cover estimates, and precision growing stock estimates are calculated. The overall accuracy of the forest cover classification is almost 96% (FSI, 2009).

Mean annual Increment (MAI) and growing stock data is required for different forest and plantation types and managed, both abandoned and regenerating. The main source of data on MAI and growing stock is from forest inventory, and from silvicultural studies conducted by universities and research institutions. The FSI has estimated the growing stock data for 22 strata in India. The estimates of MAI are available for some forest types in published field research studies. Apart from these, a published report by FSI (FSI, 1995b) also reports the mean annual increment of different species in India, used in our study. The data on annual biomass increment of different forest types is available only for 1995. In view of this, it is assumed that the mean annual biomass increment remains unchanged during the study period

(1992-2002). The total biomass increment is thus estimated separately using a relative proportion of forest area in the dense and open category. All the biomass data are converted to carbon values by assigning a carbon content of 0.5 Mg C per Mg oven dry 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 is used to determine the annual net carbon uptake for the 10-year period from 1992-2002, using the method discussed in the respective chapter.

Forest biomass estimates for large areas such as for India at national scale, are based mainly on: (a) estimates using mean biomass densities from ecological studies, (Dadhwal and Nayak, 1993; Ravindranath *et al*. 1997), (b) estimates using field inventory of growing stock and biomass expansion factors, (Dadhwal and Shah, 1997; Lal and Singh, 2000). In this thesis, the IPCC 2006 guidelines have been followed. An important and positive aspect is the separate treatment of natural forests and plantation forestry for estimation of carbon accumulation and also estimation of carbon pool for Trees Outside Forests (TOF). In order to assess the annual carbon flux, annual forest productivity and annual extraction of wood from forests needs to be estimated. Using the data from forest inventories and from literature, the phytomass carbon pool is computed and it is assumed that carbon flux due to the factors like shifting cultivation, forest fires, grazing etc. is negligible as there is only a marginal land use change during the study period. In India, CO_2 emissions from forest conversion or loss are largely offset by carbon uptake due to forest increment and afforestation (Rawat and Kishwan, 2008).

Soil carbon density is required for different land-use categories before and after the conversion of each land use category to a new land use category. The

National Bureau of Soil Survey and Land Use Planning (NBSSLUP) estimates the soil carbon density, largely for non-forest land use categories. Chhabra *et al*. (2002c) have estimated the mean soil organic C densities for various forest types in different states and union territories for two depth classes (0-50 cm and 0-100 cm). The area occupied by 16 forest types in different states is reported in the state forest report (FSI, 1987). Both these reported values were used together to estimate the reference C stocks for individual states.

Fuel wood and commercial timber production refers to the proportion of wood coming from forest clearing and from extraction from the existing forests. The volume harvested for timber and fuel wood is highly debated as the estimated consumed volume exceeds the recorded produced volume. Moreover, the number of families depending on fuel wood is decreasing thereby reducing the pressure on forests. The source of data on consumption includes forest department's statistics as well as national level fuel wood consumption studies, carried out in the past (FSI, 1987; Ravindranath *et al*. 1997; MoEF, 1999; Haripriya, 2001). The source of timber consumption is the forest department as well as the FSI. India does not have any programme or institution dedicated to monitor the consumption of fuel wood and commercial round wood from forest and non-forest sources. In order to avoid overestimation, national level timber and fuel wood consumption estimates have been taken from various published literature and reports. Further, much of the wood that is harvested from forests remains in products for different lengths of time. The time the carbon will remain in the product will depend upon the product and its use. Concurrent with IPCC it is assumed that carbon stocks in harvested wood products remain constant, hence only the biomass of trees and forests in India are accounted and considered in this study. An uncertainty analysis accounting for the various sources of uncertainty in the data used for this study has been carried out and will be discussed in Chapter 6.

1.7 Outline of the thesis

The thesis consists of six chapters. Following the introduction, Chapter 2 gives a general introduction about the area and types of forests in India. Furthermore, it reports the state wise phytomass carbon pool of Indian forests for the years 1992 and 2002 using growing stock, biomass expansion factors and biomass increment. The results were also compared with the estimates of carbon pool using an approach as recommended by IPCC 2006 guidelines i.e. accounting for biomass increment and removal approach. Using remote sensing based estimates of tree cover and growing stock outside forests, the carbon pool of trees outside forests is also estimated.

Chapter 3 compares carbon storage and sequestration potential for some selected tree species in India. The CO2FIX v. 3.1 model was used to estimate the carbon stocks in biomass, soil and wood products.

Chapter 4 deals with the effect of land use changes on carbon stocks of Indian forests. The main steps in estimation are (a) computation of carbon removal when forest land remaining as forest and (b) computation of carbon removal or emission from the land converted from one category to other.

Chapter 5 discusses the possibilities for using forest and non-forest lands for carbon storage or biomass generation for substituting fossil fuels. In addition prospects for woody biomass generated from short rotation poplar plantation and used for substituting coal for power generation is discussed.

Chapter 6 contains a general discussion and synthesis of the research results is presented. Practical measures and research priorities are proposed, to develop and implement strategies both for protection and for safeguarding the livelihoods of forest dependent people, and to ensure production of round wood for industrial and commercial needs.

CHAPTER 2

Phytomass carbon pool of trees and forests in India

This chapter is submitted as:

Kaul, M., Mohren, G.M.J., Dadhwal, V.K., 2009. Phytomass carbon pool of trees and forests in India

ABSTRACT

The study reports estimates of above ground phytomass carbon pools in Indian forests for 1992 and 2002 using two different methodologies. The first estimate was derived from remote sensing based forest area and crown density estimates, and growing stock data for 1992 and 2002 and the estimated pool size was in the range 2626 – 3071 Tg C (41 to 48 Mg C ha^{-1}) and 2660 – 3180 Tg C (39 to 47 Mg C ha^{-1}) for 1992 and 2002, respectively. The second methodology followed IPCC 2006 guidelines and using an initial 1992 pool of carbon, the carbon pool for 2002 was estimated to be in the range of 2668 – 3112 Tg C (39 to 46 Mg C ha^{-1}), accounting for biomass increment and removals for the period concerned. The estimated total biomass increment was about 458 Tg biomass over the period 1992-2002. Removals from forests include mainly timber and fuel wood, whereby the latter includes large uncertainty, as reported extraction is lower than actual consumption. For the purpose of this study, the annual extraction values of 23 million m^3 for timber and 126 million m^3 for fuel wood were used. Out of the total area, 10 million ha are plantation forests with an average productivity (3.2 Mg $ha^{-1}yr^{-1}$) that is higher than natural forests, a correction of 408 Tg C for the 10 year period was incorporated in total estimated C-pool of Indian forests. This results in an estimate for the net sink of 4 Tg C yr^{-1}. Both approaches indicate Indian forests to be sequestering carbon and both the estimates are in agreement with recent studies. A major uncertainty in Indian phytomass carbon pool dynamics is associated with trees outside forests and with soil organic carbon dynamics. Using recent remote-sensing based estimates of tree cover and growing stock outside forests, the estimated phytomass carbon pool for trees outside forests for the year 2002 is 934 Tg C with a national average tree carbon density of 4 Mg C ha^{-1} in non-forest area, in contrast to an average density of 43 Mg C ha^{-1} in forests. Future studies will have to consider dynamics in both trees outside forests and soil for total terrestrial carbon dynamics.

Keywords: Carbon uptake, Forest biomass, Growing stock, Carbon cycle, Trees outside forests.

2.1. Introduction

Tropical forests play an important role in the global carbon cycle based both in terms of regulating the carbon flux between the biosphere and the atmosphere, and in terms of the amount of carbon stored. Indian forests are a major tropical forest ecosystem constituting nearly 67.83 million hectares (Mha), 20.66% of the geographical area of country (329 Mha, FSI, 2003). India’s geographical area constitutes 2.4% of the world land area and about 2% of the global forests, while supporting 16% of the world’s human population. Indian forests are known to be one of the richest in terms of vegetation types and species diversity. The revised forest type classification of Champion and Seth (1968) is the most widely used classification systems for Indian forests (Champion and Seth, 1968). They classified the forests into five major groups based on climatic factors (Table 2.1). These major groups have been further divided into 16 types based on temperature and moisture contents. To cover the basic needs of the population, forests in India have been exploited not only for timber, fuel and fodder extraction but have also been subjected to overgrazing, shifting cultivation and conversion to non- forestry purposes such as roads, industries, mining, irrigation, hydro electric projects, transmission lines etc. thereby contributing to deforestation and degradation. It is estimated that between 1950 and 1980, the forest area converted for other purposes was 4.3 Mha in total, with an annual rate of 0.14 Mha (Lal, 1989). For effective management of forest resources, the Forest Conservation Act (FCA) came into force in 1980, which prohibited conversion of forest land for other purposes without the prior approval of the Central Government. As a result, between 1980 and 2002 only 0.88 Mha of forest lands was converted for other purposes, at an annual rate of 0.04 Mha (Forests & Wildlife statistics of India, 2004). Hence, the reduction in the rate of deforestation over the years was from 0.14 Mha to 0.04 Mha annually.

According to the Forest Survey of India (FSI) assessment for 2002, the total forest cover in India is 67.83 Mha and the total recorded forest area 77.47 Mha (23.57% of the country’s geographical area) (FSI, 2003). The difference in the two figures is due to the fact that the recorded forest area includes all lands statutorily notified as forest though they may not necessarily bear tree cover, whereas forest cover takes into

TABLE 2.1 **Broad grouping of forest ecosystems in India and their distribution and extent**

Forest Type	Area (Mha)	% of forest area	Occurrence in States/Union Territories of India
Tropical Forests			
Tropical wet evergreen forest	4.5	5.8	Arunachal Pradesh, Assam, Karnataka, Kerala, Mizoram, Manipur, Nagaland, Tamil Nadu, Sikkim, Andaman & Nicobar Islands and Goa
Tropical semi-evergreen forest	1.9	2.5	Assam, Karnataka, Kerala, Maharashtra, Nagaland, Orissa, Tamil Nadu, Andaman & Nicobar Islands and Goa
Tropical moist deciduous forest	23.3	30.3	Andhra Pradesh, Assam, Bihar, Gujarat, Karnataka, Kerala, M.P., Maharashtra, Manipur, Meghalaya, Mizoram, Tripura, Nagaland, Orissa, Tamil Nadu, U.P., West Bengal, Andaman & Nicobar Islands, Goa and Dadra & Nagar Havelli.
Littoral and swamp forest	0.7	0.9	Andhra Pradesh, Gujarat, Maharashtra, Orissa, Tamil Nadu, West Bengal, Andaman and Nicobar Islands.
Tropical dry deciduous forest	29.4	38.2	Andhra Pradesh, Bihar, Gujarat, Haryana, Himachal Pradesh, Karnataka, Kerala, M.P., Maharashtra, Jammu & Kashmir, Punjab, Rajasthan, Tamil Nadu and U.P
Tropical thorn forest	5.2	6.7	Andhra Pradesh, Gujarat, Haryana, Himachal Pradesh, Karnataka, M.P., Maharashtra, Punjab, Rajasthan, Tamil Nadu and U.P.
Tropical dry evergreen forest	0.1	0.1	Andhra Pradesh and Tamil Nadu
Sub-Tropical Forests			
Sub tropical broad leaved hill forest	0.3	0.4	Assam and Meghalaya
Sub tropical pine forest	3.7	5.0	Arunachal Pradesh, Himachal Pradesh, Jammu & Kashmir, Manipur, Meghalaya, Nagaland, Sikkim, Haryana, U.P. and Punjab
Sub tropical dry evergreen forest	0.2	0.2	Himachal Pradesh and Jammu & Kashmir
Temperate Forests			
Montane wet temperate forest	1.6	2.0	Arunachal Pradesh, Karnataka, Manipur, Nagaland, Sikkim and Tamil Nadu.
Himalayan moist temperate forests	2.6	3.4	Himachal Pradesh, Jammu & Kashmir and Uttar Pradesh
Himalayan dry temperate forests	0.2	0.2	Jammu & Kashmir and Himachal Pradesh
Sub-Alpine & Alpine Forests			
Sub-alpine forest	–	–	Arunachal Pradesh and Himachal Pradesh
Moist alpine-scrub	3.3	4.3	Jammu and Kashmir and Uttar Pradesh
Alpine scrub	–	–	Jammu and Kashmir and Uttar Pradesh
Total	**77**	**100**	–

Source: Forest Survey of India, Ministry of Environment and Forests, Govt. of India 1995a.

account only those areas, which bear tree cover, and ignores those areas which may legally have the status of forest but have no trees.

The total forest cover includes 38.89 Mha dense forest (about 57% of the total forest cover), 28.61 Mha (about 42%) open forest and 0.45 Mha (0.14%) mangroves (FSI, 2003). The classification of density is based on crown cover viz., very dense forest (D1) with more than 70% canopy density, moderately dense forest (D2) with canopy density between 40% and 70% and open forest (D3) with canopy density between 10% and 40% (FSI, 1995a). Similarly the total recorded forest area comprises of 39.99 Mha of Reserved Forest (51.6%), 23.8 Mha of Protected Forest (30.77%) and 13.64 Mha of Unclassed Forest (17.6%). Reserved Forest is an area notified under the provisions of the Indian Forest Act (IFA) or the State Forest Acts (SFA) having a greater degree of protection. Protected Forests are also notified under the provisions of IFA and SFA but the restrictions are less severe. Unclassed Forest is an area recorded as forest but not included in reserved or protected forest category. The extent of recorded forest area and forest cover in India from 1992 to 2002 is given in Table 2.2.

TABLE 2.2 **Recorded Forest Area and Forest cover in India (1992 – 2002)**

Year	**Recorded Forest Area (Mha)**				**Forest Cover (Mha)**			
	Reserved Forests	**Protected Forests**	**Unclassed Forests**	**Total Forests**	**Dense Forests**	**Open Forests**	**Mangrove Forests**	**Total Forests**
1992	41.65 (54.43)	22.33 (29.18)	12.54 (16.38)	76.52 (23.28)	38.58 (60.31)	24.93 (38.98)	0.45 (0.71)	63.96 (19.46)
1994	41.65 (54.43)	22.33 (29.18)	12.54 (16.39)	76.52 (23.28)	36.74 (57.98)	26.13 (41.26)	0.48 (0.76)	63.34 (19.27)
1997	41.66 (54.44)	22.33 (29.18)	12.54 (16.38)	76.53 (23.28)	37.74 (59.21)	25.51 (40.03)	0.49 (0.76)	63.73 (19.39)
2000	42.33 (50.09)	21.72 (27.59)	12.79 (16.64)	76.84 (23.38)	41.40 (61.28)	25.70 (38.30)	0.45 (0.66)	67.55 (20.55)
2002	39.99 (51.61)	23.84 (30.77)	13.64 (17.61)	77.47 (23.57)	38.77 (57.16)	28.61 (42.17)	0.45 (0.66)	67.83 (20.66)

Source: FSI reports 1995a, b; 1997; 1999; 2001 & 2003 (Values in parenthesis represent percentage of the total forests)

The cumulative net carbon flux to the atmosphere due to deforestation and afforestation over the period 1880-1996 from Indian forests was estimated as 3.2 Pg C (1 Pg = 10^{15} g; Chhabra and Dadhwal, 2004). A number of recent studies have been published on the forest carbon pool (Ravindranath *et al.* 1997; Chhabra *et al*. (2002a); Haripriya, (2000); Manhas *et al.* (2006); Lal & Singh, 2000), as well as on emissions from deforestation and land use changes (Ravindranath *et al.* 1997; Chhabra and Dadhwal, 2004; Kaul *et al*. 2009) in India. The phytomass carbon pool is based on growing stock from forest inventory as the primary data. Dadhwal & Nayak, (1993) and Lal & Singh (2000), both used standard expansion and conversion factors, as prescribed in the Intergovernmental Panel on Climate Change (IPCC) guidelines for preparing national greenhouse gas inventories (IPCC, 1995), while Ravindranath *et al.* (1997) and Chhabra *et al.* (2002a) used phytomass densities and biomass expansion factors (BEF) for their estimates, and Manhas *et al.* (2006) ignored belowground biomass and branches, twigs and foliage etc.

Based on two commonly followed approaches (the ecologically-based biomass density approach and the volume-based growing stock approach), the average forest carbon densities estimated in earlier studies were in the range of 30 – 68 Mg C ha^{-1} (Table 2.3). However, there is wide variation in the estimated carbon pools and fluxes because of methodological differences, different sources of data, estimates for different years, as well as paucity of reliable country wide statistics and use of detailed global parameters for biomass estimates. The ecological studies based on biomass density approach adopted by Dadhwal and Nayak (1993) estimated the forest phytomass carbon pool as 1.99 Pg C (or 31 Mg C ha^{-1}) for the year 1985. Using the Remote Sensing (RS) based areas under different forest types and biomass densities for five crown cover levels, total (above and belowground) carbon pool for the year 1986 was estimated as 4.18 Pg C (65 Mg C ha^{-1}) (Ravindranath *et al.* 1997). Dadhwal and Shah (1997) estimated the state level forest phytomass C pools based on two remote sensing based forest inventories, biomass expansion factor for two crown density, and estimates of growing stock. The results suggest that forest phytomass C-pool which was in the range of 3.68 - 4.27 Pg C in 1982 increased by 76 - 113 Tg C (1 Tg = 10^{12} g) during the period 1982 and 1991 with an annual accumulation of 8.5 – 12.5 Tg C.

TABLE 2.3 **Summary of estimated forest biomass and C-Pool for Indian Forests**

Year	Methodology adopted	Estimated Biomass (Tg)	Carbon Pool (Pg C)	Carbon density (Mg C ha^{-1})	Ref.
1985	Field inventory of Growing stock and using single conversion factor	4432	1.99	31	[1]
1986	RS based forest area, biomass densities from literature for five crown cover levels for some of the forest types and extrapolating the same for entire India.	8372	4.18	65	[2]
1982 & 1991	State wise RS based forest area, field inventory based GS, Biomass Expansion Factors (BEF) for 2 crown density classes.	7960 8142	3.98 4.07	62 64	[3]
1993	State wise field inventory based data on growing stock, Biomass Expansion Factors (BEF) for 3 crown density classes and 4 forest categories.	8685	4.34	68	[4]
1993	Species wise forest inventory data, mean wood density of various strata and BEF ranging from 1.51 to 1.59 for different forest composition	4313	2.16	34	[5]
1984 & 1994	Strata wise estimation of GS based on forest inventories, thematic maps and vegetation maps for different density class. Wood biomass was further estimated using specific gravity and calculated GS for each state.	2398 2395	1.085 1.083	17 17	[6]
1988 & 1994	District wise RS based forest area, field inventory based GS, BEF for 2 crown density classes.	7742 7748	3.871 3.874	60.5 61	[7]
1995	Stratum wise field inventory of growing stock as reported by FSI and standard conversion factor as per IPCC guidelines.	4504	2.03	32	[8]
1992 & 2002	State-wise RS based forest area; field inventory based GS; state wise mean wood density and 2 different values of Mean BEFs calculated from earlier studies.	5253 / 6141 & 5321 / 6359	2.6 / 3.1 & 2.7 / 3.2	41/48 & 39/47	[9]

Pg C= 10^{15} g C. [1] Dadhwal & Nayak (1993); [2] Ravindranath *et al*. (1997); [3] Dadhwal and Shah (1997); [4] Chhabra *et al*. (2002a); [5] Haripriya (2000); [6] Manhas *et al*. (2006); [7] Chhabra *et al*. (2002b); [8] Lal & Singh (2000); [9] This study.

The total phytomass carbon pool of 4.34 Pg C (about 68 Mg C ha^{-1}) for the year 1992-1993 was estimated using biomass expansion factors together with growing stock volume density, for three crown density classes and four major forest types (Chhabra *et al*. 2002a). Based on the stratum wise forest inventory data, mean wood density and biomass expansion factors, the above ground carbon pool was estimated to be 2.16 Pg C (about 34 Mg C ha^{-1}) for the year 1993 (Haripriya, 2000).

Manhas *et al*. (2006) used growing stock data and specific gravity to estimate the wood (stem or bole) biomass and carbon pool of Indian forests for 1984 and 1994. Total carbon stored in Indian forests (wood only) was 1.09 Pg C and 1.08 Pg C at a density of 24.9 and 24.5 Mg C ha^{-1} for 1984 and 1994 respectively. Chhabra *et al.* (2002b) estimated the total carbon pool of 3.87 Tg C (with an average density of 61 Mg C ha^{-1}) for the year 1994, using district level remote sensing based ground inventory on growing stock volume, and biomass expansion factors based on two crown density classes. Based on the stratum wise growing stock and using single expansion and conversion factors (as prescribed by IPCC) for the year 1995, Lal & Singh (2000) estimated forest carbon pool as 2.03 Pg C (about 32 Mg C ha^{-1}).

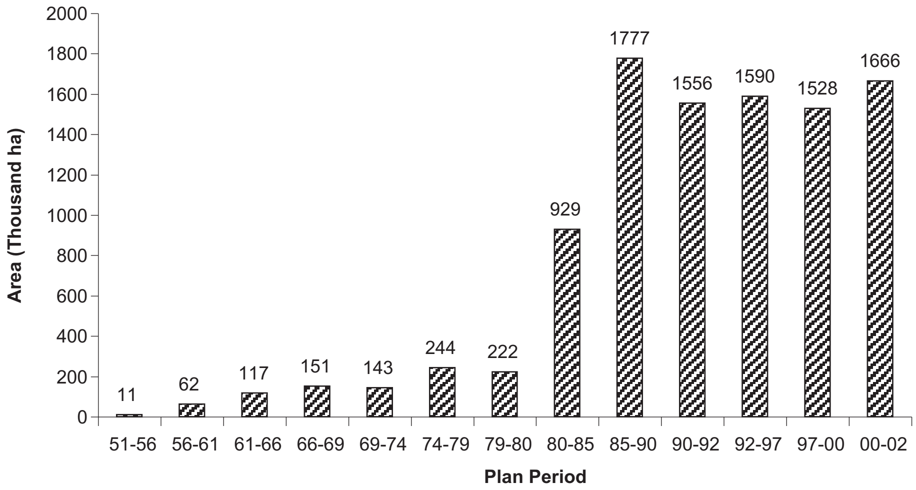

FIGURE 2.1 **The annual rate of plantation (1951-2002)**

Source: (FSI, 1999; Forest & Wildlife Statistics of India, 2004)

Forest plantations constitute a very important part of the forest resources. Due to varied agro-climatic conditions, a large number of species are planted. A lot of wood produced in India now comes from tree plantations established within and outside forest reserves. About 36 Mha of degraded and non-forest lands have been afforested during the period 1951 to 2002, as shown in Figure 2.1 (FSI, 1999; Forests & Wildlife Statistics of India, 2004). With agro forestry and policy changes in forest use, the role of trees outside forest is becoming increasingly important, but this has not been considered earlier in carbon studies.

In this paper, reported data on growing stock and forest area (FSI, 1995a, b; FSI, 2003), estimated mean wood density and biomass expansion factor for individual states were synthesized to estimate phytomass carbon pool for 1992 and 2002 and the net carbon flux over the ten year period. Next, the estimates for 2002 were compared with the results estimated by using an approach as recommended by IPCC 2006 guidelines, i.e., accounting for biomass increment and removal of wood from forests (IPCC, 2006). In India, the volume of wood extracted for timber and fuel wood is highly debated as the actual consumption exceeds the recorded production (Haripriya, 2003). Thus, for this approach, the assumed removal of wood from forests per year is subtracted only from the national estimate of phytomass carbon pool. The parameters used for estimating biomass and carbon pools can further be used as inputs to models to estimate the net carbon flux from Indian forests due to land use changes, primarily deforestation.

2.2. Materials and Methods

Forest Survey of India carries out assessment and monitoring of the forest cover of the country on a two-year cycle and publishes the findings in the form of "State Forest Reports" (SFR) on biennial basis. The data for this study has been taken from FSI on growing stock and forest area under three crown density classes (D1, D2 and D3) for various States/Union Territories (FSI 1995a & b; FSI, 2003). To estimate the state-wise phytomass carbon pool for 1992 and 2002, the overall approach was to first estimate the state wise mean density of wood, mean biomass increment and mean biomass expansion factor using a change matrix.

State-wise phytomass C-pool for 1992 and 2002 were estimated using growing stock volume, strata-wise wood density and biomass expansion factors using the following equation:

$$C_y = (V \times D \times F_j \times 0.5) \qquad \ldots\ldots\ldots\ldots\ldots\ldots.. \qquad (1)$$

Where, C_y (Pg C) is the forest phytomass C-pool for year 1992 and 2002, V is the growing stock volume (000' m^3) as reported by FSI for the year 1992 and 2002; D is the state-wise mean wood density (Mg per m^3) as estimated from Haripriya (2000) and F_j is the estimated biomass expansion factors for (j = 1 & 2 based on Haripriya, 2000, and Chhabra *et al*. 2002a, respectively). The IPCC default value of 0.5 has been used for the carbon fraction of dry matter. In the second methodology based on IPCC 2006 guidelines, the 1992 estimate was retained as above and the phytomass C-pool for 2002 was estimated by considering biomass increment and biomass removal during 1992-2002. The changes in carbon pool during the 10-year period were estimated using the gain and loss method (IPCC, 2006).

$$\Delta C - \Delta C_G - \Delta C_L \quad \ldots\ldots\ldots\ldots\ldots\ldots.. \quad (2)$$

Where, ΔC is the annual carbon stock change in the pool (Mg Cyr^{-1}), ΔC_G is the annual gain of carbon (Mg C yr^{-1}) and ΔC_L is the annual loss of carbon (Mg C yr^{1}). Gains can be attributed to growth (increase in biomass) and to transfer of carbon from one pool to another (e.g., transfer of carbon from the live biomass carbon pool to the dead organic matter pool due to harvest or natural disturbances). Losses can be attributed to transfers of carbon from one pool to another (e.g., the carbon in the slash during a harvesting operation is a loss from the above-ground biomass pool), or emissions due to decay, harvest, burning, etc. The carbon cycle includes changes in carbon stocks due to both continuous processes (i.e., growth, decay) and discrete events (i.e., disturbances like harvesting, insects, and fire). The parameters used for the estimation of phytomass carbon pool were estimated at the state level, whereas the biomass extraction and plantation figures given were applied at national level since state level data was not available. Factors such as shifting cultivation, natural decay of wood, forest fires and release of carbon from soil were not considered in this study.

Haripriya (2000) estimated the stratum wise biomass expansion factor and mean wood density (Mg/m^3) for 21 forest strata. These values together with the growing stock are used to calculate the state wise mean density of wood (D) and mean biomass expansion factor (F_1) using a change matrix. Similarly, using growing stock volume density (m^3/ha) and biomass density (Mg/ha) from Chhabra *et al*. (2002a), biomass expansion factor (F_2) was calculated state-wise separately for dense and open forests. The estimated values of annual increment, wood density, biomass expansion factor are given in Table 2.4.

TABLE 2.4 Estimated State/Union Territory wise Mean Annual Increment (I)[a], Wood Density (D)[b] and biomass expansion factor (F_1)[c] & (F_2)[d] and biomass increment (B)[e].

States	Mean I (Mg/ha^{-1})	Mean D (Mg/m^3)	Total Forests F_1	Dense Forests F_2	Open Forests F_2	Biomass Increment (B) 1992-2002 (Tg)		
						Dense Forests	Open Forests	Total Forests
Andhra Pradesh	0.763	0.79	1.59	1.88	2.55	18.8	6.0	24.8
Arunachal Pradesh	1.341	0.77	1.58	1.59	2.20	73.8	7.2	81.0
Assam	0.974	0.79	1.58	1.51	1.89	14.4	4.1	18.5
Bihar	0.675	0.71	1.58	2.20	2.94	9.4	3.6	13.0
Gujarat	0.743	0.71	1.59	2.04	2.53	5.5	1.9	7.4
Haryana	0.695	0.74	1.59	2.90	4.20	0.4	0.2	0.6
Himachal Pradesh	1.271	0.47	1.52	1.11	1.58	12.1	2.0	14.1
Jammu & Kashmir	1.434	0.43	1.51	1.11	1.15	15.9	5.6	21.5
Karnataka	1.023	0.79	1.59	1.81	2.74	25.2	3.9	29.1
Kerala	1.103	0.80	1.59	1.79	1.86	10.3	1.4	11.7
Madhya Pradesh	0.730	0.75	1.59	2.11	2.55	60.7	14.4	75.2
Maharashtra	0.784	0.70	1.58	1.97	2.77	21.3	6.0	27.4
Manipur	1.060	0.76	1.57	1.66	2.63	6.1	4.9	11.0
Meghalaya	0.838	0.76	1.53	1.42	1.90	4.5	3.5	8.0
Mizoram	0.714	0.79	1.57	1.91	2.70	4.1	3.6	7.7
Nagaland	1.245	0.80	1.58	1.61	2.30	6.0	4.5	10.5
Orissa	0.758	0.72	1.59	2.03	2.69	20.5	6.2	26.8
Punjab	0.695	0.70	1.57	3.51	4.35	0.5	0.2	0.8
Rajasthan	0.667	0.76	1.59	3.33	4.58	3.0	2.7	5.7
Sikkim	1.443	0.75	1.58	1.47	2.10	3.4	0.4	3.9
Tamil Nadu	0.770	0.80	1.59	2.24	2.93	7.8	2.8	10.6
Tripura	0.800	0.77	1.59	2.44	2.74	2.3	1.1	3.5
Uttar Pradesh	1.065	0.63	1.56	1.45	2.32	25.8	4.9	30.7
West Bengal	0.821	0.71	1.58	2.03	2.18	4.8	1.2	6.1
Goa Daman & Diu	0.889	0.76	1.59	1.67	3.40	1.1	0.1	1.2
Andaman & Nicobar	1.047	0.71	1.59	1.67	1.70	7.4	0.1	7.5
D & N Haveli	0.800	0.69	1.59	2.25	3.84	0.1	0.0	0.1
All India						**365**	**93**	**458**

Source: [a] derived from Lal and Singh (2000) and FSI (1995a, b)
[b,c] derived from Haripriya (2000) and FSI (1995a, b)
[d] derived from Chhabra et al. (2002a) and FSI (1995a, b)
[e] derived from forest inventories.

In all the previous eight SFR assessment reports, forest cover was classified into 2 broad categories: dense forest and open forest. Dense Forest included all lands with a forest cover of trees with a canopy density over 40 percent while open forest showed all lands with a forest cover of trees with a canopy density between 10 to 40 percent. In the 2002 assessment report, the earlier category of dense forest was sub-divided into two classes "very dense forest" (where canopy density is above 70 percent) and "moderately dense forest" (where canopy density lies between 40 and 70 percent).

The state-wise forest cover area and growing stock data pertaining to the study year 1992 and 2002 was obtained from state forest reports under three density classes D1 (canopy density more than 70%), D2 (canopy density between 40% and 70% and D3 (canopy density between 10% and 40%) (FSI, 1995a & 2003). For the purpose of this study the area under D1 and D2 were added together under dense category.

Lal & Singh (2000) have published per hectare value of annual biomass increment for various natural forest types for the year 1995. The area occupied by 16 forest types in different states is reported in the state forest report (FSI, 1987). Both these reported values were used to estimate the state-wise mean annual increment in tons per hectare. The mean annual biomass increment among the states varied between 0.67 Mg ha^{-1} for Rajasthan to 1.4 Mg ha^{-1} for Sikkim. The total biomass increment for the period 1992-2002 was estimated using forest area and the annual increment (dry matter, in Mg ha^{-1}) multiplied by number of years between two successive estimates for 4 time periods (i.e., 1994, 1997, 2000 & 2002).

The 10-year biomass increment was estimated as 458 Tg using equation 3. Arunachal Pradesh contributes maximum increment in biomass (81 Tg) followed by Madhya Pradesh (75 Tg) in the 10 year period:

$$B = \sum_{i=1}^{27} A \times N \times I \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (3)$$

Where B (Tg) is the total biomass increment, A (Mha) is the forest area for each state for 4 time periods, when N is the number of years between two successive estimates and I is the annual increment in biomass (Mg dm ha^{-1}) (Table 3).

Plantations are known to have higher biomass increment i.e., estimated national average being 3.2 Mg per hectare per year (Lal & Singh, 2000). To account for higher rate of increment in plantation, national level C-pool was corrected by proportionate correction of increment to the plantation area of 10 Mha for 1992-2002. The plantation rate was corrected for short rotation species only where plantation area for last 10 years was used with the success rate of 0.70. A plantation correction of 408 Tg of carbon was added nationally while estimating the final carbon pool of Indian forests for the year 2002 using the following relation:

$$P_c = A_p \text{ x } (B_p - B_{nf}) \text{ x n x } 0.5 \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

where, P_c (Tg C) is the correction for plantation pool; A_p (Mha) is the plantation area in last 10 years with succession rate of 0.70 ; B_p and B_{nf} are the biomass increments of plantation and natural forests respectively and n is the total number of years.

India's National Forest Policy (1988) aims at maintaining 33 percent of country's geographical area under forest and tree cover. FSI has been assessing country's forest cover since the 1980's using data from remote sensing satellites on a two-year cycle but tree cover due to a substantial number of trees not captured by the satellite data was estimated and reported for the first time in the 2001 assessment. This exercise, with much better inventory data on tree cover, has been continued in the 2003 assessment as well. It is important here to define "Tree Cover" and "Trees Outside Forests" (TOF). TOF means all tree crops growing outside recorded forest area. Whereas, tree cover, refers to the area covered by crown of trees that is too small to be delineated by digital interpretation of remote sensing data used for forest cover delineation. Thus, trees included in tree cover constitute only a part of TOF (FSI, 2003). An estimated 2.68 billion trees outside forests contribute an equivalent additional area of 9.99 Mha. Thus, the total forest and tree cover of the country so estimated comes out to be 77.82 Mha constituting 23.68% of its geographical area (FSI, 2003). The SFR 2003 reports the growing stock volume estimates for TOF at the state level. The total growing stock of wood is estimated to be 1632 million m^3 outside recorded forest area (FSI, 2003). The phytomass carbon pool of TOF was estimated using the approach given in equation (1).

2.3. Results and Discussion

2.3.1. Forest cover change

The forest cover as estimated using RS data in 1992 was 63.96 Mha and it increased to 67.83 Mha in 2002 (FSI, 1995a & 2003). However crown density estimates indicate that the dense forest cover changed from 38.58 Mha in 1992 to 38.77 in 2002 and open forest cover changed from 24.93 Mha in 1992 to 28.61 Mha in 2002. Thus, indicating an overall higher proportional contribution of open forest category. A study of net change in forest cover between 1992 and 2002 (Table 2.2) shows a deforestation of 0.79 Mha and afforestation of 4.64 Mha thereby, increasing the total forest cover by 3.87 Mha. Whereas, inter-comparison of forest covers at the district level, in different states highlights that overall large patches of forest cover has increased (about 0.7 Mha per year) and also about 0.3 Mha per year of deforestation has taken place.

The state-wise analysis of forest cover change indicates that for states of Assam, Gujarat, Himachal Pradesh, Jammu & Kashmir, Karnataka, Sikkim and Madhya Pradesh decreased dense forest cover is accompanied by increased open forest. Contrary to this, in Manipur, Meghalaya, Mizoram, Nagaland and Tripura decreased open forest cover is complemented by increased dense forest cover. The states of Bihar, Haryana, Kerala, Maharashtra, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh, West Bengal and Goa, Daman & Diu showed an increase in both categories. Madhya Pradesh and Andhra Pradesh are the two main states showing maximum reduction in the forest cover between 1992 and 2002. The presence of economical species such as *Shorea robusta* Gaertn. f., *Madhuca indica* J.F. Gmel, *Emblica officinalis* Gaertn, *Terminalia alata* Heyne ex Roth, *Borassus flabellifer.* S. etc. is the major cause of disturbance in these forests (Manhas *et al*. 2006).

2.3.2 Growing stock

The growing stock estimates for 1992 and 2002 by FSI are 4741 million m^3 and 4782 million m^3. The growing stock data for two periods were independently used with mean wood density (D) and biomass expansion factor (F_1/F_2) for two estimates of phytomass C-pool each for 1992 and 2002. Using directly 1992 and 2002 growing stock data and conversion factors (approach 1) the phytomass C-pool in 1992 was estimated as 2626 and 3071 Tg C and in 2002 was estimated as 2660 and 3180 Tg C. This suggests nationally phytomass C-pool was a net sink in the range of 34 to 109 Tg C or 3.4 – 10.9 Tg C yr^{-1} for the 10-year period. Further, the predicted phytomass carbon pool for 2002, using the IPCC 2006 methodology based on the increment and removal approach (approach 2), was estimated as 2668 and 3112 Tg C with an average density of 43 Mg C ha^{-1}. Comparison of the phytomass C-pool estimates from both the approaches suggest that Indian forests are sequestering carbon and indicate a small annual national sink of 4 Tg C yr^{-1} (or 42 Tg C in 10-year period). Despite the marginal decrease in the percentage of dense forest cover between 1992 and 2002, the growing stock has registered a slight increase during this period. The increase in growing stock may be attributed to the improvement in density, without increase in area.

2.3.3 Biomass Expansion Factors

Biomass expansion factors were used to convert stand volume to aboveground biomass and account for the non-commercial components such as branches, twigs, bark, stumps and foliage. Brown *et al.* (1989) and Hall and Uhlig (1991) report these factors to be in the range 1.14 to 1.6. However, Brown *et al*. (1989) related biomass expansion factors to volume and density and the same approach was used in Chhabra *et al*. (2002a), to convert growing stock in three density classes to an estimate for the forest C-pool. Haripriya (2000) used regression equations for species such as teak (*Tectona grandis* Linn. f.*),* sal *(Shorea robusta* Gaertn. f.*)* and chir pine (*Pinus roxburghii*). The biomass expansion factors used were 1.59 for broad-leaved species, 1.51 for conifers and 1.55 for hardwoods mixed with conifers, similar to Hall and Uhlig (1991) and Brown *et al*. (1989). Biomass expansion factors were also estimated using the ratio of biomass density and growing stock volume density for three crown density classes of forest cover in each state as published in Chhabra *et al.* (2002a). The latter is based on log relation between growing stock volume density and biomass expansion factor (Brown *et al*. 1999). The approach of using density dependent biomass expansion factors from (Chhabra *et al*. 2002a) provided conversion factors in range of 1.1 – 2.4 for dense forests and 1.15 – 4.6 for open forests. The biomass expansion factors used in this study are within the range as proposed by earlier authors for tropical forests. The results from both the approaches strongly suggest that accumulation in aggrading forest in the study period have resulted in an increase in the phytomass carbon pool and furthermore indicate an annual sink of 4 Tg C at the national level. For India, Ravindranath *et al*. (1997) has estimated a marginal net sequestration of 5 Tg C for the reference year 1986. However, there are additional factors mentioned below that need to be considered before the net carbon balance for Indian forests and trees can be derived.

2.3.4. Wood extraction

In India, the volume of reported extraction of timber and fuel wood from forests is much lower than the actual consumption (Haripriya, 2003). There are different estimates for fuel wood such as 235 million m^3 per year (Ravindranath *et al*. 1997), 303 million m^3 for 1996 (FSI, 1997), 297 million m^3 for 2000 (FAO, 2002). Similar to varying estimates on fuel wood consumption, considerable difference of opinion on what fraction comes from forests exists. The National Sample Survey Organisation (NSSO) of the Ministry of Statistics and Programme Implementation estimated that annual requirement of fuel wood is 201 Tg or 251 million m^3, out of which approximately 51% (103 Tg) comes from forests (including plantation) and rest 49% (98 Tg) from farm forestry and other wooded lands outside forests. Most of the fuel wood studies conducted in India focused on the consumption aspect rather than the supply and source aspect. Since no reliable information is available on production and consumption of wood from forests, the total annual demand of wood is between 324-434 million m^3, where as the total sustainable availability of wood from all sources (public and private) is only 127 million m^3 per year (http://envfor.nic.in/nfap/Unff2.pdf). For the purpose of this study, it was assumed that approximately 23 million m^3 of timber and 126 million m^3 of fuel wood were extracted from the Indian forests annually (Haripriya, 2001). The estimated total phytomass carbon removed from the forests was 59.6 Tg carbon per year or 596 Tg C in the ten year period from 1992 to 2002, which was subtracted from the national total only. This approach has not been adopted in earlier studies, as availability of reliable data is limited. Thus, the projected phytomass carbon pool for the year 2002 was in the range 2668 – 3112 Tg C with an average carbon density of 43 Mg C ha^{-1} using the increment and removal approach.

2.3.5. Role of Trees Outside Forests

TOF include trees in cities, on farms, along roads, canals, railway tracks and in many other locations, which by definition are not forests. Trees outside forests have been making a major contribution in meeting the needs of timber and fuel wood. An estimated 2.68 billion trees outside forests contribute an equivalent additional area of 9.99 Mha. Thus, the total forest and tree cover of the country so estimated comes out to be 77.82 Mha constituting 23.67% of its geographical area (FSI, 2003). The total growing stock of wood in India is estimated to be 6414 million m^3 comprising 4782 million m^3 inside forests and 1632 million m^3 outside recorded forest area (FSI, 2003). Maximum growing stock in TOF is observed in Andhra Pradesh followed by Maharashtra and Gujarat. Most of the studies conducted so far have not considered the role of trees outside forests in carbon balance. Trees outside forests store about 934 Tg C or 4 Mg C ha^{-1}, in addition, to the Indian forests.

2.3.6. Role of soil as deforestation area is large

Soil organic carbon is the largest terrestrial carbon reservoir. Approximately 40% of the global carbon inventory resides in forest ecosystems and dynamics of forest soil organic carbon (SOC) has significant implications to global carbon budget. Although there are some recent studies on Indian forest phytomass C pool (Ravindranath *et al*. 1997; Chhabra *et al*. 2002a), litter fall (Dadhwal *et al*. 1997) and soil organic carbon (Chhabra *et al*. 2002c) but more refined and accurate estimates of soil organic carbon pool in different Indian forest types are required for computing soil carbon cycle changes due to deforestation in India.

2. 3.7. Role of stored wood products

Carbon is released from harvested materials at all stages of progressing, product use and final disposal. Due to burning of fuel wood, 90% of the harvested carbon from forests is emitted in the first year itself, and during the production process, 9% is lost as process energy (Haripriya, 2001). Of the large mass of carbon harvested in India in 1994, only 0.8% (515 Gg C out of 68880 Gg C) is remaining in the wood products in use at the end of 100 years. As fuel wood is the main source of energy in India, the amount of carbon stored into wood products is very small. Improving the processing efficiencies and increasing the durability of small and medium lifespan wood products and providing sustainable sources of energy in order to substitute for unit of carbon emitted due to burning of fossil fuels can increase the carbon sequestration into wood products.

2.3.8. Carbon loss due to forest degradation

Deforestation and other changes in land use cause significant exchanges of carbon between the land and the atmosphere. In addition to carbon release from deforestation or clear cutting, degradation of existing forests also contributes to carbon release from grazing, fire, death due to disease and pests, illegal removal of timber, non-sustainable harvest of firewood or timber, etc. Evidence of this is available from various studies (Manhas *et al*. 1996; Ravindranath *et al*. 1997; Haripriya, 2003; Chhabra and Dadhwal, 2004; Haripriya *et al*. 2006; Kaul *et al*. 2009). Ravindranath *et al*. (1997) reported that for the reference year 1986, a total of 27.6 Tg C is emitted from the Indian forests annually as a result of deforestation and 12.87 Tg C from degraded forests. Manhas *et al*. (1996) estimated that between 1984 and 1994 about 17.22 Tg wood biomass and 10.69 Tg C was removed at the rate of 1.72 Tg yr^{-1} and 1.07 Tg Cyr^{-1} respectively, from the north-eastern states. The cumulative area subject to shifting cultivation in north-eastern states during the period from 1987 to 1997 was 1.73 Mha (FSI, 1999). FSI (2003) assessment reveals that the practice of shifting cultivation in north-eastern states has affected forest cover to an extent of 0.55 Mha between the period 2001-2003. Maximum effect due to shifting cultivation was observed in Nagaland, followed by Arunachal Pradesh, Manipur, Mizoram and Meghalaya. However, due to rapid regeneration of abandoned shifting cultivation areas, where vegetation comes up quickly, the net change in forest cover of these states between 2001 and 2003 assessment showed a net gain of 0.39 Mha (FSI 2003). In India, grazing and forest fires are one of the factors increasingly contributing in the degradation process. On an average, 54.7% of forests are affected by fires and 72.1% of the forest area is subjected to grazing (Manhas *et al*. 2006). Kaul *et al*. (2009) estimated that the annual change in carbon stocks in biomass due to forest land conversion to cropland and waste land was 9.4 Tg C during 1982-1992 and 3.02 Tg C during the period from 1992-2002.

The phytomass C pool estimates are associated with significant uncertainties due to deficiencies in data, volume biomass conversion approach and the extent of the effect of human activity on ecosystems and environment, because many ecological processes depend on the carbon cycle. Comparison of our state level forest phytomass C pool estimates with earlier studies is shown in Figure 2.2. The comparison shows that the earlier studies have higher estimates of the phytomass carbon density than ours. This may be due to estimation of only wood biomass in our study or due to

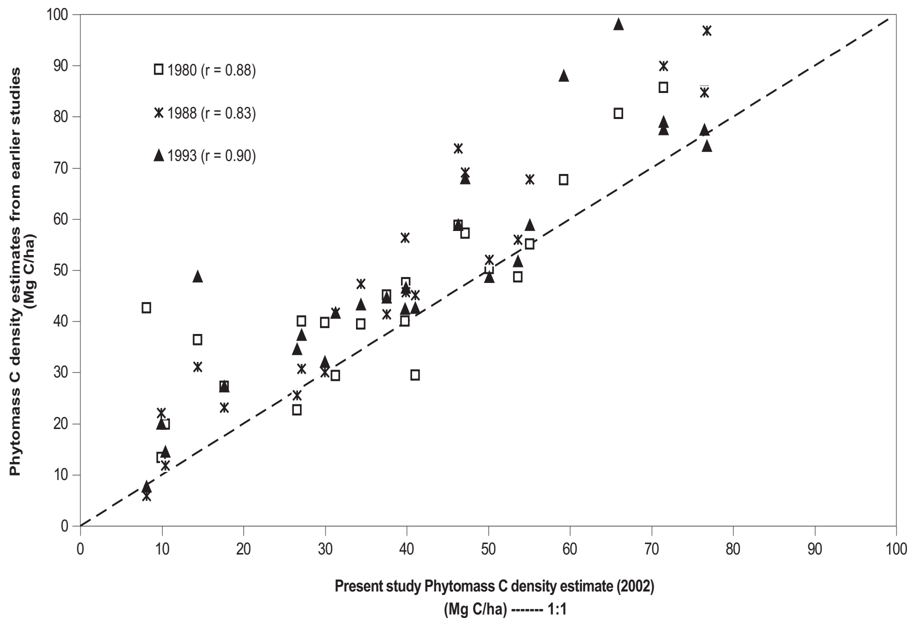

FIGURE 2.2 **Comparison of state-level forest phytomass C density estimates for 2002 with (a) Richards & Flint (1994) estimate for 1980; (b) Chhabra *et al*. (2002b) for 1988, (c) Chhabra & Dadhwal (2004) for 1993.**

higher percentage of degraded forest cover in India. Chhabra & Dadhwal (2004) used the growing stock volume density with an additional biomass expansion factor for bamboo. This estimate was ~ 21% higher than the present estimate. The correlation coefficient, r was 0.85, 0.83 and 0.90 with Richards & Flint (1994) estimate for 1980; Chhabra *et al*. (2002b) for 1988, and Chhabra & Dadhwal (2004) for 1993.

2.4. Conclusion

In spite of the fact that biomass demands and pressure on Indian forests continue to grow because of increasing population, the conversion of forest lands for other uses has actually declined since 1980. This is mainly due to enforcement and effective implementation of measures to control deforestation of our natural forests and ensure rehabilitation of major forest areas.

The results indicate that the predicted phytomass carbon pool for 2002, using the IPCC 2006 methodology based on the increment and removal approach, was in the range 2668 – 3112 Tg C with an average density of 43 Mg C ha^{-1} and using directly 2002 growing stock data and conversion factors it was estimated as 2660 - 3180 Tg C with an average density of 43 Mg C ha^{-1}. Thus, it is concluded that Indian forests are sequestering carbon when the estimates of phytomass carbon pool estimates of 1992 and 2002 are compared. The results from both the approaches strongly suggest that accumulation in aggrading forest in the study period have resulted in an increase in the phytomass carbon pool and indicate a small annual sink nationally of 4 Tg Cyr^{-1}. The estimated C-pool for trees outside forests is 934 Tg C indicating a national average tree C density of 4 Mg C ha^{-1} in non-forest area in contrast to an average density of 43 Mg C ha^{-1} in forests. However, there are additional factors mentioned earlier that also need to be considered before net carbon balance for Indian forests and trees is estimated. It is clear from the entire national, state and district level studies conducted so far that there are several fuel wood sources but the exact contribution from each source is not known. A major segment of the rural population gathers fuel wood and other bio-fuels free of cost and therefore accurate records of removal and consumption are not maintained. Since the per capita consumption of fuel wood is a dynamic entity and varies in time and space, per capita estimates of rural and urban fuel wood consumption are also not accurate. Moreover, there exists a large amount of wood resource outside the forests and accurate information about these trees is a pre-requisite for their proper management.

In spite of high pressure, forest biomass currently is not a very large source of carbon dioxide in India. This has also been concluded in studies such as Ravindranath *et al.* (1997) and Chhabra *et al*. (2002b). This is also supported by Kauppi *et al*. (2006) who have found forests to be sequestering carbon in many parts of the world. Since deforestation continues and soil also continues to lose C, the net C release could be higher. However in 10-year period, 3.85 Mha have been added, 0.79 Mha is deforestation while unrecorded extraction could be much higher. Thus, model studies and spatial analysis is needed to estimate source and sink of carbon with greater confidence. Our results provide an improvement over the previous estimates as they include biomass increment and removal at the national level. The mismatch between the periods of image acquisition for remote sensing based inventories and field inventory of growing stock by FSI may introduce uncertainty in the carbon estimates. Thus, comparable year to year growing stock estimates are not available and constant carbon density for open and dense forest category is usually assumed. However, due to continuous harvest or deforestation as well as afforestation, constant density is not likely to hold.

The Ministry of Environment and Forests (MoEF, 1999) estimates total plantation area, i.e., as forests, wastelands, village commons, and road/canal side and farmers lands. The road/canal side and farmers land plantation will be reflected in trees outside forests. In addition due to short rotation plantation (7-10 years), species are clear felled and the area is replanted. In cumulative area of plantations, replanted areas are counted doubly and areas of failed plantations are also included. Uncertainty therefore exists in the actual area of plantations. Chhabra *et al*. (2002b) therefore, suggested that if estimates are obtained at district level/ grid wise more refined numbers would be generated. Direct use of plantation area would give rise to larger overestimates and we aim to produce conservative estimate in our study.

The use of different biomass expansion factors is another major contributor to the uncertainty in phytomass carbon estimates. Results indicate that use of common BEF's can underestimate the above ground biomass as Brown *et al*. (1989) have demonstrated BEF is related to growing stock volume density. Also using different biomass expansion factors for dense and open forest categories resulted in low and high forest phytomass carbon estimates, indicating that many states which have large forest area in dense category the carbon densities are low (Dadhwal & Shah, 1997). This reflects the large pressure and use of forests in India. The biomass expansion factors used for our study are species based in dense and open density classes of Indian forest types. It is required to develop expansion factors based on Indian data to represent various forest types or species specific in order to reduce the uncertainties and improve the estimates of forest phytomass C-pools and net C flux in Indian forests. Forest carbon density changes as a result of succession, growth, harvesting, and clearing of forests for non-forest purposes and natural disturbances like fires, insect and pest outbreaks or changes in climate. In a developing country like India, because of increasing population density, forest degradation will continue thereby reducing forest carbon density and releasing carbon into the atmosphere. However, proper management of degraded forests will result in significant increase in carbon sequestration by these forests.

Chapter 3

Carbon storage and sequestration potential of selected tree species in India

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ABSTRACT

A dynamic growth model (CO2FIX) was used for estimating the carbon sequestration potential of sal (*Shorea robusta* Gaertn. f.), Eucalyptus (*Eucalyptus tereticornis* Sm.), poplar (*Populus deltoides* Marsh), and teak (*Tectona grandis* Linn. f.) forests in India. The results indicate that long-term total carbon storage ranges from 101 to 156 Mg C ha^{-1}, with the largest carbon stock in the living biomass of long rotation sal forests (82 Mg C ha^{-1}). The net annual carbon sequestration rates were achieved for fast growing short rotation poplar (8 Mg C ha^{-1}yr^{-1}) and Eucalyptus (6 Mg C ha^{-1} yr^{-1}) plantations followed by moderate growing teakforests (2 Mg C ha^{-1} yr^{-1}) and slow growing long rotation sal forests (1 Mg C ha^{-1} yr^{-1}). Due to fast growth rate and adaptability to a range of environments, short rotation plantations, in addition to carbon storage rapidly produce biomass for energy and contribute to reduced greenhouse gas emissions. We also used the model to evaluate the effect of changing rotation length and thinning regime on carbon stocks of forest ecosystem (trees + soil) and wood products, respectively for Sal and Teak forests. The carbon stock in soil and products was less sensitive than carbon stock of trees to the change in rotation length. Extending rotation length from the recommended 120 to 150 years, increased the average carbon stock of forest ecosystem (trees + soil) by 12%. The net primary productivity was highest (3.7 Mg ha^{-1}yr^{-1}) when a 60-year rotation length was applied but decreased with increasing rotation length (e.g., 1.7 Mg ha^{-1}yr^{-1}at 150 years). Goal of maximum carbon storage and production of more valuable saw logs can be achieved from longer rotation lengths. ‘No thinning’ has the largest biomass, but from an economical perspective, there will be no wood available from thinning operations to replace fossil fuel for bioenergy and to the pulp industry and such patches have high risks of forest fires, insects etc. Extended rotation lengths and reduced thinning intensity could enhance the long-term capacity of forest ecosystems to sequester carbon. While accounting for effects of climate change, a combination of bioenergy and carbon sequestration will be best to mitigation of CO_2 emission in the long term.

Key words: CO2FIX, Eucalyptus, Teak, Poplar, Sal, Forest simulation model, Thinning, Rotation length.

3.1. Introduction

Forest vegetation and soils constitute a major terrestrial carbon pool with the potential to absorb and store carbon dioxide (CO_2) from the atmosphere. The CO_2 source and sink dynamics as trees grow, die, and decay are subjected to disturbance and forest management. Evidence of climate change linked to human-induced increase in greenhouse gas (GHG) concentrations is well documented in international studies (IPCC, 2001; 2007). To contribute to reduction of GHG emissions, and to partly offset deforestation, the Kyoto protocol (KP) explicitly considered reforestation and afforestation activities for carbon sequestration accounting (IPCC, 2007). The recognized importance of forests in mitigating climate change has led countries to study their forest carbon budgets and initiate the assessment of enhancing and maintaining carbon sequestration of their forests resource. The total global technical potential for afforestation and reforestation activities for the period 1995–2050 is estimated to be between 1.1 and 1.6 Pg C (1 Pg = Peta gram, 10^{15} g) per year, of which 70% could occur in the tropics (IPCC, 2000). Afforestation and reforestation are seen as potentially attractive mitigation strategies, as wood production and carbon storage can be combined. Several carbon budget models of different complexity have been developed and used to account for forest C dynamics (e.g. Parton *et al*. 1987; Kurz *et al*. 1992; Kimmins *et al*. 1999; Price *et al*. 1999; Karjalainen *et al*. 2002; Peng *et al*. 2002; Seely *et al*. 2002; Masera *et al*. 2003). Some of these studies not only account for the carbon in the forest ecosystem but also for the carbon contained in the harvested wood products (Burshel *et al*. 1993; Karjalainen *et al*. 1994, 2002 and 2003; Harmon *et al*. 1996; Pingoud *et al*. 2001; Skog and Nicholson 1998; Winjum *et al*. 1998; Masera *et al*. 2003).

Studies of Indian forests as part of the national forest carbon balance (e.g. Ravindranath *et al*. 1997; Haripriya, 2000; Chhabra and Dadhwal, 2004; Manhas *et al*. 2006; Gupta, 2009 and Kaul *et al*. 2009) have examined strata and state/regional forest area changes. Their results range from the finding that the forests are a major source to the finding that they are a sink for atmospheric carbon. Using a simple book-keeping approach, Chhabra and Dadhwal (2004) estimated that the cumulative net carbon flux from Indian forests (1880–1996) due to land use changes (deforestation, afforestation and phytomass degradation) was 5.4 Pg C with the mean annual net C flux as 9.0 Tg (1 Tg = Tera gram, 10^{12} g) C yr^{-1}. Kaul *et al*. (2009) indicated that the Indian forest sector acted as a small source of carbon during the period 1982–1992 with the annual net C flux due to land use changes estimated as 5.65 Tg C yr^{-1}. For India, a marginal net sequestration of 5 Tg C for the reference year 1986 and of 1.09 Tg C for 2002 has been estimated by Ravindranath *et al*. (1997) and Kaul *et al*. (2009) respectively. The mitigation potential of the forestry sector, based on a biomass-demand based scenario, using short or long-term commercial forestry option is estimated to be 122 Tg C for the period 2000-2012 (Ravindranath *et al*. 2002). Further, species-specific carbon sequestration potential studies have provided entirely different estimates depending upon various factors like weather conditions, location and management activities (Negi and Chauhan, 2002; Negi *et al*. 2003; Singh, 2003).

UNFCCC has recognized the importance of plantation forestry as a greenhouse gas mitigation option, as well as the need to monitor, preserve and enhance terrestrial C stocks (Updegraff *et al*. 2004). In addition, production from plantation forests may relieve pressure on timber extraction from natural forests, and thus contribute to forest conservation. Globally, the annual planting rate is 4.5 Mha, with Asia and South America accounting for 89% (Fang *et al*. 2007). Large parts of India offer good growing conditions, good rainfall and water resources, a tropical climate and ample sunshine, so that trees may grow fast. Forest plantations (e.g. Eucalyptus, poplar, Acacia etc) constitute a very important part of the forest resources as large proportion of wood produced in India comes from tree plantations established both within and outside the forest reserves. About 36 Mha of degraded and non-forest lands have been afforested during the period 1951 to 2002, as shown in Figure 3.1 (FSI, 1999; Forests & Wildlife Statistics of India, 2004). According to the records of the National Afforestation and Eco-development Board (NAEB) of the Ministry of Environment and Forests of the Government of India, the cumulative area under forest plantations up to 2005-2006 was 42.17 Mha (Pandey, 2008). Using recent remote-sensing based estimates of tree cover and growing stock outside forests in India, the estimated 2.68 billion trees outside forests contribute to an additional national average tree carbon density of 4 Mg C ha^{-1} in non-forest area, in comparison to an average density of 43 Mg C ha^{-1} in forests (Kaul *et al*. 2010a). However, there is a large variation in the carbon sequestration potential of different plantation species and there are varying estimates of the carbon sequestration rates of common plantation species (FAO, 2003a; Negi and Chauhan, 2002).

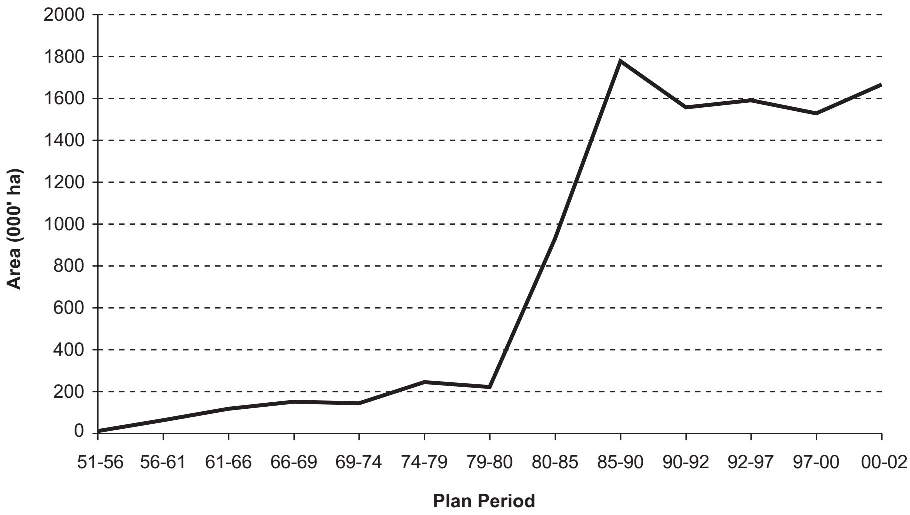


FIGURE 3.1 **Indian Government economic plan-wise annual rate of plantation (1951-2002)**

Source: (FSI, 1999, Forests & Wildlife Statistics of India, 2004)

Soil organic carbon (SOC) also plays a very significant role in the global carbon cycle, as it is the largest terrestrial carbon pool. Soil can be a source (CO_2, CH_4 and N_2O) or sink (CO_2 and CH_4) of greenhouse gases depending on land use and management (Lal, 1999). The total SOC pools in Indian forests have been estimated as 4.13 Pg C (top 50 cm) to 6.81 Pg C (top 1 m soil depths) for the period 1980-1982 (Chhabra *et al*. 2002c). Based on the national and regional soil carbon densities, Indian forest SOC pool estimates are in the range 6.7 to 9.8 Pg C (Dadhwal *et al*. 1998; Jha *et al*. 2003). Based on different forest types in India, the national average of soil organic carbon per ha in forest soil was estimated as 183 Mg C ha^{-1} (Jha *et al*. 2003).

To assess the potential of additional carbon sequestration by forest management as part of climate change mitigation strategies, it is necessary to understand the carbon storage in forest biomass, soil and wood products, and the interactions between these compartments. Forest management interferes with carbon storage through choice of rotation length, thinning intensity, stand density and spacing, and silvicultural practices such as coppicing and soil preparation etc., and may cause both increases and decreases in carbon stocks in forest biomass. For a proper evaluation of the potential for carbon storage, it is important to distinguish these options in relation to species and silvicultural treatment.

In this study, we used a dynamic model of carbon storage in forests, CO2FIX v. 3.1 (Masera *et al*. 2003; Schelhaas *et al*. 2004) to investigate the full carbon cycle of some important species in natural and short rotation plantation forestry in India. These are sal (*Shorea robusta* Gaertn. f.) as representative of natural forests, and teak (*Tectona grandis* Linn. F.), Eucalyptus (*Eucalyptus tereticornis* Sm.) and poplar (*Populus deltoides* Marsh) as exotic plantation species. The CO2FIX model also examines the effect of various thinning intensities and altered rotation length on the standing biomass and C stock of long rotation and short rotation plantation forests.

3.2 Materials & Methods

3.2.1. The model CO2FIX

The CO2FIX stand level simulation model is a tool which quantifies the carbon stocks and fluxes in forest biomass, the soil organic matter and the wood products chain, essentially using a bookkeeping approach in which biomass accumulation is converted to carbon sequestration and storage. The model calculates the carbon balance with a time-step of one year. Basic input is stem volume growth and corresponding allocation patterns to the other tree compartments (foliage, branches and roots). Carbon stocks in living biomass are calculated as the balance between growth (accumulation) on the one hand and turnover, mortality, harvest and decomposition on the other hand (Masera *et al*. 2003; Schelhaas *et al*. 2004). The model is divided into six main modules: biomass, soil (litter and humus), wood products, bioenergy, and both financial and carbon accounting. Figure 3.2 illustrates the modular structure of the model. Previously, we used the bioenergy module of the CO2FIX model to compare the carbon mitigation potential of afforestation and fossil fuel substitution for two land use categories (forest land and non-forest land) and two management practices (short vs. long rotation) (Kaul *et al*. 2010b). For the soil carbon module, the litter is grouped as non-woody litter (foliage and fine roots), fine woody litter (branches and coarse roots) and coarse woody litter (stems and stumps). Litter is produced in the biomass module through biomass turnover, natural mortality (mortality due to senescence and competition), mortality due to logging and harvesting of trees, and logging slashes. Litter remaining from thinning and final

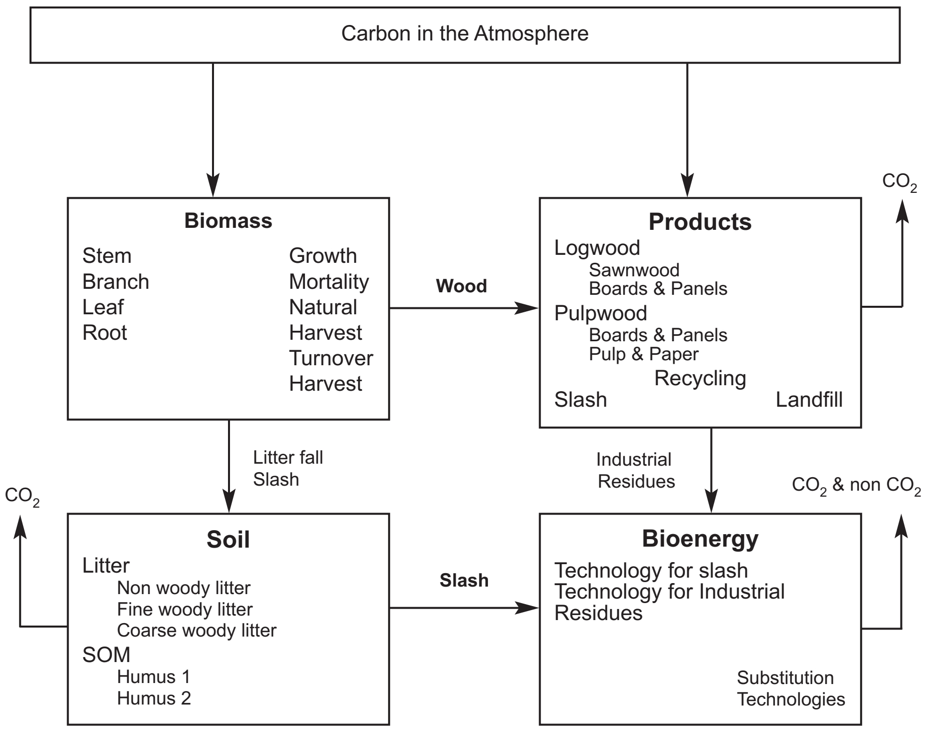


FIGURE 3.2 **Structure of CO2FIX v. 3.1 model, including major compartments used in each module, processes affecting the compartments (right hand side in the boxes), major flows between modules and fluxes of CO_2 from modules to the atmosphere.**

harvest is distributed over the decomposition compartments of extractives, celluloses and lignin-like compounds according to chemical composition.

The principle of the product module is that it tracks the carbon from harvesting to final decay. The harvested wood is allocated to different product groups depending upon the type of use of tree species, and taking into account the use of processing losses to other product groups.

Products are assumed to decay with a certain fraction per year depending upon the life span estimates. Carbon is released to the atmosphere when products in landfill decompose or through combustion when products are used for fuel wood. (Schelhaas *et al*. 2004). The products module is based on Karjalainen *et al*. (1994); a more detailed version has been applied for the European forest sector (Karjalainen et al. 2002; Eggers, 2002). The CO2FIX model has been described in detail by Nabuurs and Schelhaas, (2002); Masera *et al*. (2003) and Schelhaas *et al*. (2004). The full CO2FIX model is freely available from the web at http://www.efi.int/projects/casfor, together with numerous examples.

3.2.2. Simulation approach

The model was parameterized for the simulations using published data on growth rate and biomass amounts (Table 3.1). All the biomass data are converted to carbon values by assigning a carbon content of 0.5 Mg C per Mg oven dry biomass. Wood densities for all the species were derived from Haripriya (2000). The litter production rate for the separate biomass compartments was derived by multiplying the biomass stock with corresponding turnover coefficients (per year).

We derived these turnover coefficients for foliage, branches and roots from Negi (1984); Jha (1995); Bargali *et al*. (1992) and Lodhiyal and Lodhiyal (1997) for sal, teak, Eucalyptus and poplar respectively (Table 3.1a). Growth of foliage, branches and roots is incorporated as an additional allocation of dry matter increment relative to the stem wood derived from the ratio of net primary productivity (NPP) per component, estimated by Negi (1984); Jha (1995); Bargali *et al*. (1992) and Lodhiyal and Lodhiyal (1997) for sal, teak, Eucalyptus and poplar respectively (Table 3.1b). For each tree species a general management regime was defined, which consists of the ages when thinning takes place as shown in Tables 3.1c**.** In case of Eucalyptus and poplar, no thinning was done and final harvest took place at 9 years of age where 90% of the total volume was removed.

In the case of teak forest, in each thinning 30% of the total volume was extracted at the age of 8, 16 and 24 years, depending on the thinning practices in India

TABLE 3.1 **Summary of parameters used in simulating carbon dynamics of Eucalyptus, Poplar, Sal & Teak**

Parameter	**Eucalyptus**[1]	**Poplar**[2]	**Sal**[3]	**Teak**[4]
Basic Wood Density (Kg m^{-3})	495	380	672	643
(a) Turnover rates (1/yr)				
Foliage	0.6	.95	1	1
Branches	.02	0.1	0.01	.04
Roots	.05	0.04	0.01	.25

(b) Ratio of dry weight increase relative to dry weight increase of stem (dimensionless)

Eucalyptus[1]

Stand age (years)	0	2	3	4	5	6	7	8
Foliage	0.3	0.44	0.40	0.38	0.37	0.32	0.56	0.58
Branch	0.25	0.22	0.18	0.18	0.21	0.28	0.43	0.58
Root	0.3	0.43	0.58	0.49	0.36	0.31	0.47	0.37

Poplar[2]

Stand age (years)	1	2	3	4	5	6	7	8
Foliage	0.45	0.43	0.55	0.64	0.8	0.98	1.13	1.33
Branch	0.4	0.41	0.34	0.32	0.4	0.57	0.69	0.97
Root	0.4	0.42	0.43	0.44	0.46	0.53	0.59	0.69

Sal[3]

Stand age	0	22	33	36	43	47	52	55	91	93
Foliage	1	0.73	0.64	0.94	1.02	1.01	1.12	0.98	0.75	0.85
Branch	0.2	0.18	0.15	0.17	0.16	0.16	0.16	0.15	0.14	0.14
Root	0.4	0.39	0.3	0.34	0.31	0.32	0.31	0.29	0.27	0.37

Teak[4]

Stand age	1	5	11	18	24	30
Foliage	0.26	0.63	0.5	0.38	0.32	0.5
Branch	0.44	0.44	0.33	0.38	0.32	0.32
Root	0.44	0.48	0.63	0.6	0.77	0.82

(c) Fraction removed during thinning or harvest

Age (years)	8	9	10	16	20	24	30	40	50	60	70	90	100	120
Eucalyptus		.9												
Poplar		.9												
Sal			.02		.02		.06	.07	.07	.07	.08	.08	.08	1
Teak	.3			.3		.3	1							

Source: Estimated from [1] Bargali *et al.* (1992); [2] Lodhiyal *et al.* (1995); Lodhiyal & Lodhiyal (1997); [3] Negi (1984); [4] Jha (1995)

(Negi, 1996; Bebarta, 1999). Sal forests in India are harvested on a 120-year rotation cycle, applying thinning every 10 years, in line with standard practices (Tewari, 1995a) as given in Table 3.1c. The mean annual volume increment is 4.9 m^3/ha (Negi, 1984). In natural sal stands, it was assumed that there was no competition effect within the cohort and a moderate natural mortality of 2% per year was assumed for the period of 20 years.

TABLE 3.2 **Current Annual Increment as a function of stand age for Eucalyptus, Poplar, Sal & Teak.**

Eucalyptus[a]		**Poplar**[b]		**Sal**[c]				**Teak**[d]	
Age	CAI (m^3/ha/yr)	Age	CAI (m^3/ha/yr)	Age	CAI (m^3/ha/yr)	Age	CAI (m^3/ha/yr)	Age	CAI (m^3/ha/yr)
1	7.5	1	16.56	10	4.3	65	9.5	5	5
2	10	2	23.7	15	5.1	70	9.6	10	8.5
3	20	3	26.58	20	5.8	75	9.7	15	10.5
4	26.5	4	27.68	25	6.4	80	9.7	20	9.5
5	24	5	27.4	30	7	85	9.7	25	8.5
6	12.3	6	26.5	35	7.5	90	9.6	30	7.5
7	11.6	7	25.9	40	8	95	9.5	35	7
8	8	8	23	45	8.4	100	9.3	40	6.5
9	6.7	9	19.2	50	8.7	105	9	45	6
				55	9	110	8.7		
				60	9.3	115	8.4		
						120	8		

Source: [a] Dwivedi (1994); [b] Estimated from Lodhiyal *et al.* (1995) & Lodhiyal and Lodhiyal (1997); [c] Tewari (1995a); [d] Tewari (1995b).

The Current Annual Increment (CAI) was derived from the yield tables and computed from stem biomass using wood density (Table 3.2). The CAI for sal and teak was taken from local growth and yield tables (Tewari, 1995a & b). In case of poplar, age-related stem biomass data from Lodhiyal *et al*. (1995) and Lodhiyal and Lodhiyal (1997) was used, and stem biomass was converted to stem volume using a wood density of 380 kg m^{-3} (Haripriya, 2000). For Eucalyptus the CAI was taken from (Dwivedi, 1994).

The soil module of CO2FIX model uses climate data about precipitation, evapotranspiration and mean monthly temperatures. Initial soil and carbon data were derived from the procedure as reported by Masera *et al*. (2003). Climate data was used from http://www.indiastat.com. Degree days (above zero, 0^0) were calculated from the mean monthly temperatures using the method described by Liski *et al*. (2003). Different simulation periods were adopted for different systems, therefore for long rotations we use a 300-year simulation period and for short rotation exotic species, a 200 year simulation period was used.

TABLE 3.3 **Product allocations for thinning and harvesting**

	Logwood	**Pulpwood**	**Slash**
	Eucalyptus		
Stem - harvesting	0.02	0.5	0.48
Branch	0.02	.5	.48
Foliage	0	0	1
	Poplar		
Stem - harvesting	0.02	0.5	.48
Branch	.05	.6	.35
Foliage	0	0	1
	Sal		
Stem - harvesting	0.8	0	0.20
Branch	0.8	0	0.20
Foliage	0	0	1
	Teak		
Stem - harvesting	0.8	0	0.2
Branch	0.8	0	0.2
Foliage	0	0	1

In the product module, harvested wood was divided into logwood, pulpwood and harvest residues and foliage was categorized as slash (Figure 3.2, Table 3.3). Pulpwood and logwood were distributed to the commodities sawn wood, boards, pulp and paper and fuel wood. The fuel wood is automatically updated in such a way that the sum of the fractions is 1. The CO2FIX also allows for the specification of the conversion efficiency of main product and usage of residuals as firewood or other category of products. The lower the loss in carbon (in the form of wood products) the higher is the processing efficiency. A conversion efficiency of conversion 0.5 to 0.7 was adopted (Buekiering and Sharma, 1998; Haripriya, 2001). Production losses were reallocated to lower grade production lines, used as fuel wood or dumped at the mill site. It is difficult to ascertain the half life for various products as there are different estimates across studies (Karjalainen *et al*. 1994; Harmon *et al*. 1996; Ravindranath *et al*. 1997). To indicate the life of wood products, the produced products were divided into different life span categories.

For this study, the ratio of partitioning to long-, medium- and short-term products and their half-life were adopted from a study by Haripriya (2001) in which a number of original references are also cited. The half life span (50% of the original products produced in one year still in use) of products was one year for short, 10 year for medium and 20 years for long lifespan products. The residues from the pulping process are largely burnt and released into the atmosphere as CO_2. Of the remaining volume after debarking, 5 percent of the carbon is lost as process energy during conversion of pulpwood to mechanical pulp and 50% is lost during conversion to chemical pulp (Haripriya, 2001).

To address the effect of thinning intensity and changing rotation length on C stock, we study teak and sal forests as an example, respectively. Thinning operations provide an important source of wood for the forest industry and increase the growth of the remaining trees in a stand. At the end of the applied rotation period, stands were clear-felled and stem wood was removed from the site. The timing and intensity of thinning was based on the current management recommendations (i.e., based on a function of basal area and dominant height) (Bebarta, 1999). Three different thinning regimes were examined: ‘low thinning’, ‘one heavy thinning’ and ‘no thinning’. For subsequent thinning operations in the ‘low thinning’ the intensity was determined by the development of the basal area. In “low thinning” operations, only 10% of the standing volume was removed at the age of 5 and 15 years followed by complete harvest at 30 years of age. In “one heavy thinning” operation, 70% of the standing volume was removed at 15 years of age with final harvest at 30 years and in the ‘no thinning’ cases, there was no interim harvesting of trees before the final cut at a rotation length of 30 years.

The carbon pool in forest biomass (trees + soil) and harvested wood products was analysed for the changed rotation of 60, 90 and 150 years of age, taking sal forests as an example for natural forests. At the end of the rotation age, the stem wood was fully removed from the site and the rest of the biomass was left as harvest residue.

3.3. Description of the species and study area

The four species addressed in this study are natural sal (*Shorea robusta* Gaertn. f.) and three exotic species:, Eucalyptus (*Eucalyptus tereticornis* Sm.), poplar (*Populus deltoides* Marsh) and teak (*Tectona grandis* Linn. f.).

3.3.1. For Eucalyptus and poplar plantations, we have focused on the Terai region of the Central Himalaya (a level area of superabundant water). The climate of the Terai belt is sub-tropical monsoon, with a long dry season from early October to mid-June and a wet season from mid-June to early October. Of the average annual rainfall of 1593 mm (average for 1985-1989), about 86% falls from mid-June to September. The mean monthly temperature ranges from 14.4 ^{0}C (January) to 31.3 ^{0}C (June). The soil is deep and fertile, moist alluvial loam, conspicuously free from boulders and gravels. The plantation density of Eucalyptus was 2000 trees per ha, whereas the tree density in poplar stands was 400 trees per ha. The rotation length for Eucalyptus and poplar is 9 years. In the Terai belt, previous land use was natural sal mixed broad-leaved forest (Champion and Seth, 1968), which was clear felled before establishing plantations. In the Terai belt, the foresters have been raising poplar plantations for the last three decades and presently the plantation covers an area of about 16000 ha under various poplar clones (Lodhiyal and Lodhiyal, 1997) on short rotations of 6-8 years, with a high productivity of 20 m^3 ha^{-1} yr^{-1}.

3.3.2. In India, sal (fam. Dipterocarpaceae), a fairly large deciduous tree is found in forests covering about 12 Mha, representing about 16% of the total forested area (Tewari, 1995a). Sal is the dominant species forming nearly pure stands, due to its resistance to fire, coppicing ability and adaptability to various conditions of soil and site. Sal is one of the most important timber-yielding plants in India, and is known for its heavy, hard and tough wood. Sal occurs in mixed forests with other trees in Himalayan foothills and central Indian belts. This type occurs throughout northern India except in the dry northwest and much of the wet northeast. The type is important is Uttar Pradesh, Bihar, Assam, Orissa, Madhya Pradesh, and Bengal, and constitutes their most important forests. The mean annual temperature typically lies between 21 ^{0}C and 26 ^{0}C. The typical rainfall is around 1300 mm to 1500 mm.

3.3.3. Teak, a natural species in South Asia, is one of the most widely introduced exotics in tropical countries. In India, it occurs naturally from the eastern parts of Rajasthan in the west to Kerala in the south and Tripura in the north central and eastern parts of the country. Of the net area of teak plantations in 1995, about 94% lay in tropical Asia, with 44 percent in India (Ball *et al*. 1999). Teak is a fine quality timber-yielding deciduous species particularly suitable for rapid production of large volumes of timber, poles and fuel wood. Pure teak plantations (of 1, 5, 11, 18, 24 and 30 years old) raised in moist deciduous forests in Northern India (in Haldwani) was selected for study (Jha, 1995). The soil is of a well-drained sandy loam type, reddish brown in colour. The climate is a typical monsoon one, showing three distinct seasons: a hot dry summer (March to June), a warm humid rainy season (July to October), and a cool dry winter (November to February) (Jha, 1995). Average annual rainfall is 762 mm and over 90% of this occurs during the rainy season.

For the purposes of this study, the model was parameterized for four different forest species representing tropical dry and moist deciduous forests and plantations of short rotation species like Eucalyptus and poplar. The study sites for natural sal forests were situated in dry tropical regions of northern India, East & West Dehradun forest divisions while for plantations the sites were located between 29° 3′ and 29° 12′ N latitude and 79° 20′ and 79° 23′ E longitude in the Terai belt of Central Himalaya.

3.4. Results

The model was tested and validated for four representatives of short and long rotation species. The model-simulated data was compared with the field data of total dry matter (as published in Negi, 1984; Lodhiyal *et al*. (1995); Lodhiyal and Lodhiyal, 1997; Bargali *et al*. 1992 and Jha, 1995). The comparison of model-simulated and measured dry matter in four species is given in Fig. 3.3. A sensitivity study done earlier on for the model showed reasonable model performance.

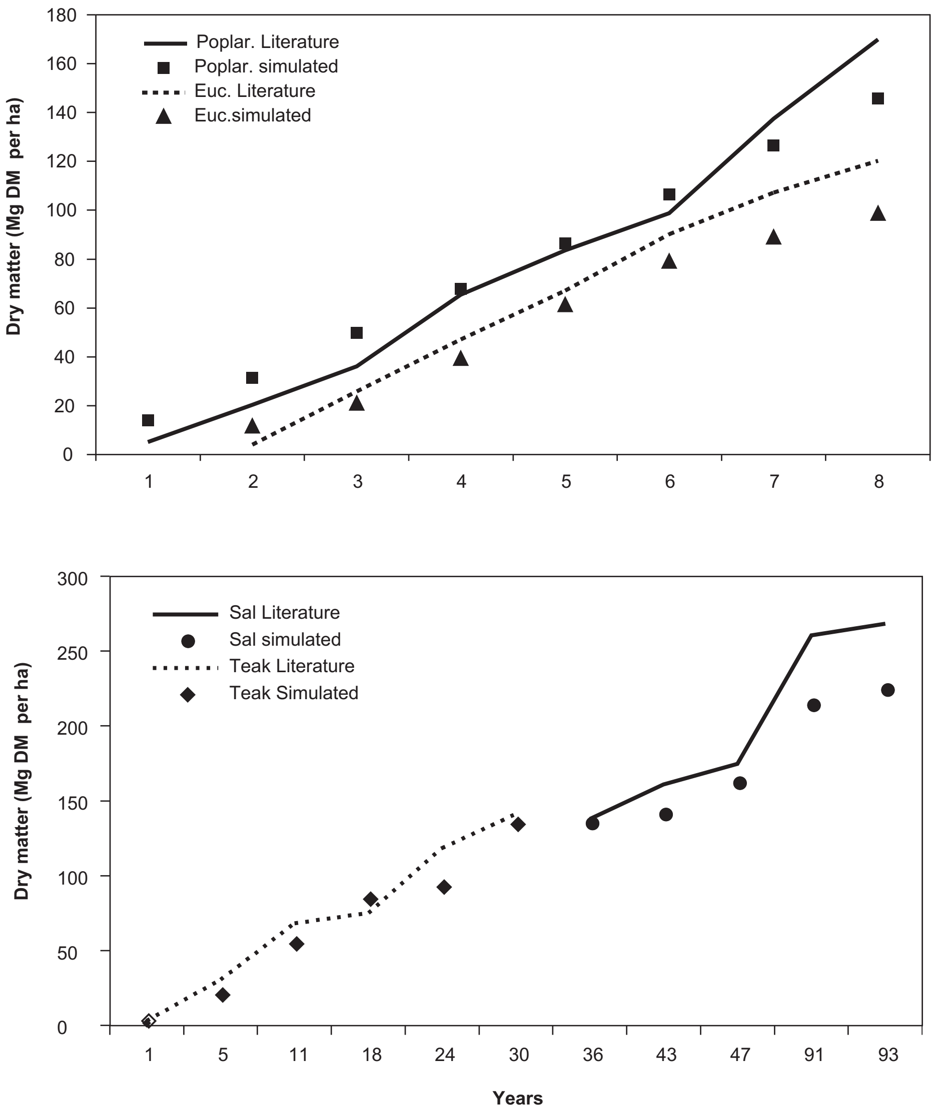


FIGURE 3.3 **Simulated and measured dry matter in a) Eucalyptus & Poplar, and b) Sal & Teak**

The 95% confidence interval for the long-term average (after 300 years simulation) carbon stock of the whole system was found to be ± 23%. Van der Voet (in: Nabuurs and Mohren, 1993) carried out an uncertainty analysis of the model CO2FIX for the Norway spruce forest type in central Europe.

For the 32 independent inputs to the model, he found that for the total carbon stock, the average amounted to 316 Mg C ha^{-1}, whereas the 95% confidence interval for the long term average ranged from 254 to 403 Mg C ha^{-1} which was found to be reasonable. The main uncertainty was caused by uncertainty over the soil organic matter dynamics and the carbon content of dry matter. Since the main input in our study was based on widely accepted growth and yield tables, the present study would probably give a comparable span in results. Although, the growth and yield tables are known to be based on rather old monitoring data, which do not represent current site conditions, there, are chances of carbon sequestration potential being underestimated. But on the other hand, yield tables also represent fully stocked forests, which do not occur very often in practice (Nabuurs and Schelhaas, 2002).

3.4.1. Long-term average C stocks

Using CO2FIX parameters simulation of biomass carbon pools and fluxes was carried out for Eucalyptus (*Eucalyptus tereticornis* Sm.), poplar (*Populus deltoides* Marsh), teak (*Tectona grandis* Linn. f.) and sal (*Shorea robusta* Gaertn. f.), with rotation length of 9, 9, 30 and 120, respectively. Figure 3.4 shows the long-term (in a simulation period of 300 years) average carbon stocks in soil, products and tree biomass. Although the natural sal forest looses carbon from soil, it still maintains the largest long-term carbon stock in a simulation period of 300 years. The soil compartment displays a slow decrease in stock from 118 Mg C ha^{-1} in the initial year to 52 after 300 years (a net source of 0.2 Mg C ha^{-1} per year). The largest carbon stock in biomass and products was achieved in sal forests (101 Mg C ha^{-1}). The long-term average stocks in forest biomass and wood products respectively for Eucalyptus, poplar and teak was 41, 55 and 50 Mg C ha^{-1}. The long-term average stocks in wood products were small as compared with the stocks in forest biomass and soil organic matter. The initial soil C pool based on the use of Yasso (Liski *et al*. 2003) model was

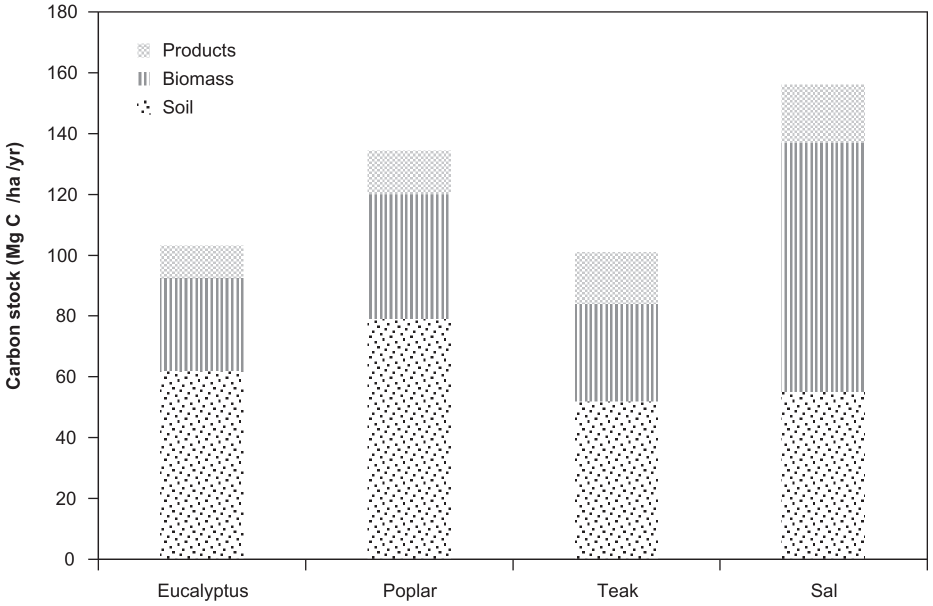


FIGURE 3.4 **Long-term average carbon stock in soil, biomass and products of the four forest types**

75, 67 and 52 Mg C ha^{-1} for Eucalyptus, poplar and teak, respectively and increased to 85, 102 and 73 Mg C ha^{-1} by the end of the first rotation. This slow increase is mainly due to accumulation of litter and dead wood. Where as in case of natural sal forests, after a slow decrease from 118 Mg C ha^{-1} from the initial year to 49 Mg C ha^{-1}, soil carbon gradually increases to 117 Mg C ha^{-1} by the end of first rotation.

The tree species studied differ in the carbon stocks in biomass and soil at the end of the rotation period. At the rotation age, the live biomass disappeared and carbon in products rose to 107 Mg C ha^{-1} and 50 Mg C ha^{-1} for sal and teak, respectively. The dry matter at the end of the rotation period was 98 Mg dm ha^{-1} for Eucalyptus (9 years), 146 Mg dm ha^{-1} for poplar (9 years), 127 Mg dm ha^{-1} for teak (30 years) and 312 Mg dm ha^{-1} for sal (120 years). This represents a mean annual biomass accumulation of 11 Mg ha^{-1} yr^{-1}, 16 Mg ha^{-1} yr^{-1}, 4 Mg ha^{-1} yr^{-1} and 2.6 Mg ha^{-1} yr^{-1} for Eucalyptus, poplar, teak and sal, respectively. Figure 3.5 (a, b, c & d) shows the time evolution of the carbon stocks in a stand separately for biomass (above and

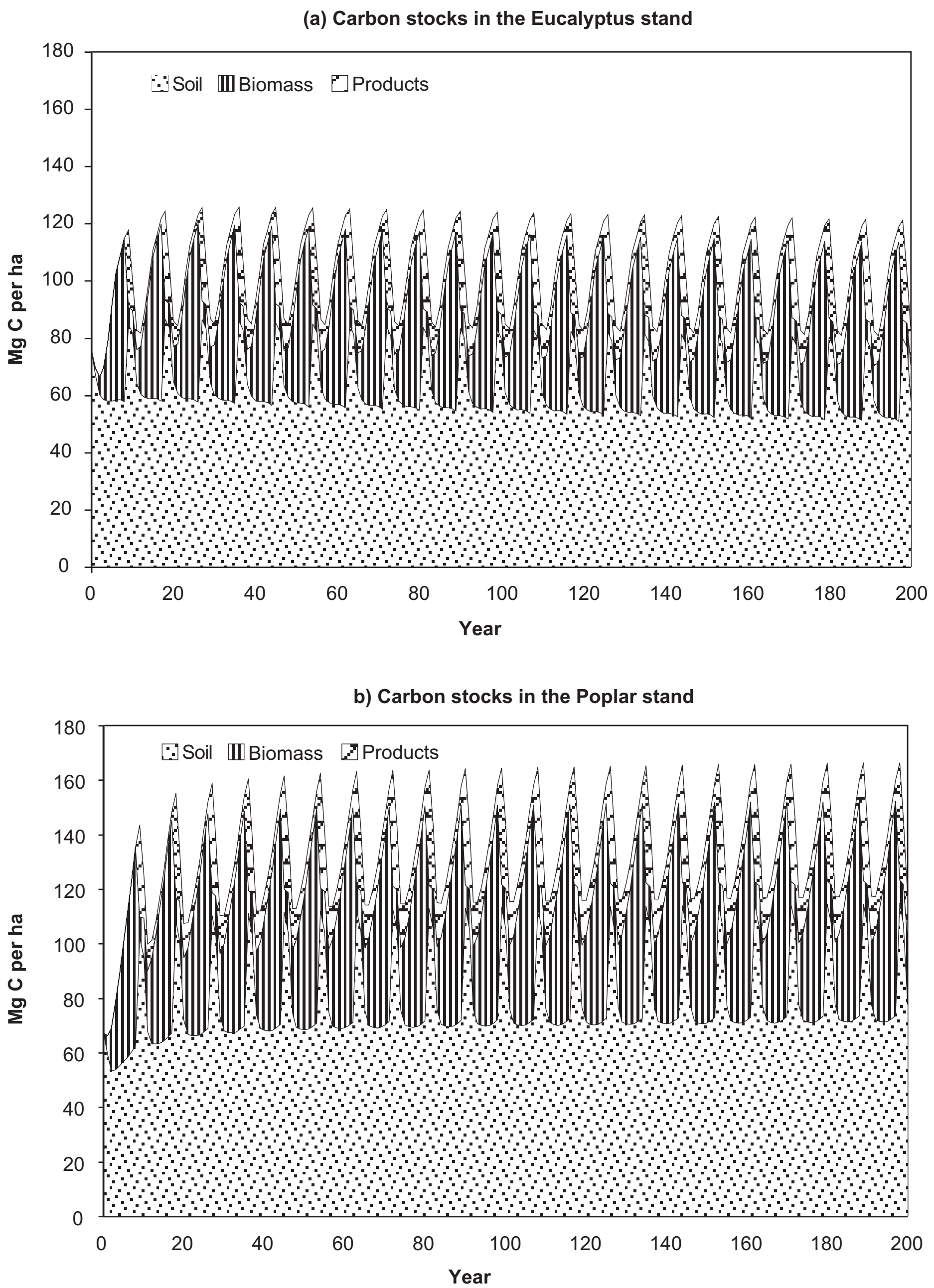
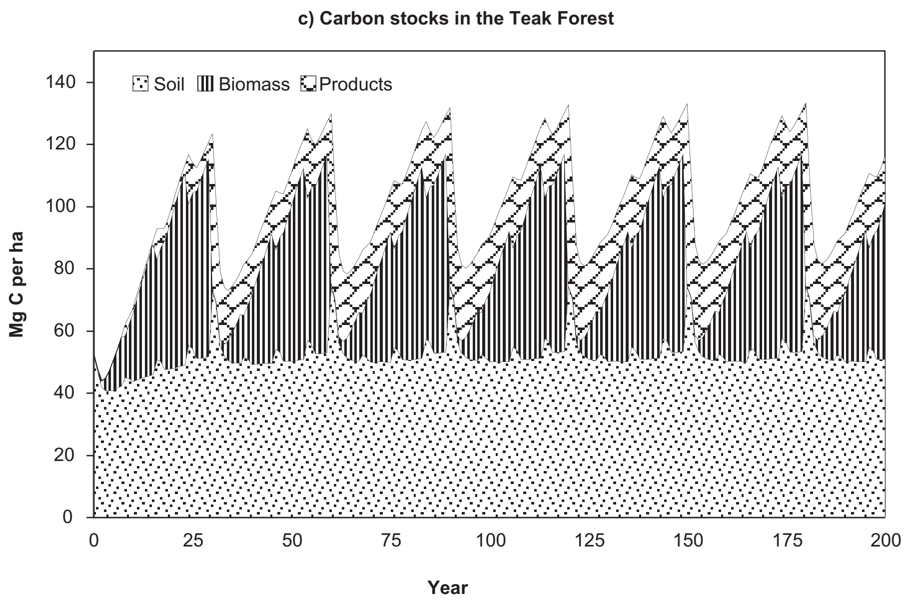


FIGURE 3.5 **Evolution of carbon stocks in different forest species (a) Eucalyptus, b) Poplar.**



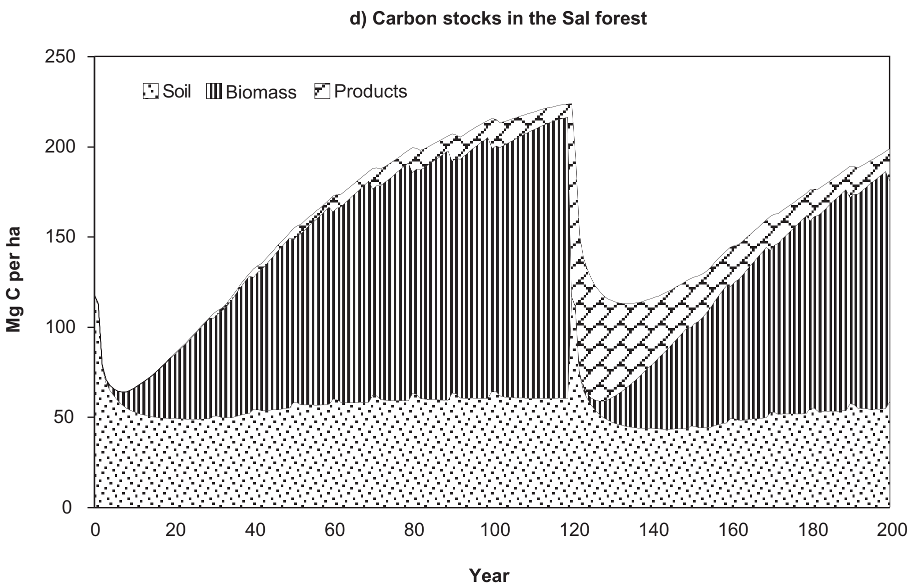


FIGURE 3.5 **Evolution of carbon stocks in different forest species (c) Teak and d) Sal.**

below-ground), soil (including humus, fine and coarse litter) and wood products for each species.

In case of sal forests, the simulation results show that, before the final cut, the amount of carbon in forest biomass and products was limited to 156 and 7 Mg C ha^{-1} respectively. By this time, the amount of carbon in the litter layer had increased to 14 Mg C ha^{-1} and the amount in the stable humus remained stable at 40 Mg C ha^{-1}. After the final cut, the amount of carbon in the forest biomass was reduced to 0, the amount in the litter layer rose to 70 Mg C ha^{-1} and the amount in the products rose to 107 Mg C ha^{-1}. The total amount accumulated at the end of the first rotation is the sum of 156 Mg C ha^{-1} (forest biomass) plus 14 Mg C ha^{-1} (litter layer) plus 7 Mg C ha^{-1} (products).

Maximum net annual carbon storage flux was 1 Mg C ha^{-1} yr^{-1} for slow-growing long-rotation sal forests, 6 and 8 Mg C ha^{-1} yr^{-1} for fast-growing short rotation Eucalyptus and poplar forests, respectively and 2 Mg C ha^{-1} yr^{-1} for moderate-growing short rotation teak forests. Figure 3.6 shows the model results on net annual carbon stock since starting year for all the species. The largest carbon sequestration

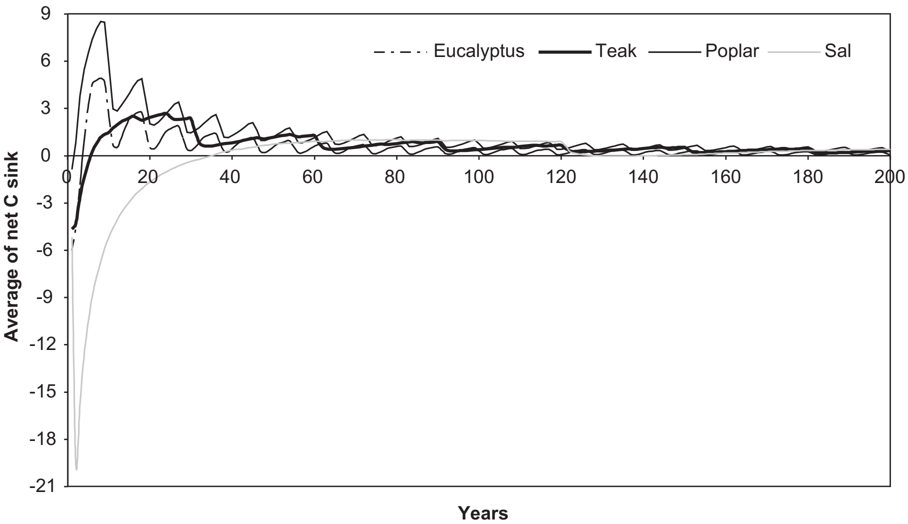


FIGURE 3.6 **Net effects in carbon stock since year 0 for four forest species.**

potential was found for poplar and Eucalyptus stands (with peaks in the advancing mean in the range of 3 – 8.5 Mg C $ha^{-1}yr^{-1}$). The smallest potential was found for sal forests (with peak in the advancing mean around 1.2 Mg C $ha^{-1}yr^{-1}$). For short rotation species, the amount of carbon offset increases linearly with time the net sink saturated. In case of long rotation sal forests the carbon balance is negative in the beginning (due to enhanced decomposition) but it turns positive after about 34 years of age. Naturally, in all the cases the net sink saturated, causing the advancing mean to diminish to values of around 0.7 Mg C $ha^{-1}yr^{-1}$ (ranging from 0.5 to 1.7 to) after 120 years.

3.4.2. Opportunities for forest management

Choice of rotation length and thinning intensity are commonly used to manage timber yield and carbon stocks of forests. These management practices affect all forms of carbon stocks (i.e., tree, soil and wood products). To study the effect of changing rotation length and thinning intensity on the carbon stocks, we discuss the results for natural and plantation forests taking sal and teak as examples in our study and discuss in detail in the following section.

3.4.2.1. Effect of changing rotation length

Figure 3.7 shows the mean C stocks in the forest ecosystem and wood products at different rotation lengths. The mean values of above ground biomass for rotation lengths of 60, 90, 120 and 150 years ranged from 52 to 97 Mg C ha^{-1} for natural sal forests. An increased rotation length from 120 to 150 years increased the carbon sequestration of trees by 18% from 82 to 97 Mg C ha^{-1}. This shows an increase in the carbon stock of trees with increasing rotation length due to the fact that the amount of wood harvested annually decreased with increasing rotation length. In general, soil carbon increased with the increase in the rotation length but the difference was less pronounced. The estimated total carbon stock in forest biomass and wood products ranged from 123 to 168 Mg C ha^{-1} indicating that increased rotation length yielded higher total carbon storage. In sal forests, the net primary productivity, i.e. the carbon flux to the system, was highest (3.7 Mg $ha^{-1}yr^{-1}$) when a 60-year rotation length was applied, but (i.e., 1.7 Mg $ha^{-1}yr^{-1}$ at 150 years). The tree

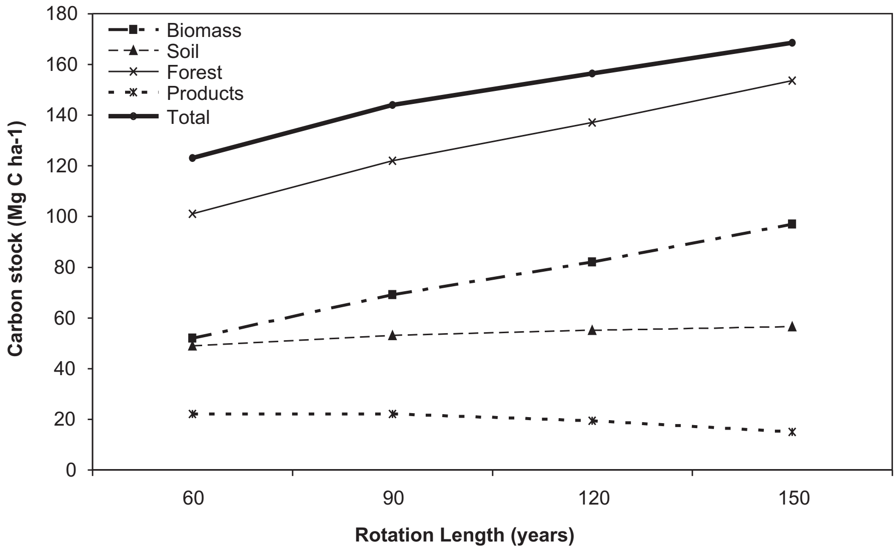


FIGURE 3.7 **Mean C stocks over different rotation periods in natural Sal stands.**

biomass produced a lot of litter but because of the decreased harvests, fewer harvest residues were produced. When the 150-year rotation length was applied instead of 120 years, the average carbon stock of wood products decreased by 4 Mg C ha^{-1} (23%). The carbon stocks in wood products were in the order of 22, 19 and 15 Mg C ha^{-1} at 90, 120 and 150 years rotation length respectively.

3.4.2.2. Effect of changing thinning intensity

Table 3.4 summarizes the simulated effects of changing thinning intensity on the carbon stocks of forest ecosystem and wood products of teak forests. The total carbon storage in the forest ecosystem was 116, 143, 140 and 121 Mg C ha^{-1} for "basic thinning", "no thinning", "low thinning" and "one heavy thinning", respectively. As compared to the "basic thinning" regime, the carbon stock in trees was 42%, 38% and 9% higher in "no thinning", "low thinning" and "one heavy thinning" regimes, respectively. The carbon stock in forest ecosystem was the highest when no thinning was applied. An increase in the thinning threshold increased C stock in trees, especially if the remaining basal area was increased. In the "no thinning" regime, the total carbon in harvested timber was 67 Mg Cha^{-1}**,** which is 34% more than that under the basic thinning regime. Carbon stock in timber yield tended to increase when thinning was done earlier and of less intensity than in the basic thinning regime. The increment in carbon stock in harvested timber as compared to the "basic thinning" regime was 8% and 26% under "one heavy thinning" and "low thinning" regime, respectively (Table 3.4).

TABLE 3.4 **Total C stock in forest ecosystem (trees + soil) (Mg C ha^{-1}) and % change in C stock as compared to basic thinning in teak stands of rotation length of 30 years.**

Management regime		**Basic thinning**	**No thinning**	**Low thinning**	**One heavy thinning**
Total C in forest ecosystem	Mg C ha^{-1}	116	143	140	121
(trees + soil)	%	-	23	21	4
Total C above ground	Mg C ha^{-1}	64	91	88	70
	%	-	42	38	9
Total C in soil	Mg C ha^{-1}	52	52	52	51
Total C in products	Mg C ha^{-1}	50	67	63	54
	%	**-**	**34**	**26**	**8**

Source: Estimated.

3.5. Discussion & Conclusion

Previous authors have estimated high potential of carbon storage in Indian forests, especially through raising plantations (e.g. Bhadwal & Singh, 2002; Lal & Singh, 2000); Manhas *et al*. 2006; Hooda *et al*. 2007, Baishya *et al*. 2009). Bhadwal & Singh (2002) used the Land Use and Carbon Sequestration Model (LUCS) model and estimated that under a regular plantation forestry scenario in India, 7 Pg of carbon would be sequestered between 2000 and 2050. Lal & Singh (2000) estimated that with the currently reported rates of biomass productivity of natural forest cover (1.1 Mg ha^{-1} yr^{-1}) and plantations (3.2 Mg ha^{-1} yr^{-1}), the carbon sequestration potential was in the range of 1.1 and 2.7 Pg C, respectively, by the years 2020 and 2045 (cumulative carbon uptake from the atmosphere). Baishya *et al*. (2009) compared the carbon storage potential of natural semi-evergreen forest and sal plantation forest in the humid tropical region of northeast India. Their results suggest that the natural forest had lower aboveground biomass (324 Mg ha^{-1}) than the plantation forest (406.4 Mg ha^{-1}). Although both the forests had potential for carbon sequestration but the plantation forestry had an edge over the natural forest because of better silvicultural practices (Baishya *et al*. 2009).

The simulation results presented in our study reflects variation in tree species potential, site conditions and management regimes. Simulation also indicated the relative distribution of dry matter as 62% in stem, 8% in leaf, 15% in branch and 15% in root in Eucalyptus forest. In teak stands the relative distribution observed was 61% in stem, 4% in leaf, 20% in branch and 15% in roots. The relative distribution of dry matter in natural sal stands was 69% in stem, 3% in leaf, 9% in branch and 19% in root. This is a realistic allocation when compared with the figures in Bargali *et al*. (1992); Negi (1984) and Jha and Singh (1999).

The total long-term average carbon stocks in biomass and wood products was 156 Mg C ha^{-1} for slow growing long rotation forests and in the range of 101 – 134 Mg C ha^{-1} for fast growing short rotation forests. The carbon stock in wood products was in the range of 11-19 Mg C ha^{-1} or 10-12 percent of the total carbon stock. Average net annual carbon flux was in the range of 1 Mg C ha^{-1} for slow growing long rotation forests, 6 - 8 Mg C ha^{-1} for fast growing short rotation forests. In case of short rotation forests, the carbon pool in soil was higher than the carbon levels in living biomass. Post *et al*. (1990) reported that the ratio between SOC and biomass carbon is 2.5 to 3 times in the terrestrial ecosystem. However, in the tropical forest, the carbon in the soil is roughly equivalent to or less than the aboveground biomass due to degradation (cited in Ramachandran *et al*. 2007). Ravindranath *et al*. (1997) reported that the ratio of SOC and biomass carbon was 1.25. In our study the ratio between SOC and biomass carbon was in the range of 0.7 to 2. The present study indicates that in the plantations, the carbon content in the soil was almost double the biomass carbon but not 2.5 to 3 times the biomass carbon as recorded earlier. The fact that the SOC content was higher than the aboveground biomass carbon indicates that the sequestered SOC came from the original vegetation in the past before exploitation. Soil carbon estimates in sal forests were lower than the biomass carbon, which could be due to initial soil conditions and longer rotation periods.

Fast growing species seem to store large amounts of carbon according to one criteria, but results are limited according to another criterion, e.g., poplar plantations contain 73 Mg C ha^{-1} at the end of rotation but the long term average is only 41 Mg C ha^{-1}. Fast growing short rotation plantations usually show high net annual carbon fluxes during a short period, but they soon reach to relatively low equilibrium biomass and the high flux quickly tends to reach zero. Thus, the criterion of net annual C flux is only valid for the first rotation, as there is no net storage when the long-term average amount of carbon in biomass, soil and products has reached its equilibrium value.

Among the fast-growing species, Eucalyptus and poplar have gained importance with large-scale adoption by farmers and government agencies in plantations for meeting the rising demands for fuel wood and industrial consumption. Comparison with other forests of similar ages indicates that the present estimates of biomass for sal are evidently higher than the value 70 Mg ha^{-1} reported for sal forests that are more than 100 years old (Singh, 1979). The values of aboveground biomass in the present study are comparable with those of Eucalyptus hybrid, 95 Mg ha^{-1} at 7 years, Negi and Sharma (1985); 21.9 Mg ha^{-1} at 10 years, Pandey *et al*. (1987), 263 Mg ha^{-1} for Oak forest, Negi *et al*. (1983) and 113-283 Mg ha^{-1} for Pinus roxburghii, Chaturvedi (1983). Poffenberger *et al*. (2001) reported sequestration levels varying between 0.5 and 3.4 Mg C $ha^{-1}yr^{-1}$ in community-based teak forests in Harda forest division, Madhya Pradesh, figures which are comparable to our estimates. The results indicate that among the species studied, poplars have the highest potential to sequester carbon, followed by Eucalyptus plantations. These plantations hold promise for higher organic matter production in the Terai region. For a tropical country like India, having vast range of forest types, weather and soil conditions, it is not possible to select one forest type that is most suitable for carbon sequestration. Long rotation forests have larger long-term carbon storage in forest biomass and product pools and short rotation plantations, in addition to carbon storage rapidly produce biomass for meeting the demand for fuel and fibre, and thus have higher carbon emission mitigation potential.

The total carbon stock in the forest ecosystem increased with increasing rotation length. A 30-year increase in the rotation length from recommended 120 years increased the average carbon stock of forest ecosystem (trees + soil) by 12%. In old forests, despite the increase in the rotation length, NPP may decrease due to the increased respiration burden caused by increasing woody biomass, decreased light interception, or a shift in carbon allocation from aboveground to belowground production (Smith and Resh, 1999). Due to the increase in litter production and harvest residues, the carbon stock in soil also increased, thereby substantially enhancing the carbon sink function of forests. The longer rotation lengths mean decrease of harvesting possibilities and also of the amount of harvest residues that could be used to produce bioenergy. Goal of maximum carbon storage and production of more valuable saw logs can be achieved from longer rotation lengths. More research is needed on the carbon dynamics and end use of wood for small and long rotation species.

The results showed that the intensity of thinning regime changed the carbon stock of trees and products. Highest carbon stock (143 Mg C ha^{-1}) was achieved in "no thinning" regime. From an ecological perspective, if only carbon storage is the aim, "no thinning" could be preferred. But this is not a viable option, because increasing the carbon pool by way of zero thinning will not decrease emissions of fossil fuels since storing carbon is an indirect solution and will not decrease the need of fossil fuel for transportation or combustion and such patches could have high risks of forest fires, insects etc. (Erikson, 2006). Moreover, from an economical perspective, there will be no wood available from thinning operations to replace fossil fuel for bioenergy and to the pulp industry. The "low thinning" regime also gave the higher carbon stock in the forest biomass (140 Mg C ha^{-1}) as compared to "basic thinning". In our study, the management effect on carbon stock in trees was higher than the carbon stock in soil (which tends to be more stable). However, the carbon stocks also depend upon the tree species, site properties, spacing, climate conditions, age class distribution etc. (Vucetich *et al*. 2000; Pussinen *et al*. 2002). There are some detailed studies on thinning intensity and its effect on various species e.g., mixed and pure plantations in Costa Rica (Pitto *et al*. 2003), teak in Costa Rica (Kanninen *et al*.

2004), picea abies & pinus sylvestris L. in Sweden (Erikson, 2006) and picea abies in Norway (Nilsen and Strand, 2008). Kanninen *et al*. 2004 suggests that for sawn timber productivity objectives, high intensity thinning offer great advantage over "low-thinned" or "no thinning" stands. Perez & Kanninen (2005) suggested that moderate and heavy thinning yielded the highest percentage of heartwood volume (25 to 30% of the total stem volume) suggesting that early stages teak stands could be managed under different thinning programmes without negatively affecting the quality of wood under humid tropical conditions. Extended rotation lengths and reduced thinning intensity could enhance the long-term capacity of forest ecosystems to sequester carbon. Our results on the effect of management practices on carbon stocks could not be compared to any measurements due to the lack of such results or of earlier studies based on Indian conditions. This also implies that more thorough and detailed data sets are required for obtaining more accurate results and making comparisons at the state and national levels. Future studies will also have to consider dynamics in both trees outside forests and soil for total terrestrial carbon dynamics. Projected climate changes include strengthening of monsoon circulation, increases in surface temperature, and increases in the magnitude and frequency of extreme rainfall events. In a case study of Kerala (Achanta and Kanetkar, 1996), results indicate that under the climate change scenarios, soil moisture is likely to decline and in turn reduce teak productivity from 5.40 m^3/ha to 5.07 m^3/ha. The study also shows that the productivity of moist deciduous forests could decline from 1.8 m^3/ha to 1.5 m^3/ha. Changes in forestry could potentially result in extinction of some species and loss of biodiversity. In semi-arid regions of Tropical Asia, tropical forests generally are sensitive to changes in temperature and rainfall, as well as changes in their seasonality. Fire is also influenced by these changes and would significantly affect the structure, composition, and age diversity of forests in the region. Fire frequency could be affected by the human activities like, slash and burn agriculture, as well as by variations in climate (e.g., longer or shorter dry seasons).

Our study does not include the criteria, e.g., a) reduction in carbon emissions through fossil fuel substitution using wood energy; b) carbon stock estimation of forest biomass and soil in mixed forests (e.g. dominated by sal) is also not evaluated;

c) future changes in forest growth due to changes in environmental conditions and as a consequence of climate change. In recent years, the forest areas in India have stabilized, but location-specific deforestation and high annual plantation rates suggest big changes in the carbon cycle pattern, which cannot be captured using a national-scale approach. Species and use-dependent carbon cycle estimates that also account for soil, wood products and energy usage can be gained using models such as CO2FIX. This requires parameters per species. There is a need to further investigate the full carbon cycle for all the important species in India and the management practices for sustainable production of biomass to replace fossil fuels and increase carbon stocks.

CHAPTER 4

Land use change and net C flux in Indian forests

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ABSTRACT

This paper reports on the net carbon flux caused by deforestation and afforestation in India over the period from 1982 - 2002, separately for two time periods, 1982 - 1992 (PI) and 1992 to 2002 (PII), using the IPCC 2006 guidelines for greenhouse gas inventories. The approach accounts for forest and soil carbon pool changes for (a) forest areas remaining as forests, (b) afforested areas and (c) deforested areas. The data set used were, remote sensing based forest cover for three time periods (1982, 1992, 2002), biomass increments, biomass expansion factors and wood density. In addition a number of required coefficients and parameters from published literature were adopted. In the 1982 - 2002 periods, the forest cover changed from 64.20 Mha in 1982 to 63.96 and 67.83 Mha in 1992 and 2002 respectively. During the PI and PII periods, plantations were also established of 0.2 and 0.5 Mha yr^{-1}, while the annual deforestation rate was about 0.22 and 0.07 Mha in these periods, respectively.

The average net flux of carbon attributable to land use change decreased from a source level of 5.65 Tg Cyr^{-1} (or 0.09 Mg C $ha^{-1}yr^{-1}$) during PI (1982-1992) to a sink level of 1.09 Tg C yr^{-1} (or 0.02 Mg C $ha^{-1}yr^{-1}$) during PII (1992-2002). Over recent years, Indian forests have acted as a small carbon sink. The results indicate that the conversion of land to forest (regeneration/afforestation) led to a net uptake of 0.86 and 1.85 Tg C yr^{-1} in PI and PII, respectively. By contrast, the net C emissions from the forest land conversion to another land use (deforestation) resulted in annual emissions of 9.9 and 3.2 Tg C during PI and PII, respectively. The cumulative net carbon flux from Indian forests due to land use change between 1982 - 2002 was estimated as 45.9 Tg C. The largest fluxes result from the conversion of forest land to cropland and waste lands, and since there are uncertainties in input variables (due to very large spatial heterogeneity) that affect net C flux from land use change, there is an urgent need for more reliable district-based data to facilitate accurate and refined estimates in future. This study was intended to improve consistency and completeness in the estimation and reporting of greenhouse gas emissions and removals.

Key words: Carbon emission, Indian forests, Land use change, Deforestation, IPCC

4.1. Introduction

The land use change and forestry sector is being considered, increasingly, an option for limiting green house gases (GHG) concentration in the atmosphere. Land use change is realized through the activities like change of forest lands to another land use or vice versa. There is an ongoing effort to accurately quantify the effect of various land use changes on the global carbon stocks (DeFries *et al*. 2002; Achard *et al*. 2004; Houghton, 2008), with an emphasis on tropical forests (Lasco and Pulhin, 2000; De Jong *et al*. 2000; Haripriya, 2003; NATCOM, 2004; Woomer *et al*. 2004) and their rates of deforestation. The estimated global net flux due to land use change during the period 1850-2000 is 148.6 Pg C, about 55% of which is from the tropics. The global total flux averaged 1.5 Pg C yr^{-1} during the 1980s and 1.56 Pg C yr^{-1} during the 1990s (but generally declined during the latter decade), dominated by fluxes from tropical deforestation (Houghton, 2008). However, on the positive side, it is also possible to mitigate climate change through conserving existing forests, expanding carbon sinks, substituting wood products for fossil fuels and reducing emissions from deforestation and degradation (known as REDD mechanism). REDD is a mechanism that would reward countries with carbon credits for preserving their forest cover. Under the recent initiative, known as Forest Carbon Partnership Facility (FCPF), the 14 developing countries will receive grant support as they build their capacity for REDD through measure including establishing emissions reference levels, adopting strategies to reduce deforestation and designing monitoring systems.

India is a party to the United Nations Framework Convention on Climate Change (UNFCCC) and attaches great importance to climate change issues. To meet its obligations under the UNFCCC and to best understand the interactions between the national concerns and global environmental problems, India carried out a national inventory of its anthropogenic emissions of greenhouse gases. A comprehensive inventory of the GHG emissions from all the sectors was submitted to the UNFCCC on 22^{nd} June 2004 for the base year 1994 using IPCC guidelines using Tier I, Tier II or Tier III approach.

In accordance with Article 12 of the climate convention, the signatory countries are required to submit on a continuous basis information on greenhouse gas emissions by sources and removals by sinks using agreed methodologies, as outlined in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/OECD/IEA, 1997), *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC, 2000), *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (IPCC, 2003) and *IPCC Guidelines for Greenhouse Gas Inventories* (IPCC, 2006). The IPCC section dealing with Land Use Change & Forestry (LUCF) accounts for changes in terrestrial carbon (C) storage in plant biomass and in soils. In the LUCF sector, the fundamental basis for GHG inventory estimates is the fact that the flux of CO_2 to or from the atmosphere is assumed to be equal to the changes in carbon stocks in existing biomass and soils, and that changes in carbon stocks can be estimated by first establishing rates of change in land use and the practices used (e.g., burning, clear cutting and selective felling etc.). A series of coefficients based on climate, productivity, and residue management are used to estimate the changes in soil carbon (IPCC, 2006).

The net annual balance estimates in India from various land use changes vary from emissions of around 0.67 Tg (Tg = 10^{12}g) to a positive sink of 5 Tg. For India, Ravindranath *et al*. (1997) estimated a marginal net sequestration of 5 Tg C for the reference year 1986. Another recent study in India by Tata Energy Research Institute (TERI) (ALGAS, 1998) used the IPCC (1997) methodology in preparing the carbon emissions inventory from forests and concluded that the net emissions from land use change and the forestry sector were 0.4 Tg for the year 1990. In the past, Indian carbon cycle studies have been published by Ravindranath *et al*. (1997); Chhabra *et al*. (2002a); Haripriya (2000); Lal & Singh (2000) and Manhas *et al*. (2006). Some results are based on the growing stock (GS) volume data of forest inventories and an appropriate conversion factor related to both biomass and carbon, while others have adopted methodologies suggested by IPCC. This paper presents an estimate of the net flux of carbon from Indian forests that result from land use changes associated with wood harvesting, the conversion of forests to croplands and waste lands and the establishment of plantations. In the present study we estimate C flux from land use change and the forestry sector using the latest IPCC guidelines from 2006, while taking into account the many recently published results on various aspects of C cycle in India, incorporating new data on rates of deforestation and biomass, and using default parameters.

4.2. Materials and methods

Land use change results from activities such as the conversion of forest lands to another land use or vice versa. The forest carbon fluxes resulting from land use change have been estimated using the procedure described in the IPCC (2006) guidelines for the Agriculture, Forestry and Other Land Use (AFOLU) sector. These guidelines integrate the previously separate methodology for Agriculture and Land use, Land Use Change and Forestry into a single unified forest C balance. The IPCC approach calculates the annual net flux of carbon between the atmosphere and terrestrial ecosystems based on the changes in vegetation and soil following a change in land use.

Carbon emissions in the LUCF sector occur from (a) loss of aboveground biomass due to extraction in the existing forests, (b) forest conversion to croplands/waste lands and (c) soil management. Conversely, C removal from the atmosphere occurs when croplands/ waste lands are abandoned and forests re-grow, so that carbon is accumulated again in vegetation and soil. The main steps in estimation are (a) computation of carbon removal when forest land remaining as forest and (b) computation of C removal or emission from the land converted from one category to other (described category wise in detail in following section). In cases where forest land remained as forest land, C removal from the atmosphere due to biomass growth and loss due to disturbance and biomass removals (both fuel wood and timber) were considered. The later is associated more with degradation due to removal of twigs and branches than with deforestation (Ravindranath *et al*. 1997). The values corresponding to important parameters are given in Table 4.1. The estimates for various parameters were made at the state level, whereas the biomass extraction and plantation figures given applied at national level since state level data was not available.

TABLE 4.1 **Estimated State-level parameters for estimating C emissions from land use change.**

States/ UT	Mean Biomass Expansion Factor	Mean Wood Density (Mg/m^3)	Biomass ($Mg\ ha^{-1}$) 1982	1992	2002	Ratio of below ground biomass to above ground biomass	Average above Ground Biomas Growth ($Mg\ dm\ ha^{-1}\ yr^{-1}$)	Soil Organic Carbon $Mg\ ha^{-1}$
Andhra Pradesh	1.59	0.79	85.26	90.05	122.10	0.27	1.85	89.35
Arunachal Pradesh	1.58	0.77	126.32	160.41	115.96	0.26	1.88	138.03
Assam	1.58	0.79	166.74	182.96	130.73	0.25	1.93	111.60
Bihar	1.58	0.71	55.32	47.14	53.75	0.28	1.90	73.85
Gujarat	1.59	0.71	46.71	68.09	73.58	0.26	1.28	86.83
Haryana	1.59	0.74	8.03	32.33	21.27	0.27	1.89	77.57
Himachal Pradesh	1.52	0.47	127.45	167.77	194.95	0.28	1.80	131.89
Jammu & Kashmir	1.51	0.43	166.11	168.69	87.18	0.25	1.75	145.91
Karnataka	1.59	0.79	107.69	122.14	142.12	0.24	1.98	102.97
Kerala	1.59	0.80	126.49	141.06	122.83	0.26	1.99	132.93
Madhya Kashmir	1.59	0.75	76.40	71.16	48.10	0.26	2.04	87.44
Maharashtra	1.58	0.70	56.59	65.86	59.18	0.27	1.99	80.36
Manipur	1.57	0.76	62.71	75.15	89.16	0.27	1.85	120.63
Meghalaya	1.53	0.76	84.95	88.92	58.66	0.27	1.69	111.60
Mizoram	1.57	0.79	47.49	51.43	46.89	0.27	1.68	111.60
Nagaland	1.58	0.80	107.15	97.45	59.34	0.28	2.04	134.63
Orissa	1.59	0.72	62.15	69.48	80.10	0.27	2.45	101.29
Punjab	1.57	0.70	11.58	8.97	88.89	0.27	1.11	73.63
Rajasthan	1.59	0.76	13.46	13.61	28.32	0.32	1.55	70.08
Sikkim	1.58	0.75	185.77	172.78	139.65	0.31	2.05	138.90
Tamil Nadu	1.59	0.80	54.22	57.83	119.66	0.26	1.83	76.89
Tripura	1.59	0.77	36.62	39.44	23.60	0.28	1.74	111.60
Uttar Pradesh	1.56	0.63	106.74	113.22	174.90	0.28	2.55	113.82
West Bengal	1.58	0.71	87.66	35.91	132.79	0.26	2.39	92.27

Continue…

Goa Daman & Diu	1.59	0.76	93.12	141.57	33.01	0.27	2.27	138.90
Andaman & Nicobar	1.59	0.71	23.64	137.01	97.09	0.26	2.73	138.90
D & N Haveli	1.59	0.69	74.80	54.45	209.45	0.28	0.91	111.60
All India			**89.21**	**98.09**	**93.27**			

Source: Kaul *et al.* (2010a), Chhabra *et al.* (2002c), Manhas *et al*. (2006).

As described in the IPCC (2006) guidelines, methodologies adopted for estimating the annual C balance in the different land use categories come under three tiers. T1: consists of simple equations and default data sets or emission factors; T2: uses the same equations as in Tier 1 but demands country-specific parameters that better account for local climate, soil and management practices; T3: uses methods based on more complex models and inventory-based systems. The full set of equations used for estimating CO_2 emission and removal from the LUCF sector is summarized in Annex II.

4.2.1. Forest land remaining as forest

The changes in carbon stock in biomass for land remaining in the same category were based on annual gain and loss in biomass stocks (Gain-loss method). The carbon cycle includes changes in carbon stocks due to both continuous processes (i.e., growth, decay) and discrete events (i.e., disturbances like harvesting, insects, and fire). In this paper, RS-based state forest cover data for three time periods (1982, 1992 and 2002), average annual (above- and below-ground) biomass growth rates and loss of carbon due to biomass removals were used to estimate the net carbon uptake in Indian forests.

The growth rates were based on the forest type using area weighted growth rate for each state. Thus, as long as afforestation/deforestation does not very significantly alter the proportion of forest types in the states, same growth rate was used. The mid years of the satellite assessments 1982 (for 1981-1983), 1992 (for 1991-1993) and 2002 were used to represent the annual net carbon flux estimation. The state wise forest cover for the years 1982, 1992 and 2002 are summarized in Table 4.2.

TABLE 4.2 **Area under forest over (Mha) by State/UT for 1982, 1992 and 2002.**

States/UT	**Forest cover (Mha)**		
	1982	**1992**	**2002**
Andhra Pradesh	5.02	4.71	4.44
Arunachal Pradesh	6.05	6.86	6.80
Assam	2.64	2.41	2.78
Bihar	2.87	2.66	2.83
Gujarat	1.36	1.23	1.49
Haryana	0.06	0.06	0.15
Himachal Pradesh	1.29	1.25	1.44
Jammu and Kashmir	2.09	2.04	2.13
Karnataka	3.23	3.24	3.64
Kerala	1.04	1.03	1.56
Madhya Pradesh	12.77	13.52	13.24
Maharashtra	4.74	4.38	4.69
Manipur	1.77	1.76	1.72
Meghalaya	1.65	1.57	1.68
Mizoram	1.91	1.86	1.84
Nagaland	1.44	1.43	1.36
Orissa	5.32	4.71	4.84
Punjab	0.08	0.13	0.16
Rajasthan	1.25	1.33	1.58
Sikkim	0.28	0.31	0.33
Tamil Nadu	1.84	1.78	2.26
Tripura	0.57	0.55	0.81
Uttar Pradesh	3.14	3.40	3.86
West Bengal	0.88	0.83	1.23
Goa Daman and Diu	0.13	0.13	0.22
Andaman and Nicobar	0.76	0.76	0.70
Dadra and Nagar Haveli	0.02	0.02	0.02
All India	**64.20**	**63.96**	**67.83**

Source: FSI (1987, 1995a, b), FSI (2002)

In India very little information exists about the rate at which the different forest ecosystems sequester carbon. In 1995 per hectare values of biomass increments for different forest types were reported by Lal and Singh (2000). The area occupied by different forest types in India is recorded in the State Forest Report (FSI, 1987).

Additional published and unpublished studies and the NPP reported by various studies were used to determine state level biomass increment values (Ravindranath *et al*. 1997; Dr. JDS Negi, *personal. communication*, Kaul *et al*. 2010a).

Chhabra *et al*. (2002a) estimated the total standing biomass (above-ground and below-ground) using the information on growing stock volume in state and union-territory field inventories and the corresponding area under three different crown density classes grouped under different forest categories. For the purpose of the present study, the state level value of R (the ratio of below-ground biomass to above ground biomass) was estimated from Chhabra *et al*. (2002a) as given in Table 4.1.

In India, forests are exploited mainly for extraction of timber, fuel wood and green fodder. In India, the statistics on volume harvested (legally) are available but the estimates of volume extracted for timber and fuel wood from forests is much lower than the actual consumption (Haripriya, 2003). Most of the fuel wood which is in the form of dead and dry wood is extracted from forests by the head-load by the villagers living near the forests and this extraction of fuel wood and the consequent production remains unrecorded. There are different estimates for fuel wood such as 235 million m^3 yr^{-1} (Ravindranath *et al*. 1997), 297 million m^3 for 2000 (FAO, 2002). Based on the estimates by the Planning Commission, the percentage share of fuel wood in per capita consumption in the household sector was 68.5% in rural areas and 45.5% in urban areas. Furthermore, the Ministry of Environment and Forests reported in 1996 that out of the total demand of around 201 Tg (251 million m^3) of fuel wood in India, around 17 Tg came from the forest areas, and 98 Tg from farm forests and other woodlands (MoEF, 1999). This means that, every year nearly 86 Tg more fuel wood is removed from the forests (including plantations) of India than they can produce on a sustainable basis. It was further reported that of the total demand for timber, estimated at 64 million m^3, nearly 31 million m^3 came from farm forestry and other woodlands and 12 million m^3 from forests. The outstanding 21 million m^3 is removed as small timber from plantations and natural forests to meet domestic need. Most of the fuel wood studies conducted in India focused on the consumption aspect rather than the supply and source aspect. Since no reliable information is available on production and consumption of wood from forests, the total annual demand of wood is between 324-434 million m^3.

For the purpose of this study, it was assumed that the average annual consumption of wood during 1982-1992 and 1992-2002 was 262 and 270 million m^3 respectively (FSI, 1987; Haripriya, 2001). As with the varying estimates on fuel wood consumption, there are considerable differences of opinion on what fraction of this wood comes from forests. Altogether, firewood from the forests accounts for approximately 43 percent of the total fuel wood consumption and the rest (57%) of the firewood may come from (i) trees in village ecosystems, or (ii) shrubs such as *Prosopis juliflora, Lantana camara* and *Cassia auriculata* (Ravindranath *et al*. 1997). Thus, out of the total annual consumption of 235 million m^3 in PI and 247 million m^3 in PII, 101.05 million m^3 and 106.21 million m^3 was consumed only from the forests in PI and PII respectively. The remaining 133.95 million m^3 in PI and 140.79 million m^3 in PII were consumed per year from outside forests. Similarly, based on the report by Forestry statistics of India (FSI, 2000), rates of harvest were assumed to have increased slowly between 1982 and 2002.

According to the IPCC 2006 guidelines, fuel wood removal takes two forms, removal of whole trees and removal of tree parts such as twigs, branches etc (considering 50:50 ratio). The biomass conversion and expansion factors (BCEF's) are used to convert the merchantable volume of growing stock directly into its equivalent above ground biomass. Haripriya (2000) reports the biomass expansion factor and wood density for different strata, these values were used together with growing stock values of various strata in different states and union territories to estimate state level mean BEF and wood density, as reported in Kaul *et al*. (2010a).

4.2.2. Land converted to a new land use

The estimation of emissions and removals of carbon from land use conversion to forest land is divided into three sub-sections: change in carbon stocks in biomass, change in carbon stocks in dead organic matter, and change in carbon stocks in mineral soils. The annual changes in C stocks on land converted to forest land were calculated using equations 4, 5 & 6 (Appendix II). The methodology adopted in both the conversions is outlined below:

4.2.2.1. Land converted to forest land

Land is converted to forest land by afforestation or reforestation, either by natural or by artificial regeneration (including plantations). Land conversion may result in an initial loss of carbon due to changes in biomass, dead organic matter and soil carbon. But plantation practices lead to carbon accumulation and that is related to the changes in the area of plantations and their biomass stocks. For calculating the annual increase in biomass carbon stocks due to biomass growth, state land area converted to forest land and average annual growth rates were used. The annual state estimates for afforested area were obtained by dividing the positive changes in the forest area between the first and the last years of the respective inventory periods by the total number of years. The biomass data are converted to carbon values by assigning a carbon content of 0.5 Mg C per Mg oven dry biomass.

Using the IPCC 2006 guidelines, the initial (pre-conversion) soil organic C stock, and the C stock in the last year of the inventory time period were determined from the country-specific reference soil organic C stocks (SOC_{ref}) and default stock change factors (F_{LU}, F_{MG}, F_I) as appropriate for describing land use and management, both pre- and post-conversion. Annual rates of stock change were calculated as the difference in stocks (over time) divided by the time dependence (D) of the stock change factors (with a default value of 20 years). The stock change factors include 1) a land use factor (F_{LU}) that reflects C stock changes associated with the type of land use, 2) a management factor (F_{MG}) representing the principal management practice specific to the land-use sector and 3) an input factor (F_I) representing different levels of C input to soil. Chhabra *et al*. (2002c) have estimated the mean soil organic C densities for various forest types in different states and union territories for two depth classes (0-50 cm and 0-100 cm) for the period 1980-1982. The area occupied by 16 forest types in different states is reported in the state forest report (FSI, 1987). Both these reported values were used together to estimate the reference C stocks for the state (as given in Table 4.2). Based on the Tier I approach, for F_{LU}, F_{MG} and F_I, a default value of 1 was considered for the last year of the inventory period (i.e., forest land) and a default value of (0.48-0.64), 1 and 0.92 respectively for the first year of the inventory period (i.e., cropland/waste land) (IPCC, 2006). The annual change in organic C stocks in mineral soils is estimated using the eq.6 (Appendix II).

4.2.2.2 Forest land converted to another land

The IPCC 2006 guidelines adopt the method of estimating the carbon in the biomass stocks prior to and following conversion, based on estimates of the areas converted during the two periods. To estimate the C emissions from the deforested area, aggregate deforestation rate was used from all states and union territories where there was a decline in forest area between the years 1982-1992 (for PI) and 1992-2002 (for PII). The deforested area includes forest blanks, crop lands and waste lands. At the national level, 60 – 63 percent of deforestation is due to conversion to crop land and the rest is used for non-forest purposes like river valley projects, construction etc. (Ravindranath *et al*. 1997; Lal, 1989). Same proportion was used to estimate C pool in biomass and soil for crop land and waste land during PI and PII separately. The difference between the initial and the final biomass C pools was used to calculate the carbon stock change from land use conversion. Tier 2 and 3 method were used to estimate the annual change in biomass C stock on land converted to cropland and waste land, where the changes in carbon stock were calculated as the sum of: the increase in carbon stock due to biomass growth, changes due to actual conversion (difference between biomass stocks before and after conversion), and the decrease in carbon stocks due to losses. Biomass before conversion and annual loss of biomass carbon were calculated using the parameters of BEF, wood density, volume (m^3ha^{-1}) and a root correction factor of 1.16 (Hall & Uhlig, 1991; Haripriya, 2000; Manhas *et al*. 2006). In addition, a value is needed for C stocks after one year of growth after conversion. Based on the original IPCC guidelines recommendation of 10 Mg of dry biomass per hectare, the default value of 5 Mg Cha^{-1} was used for C stocks after one year of growth for lands planted with annual crops (IPCC, 1995). Similarly, for waste lands the default value for biomass immediately after conversion is 0 Mg ha^{-1} (IPCC, 2006). In case of soil, the default values for stock change factors, F_{LU} (land use system), F_{MG} (management) and F_I (C input) were adopted, based on the Tier 1 approach. For F_{LU}, F_{MG} and F_I default value of 1 was used for the first year of the inventory period and a default value of (0.48-0.64), 1 and 0.92 respectively for the last year of the inventory period. Each of these factors represents the change over a specified number of years (i.e., a default figure of 20 years), which can vary across sectors, but is typically invariant within sectors.

4.3. Results

The total area under forest cover as estimated by RS-based analysis was 64.20 Mha, 63.96 Mha and 67.83 Mha in 1982, 1992 and 2002 respectively (FSI 1987, 1995 & 2003). The assessment of the latest state forest reports based on remote sensing biennial assessment indicates a nationwide increase in forest cover. The forest cover which was 64.20 Mha as per the SFR 1987 (based on 1981-83 satellite data) increased to 67.83 Mha as per FSI (2003) estimates covering 20.64 percent of the geographic area. For the first time FSI estimated a tree cover (forest patches of less than 1 hectare) of 9.99 Mha (3.04%) in 2002. This was in addition to the forest cover of 67.8 Mha so that the total area under forest and tree cover is 77.82 Mha (23.68%). However, for equivalency with earlier periods only forest cover of 67.8 Mha (for 2002) has been used in our analysis. According to the FAO's Global Forest Resources Assessment (2005), India along with China is amongst the few developing countries to show a net positive change in forest area during the 1990s.

Emissions and removal of CO_2 from land use change come under three categories, namely, a) reduction in forest cover resulting from industrial logging, fuel wood harvest and shifting cultivation, b) clearing of forests for conversion to permanent cropland/ waste lands, and c) clearing of land for conversion to forest lands (including plantations). The CO_2 emissions from land use change were reported at the national level for two decades 1982-1992 (PI) and 1992-2002 (PII), using the IPCC 2006 methodology. The results are described in detail in the following sections and summarized in Table 4.3.

4.3.1. Net C flux due to forest land remaining forest land

The net C change in lands remaining as forests is estimated as the difference between the C gain due to annual increment and various losses, such as wood extraction (timber and fuel wood). The estimated annual increase in C stocks due to biomass growth in Indian forests was 77.82 Tg C and 79.65 Tg C for 1982-1992 and 1992-2002, respectively. These estimates are significantly higher than the earlier estimates made by Lal & Singh (2000), but are very similar to the C stock estimates as in India's national communication to UNFCCC (NATCOM).

TABLE 4.3 **Land Use/Transformation Category Net C flux (Tg Cyr^{-1})**

Land Use/Transformation Category	**Net C flux (Tg Cyr^{-1})**	
	1982-1992	**1992-2002**
A) Forest land remaining forest land	61.97 (Mha)	63.44 (Mha)
A1. Annual increase in biomass carbon stocks due to biomass growth	77.82	79.65
A2. Annual decrease in biomass carbon stocks due to biomass removals	74.41	77.21
Net C change [A1 – A2]	3.41	2.44
B) Land converted to Forest land		
B1. Area of land converted to forest land annually	0.2 (Mha)	0.5 (Mha)
B2. Annual change in carbon stocks in biomass	0.28	0.62
B3. Annual change in carbon stocks in mineral soils	0.58	1.23
Net C change [B2 + B3]	0.86	1.85
C) Forest land converted to cropland		
C1. Area of land converted to cropland	0.22 (Mha)	0.07 (Mha)
C2. Annual change in carbon stocks in biomass	- 9.40	- 3.02
C3. Annual change in carbon stocks in mineral soils	- 0.52	- 0.18
Net C change [C2 + C3]	- 9.92	- 3.20
**Net C Emissions /removals from Land use change	+ 5.65	- 1.09

Source: **For the purpose of reporting, it is necessary to reverse the sign so that the resulting value is expressed as (-) for removal/ uptake or (+) for emission.

Madhya Pradesh which has the largest forest area reported biggest increase in biomass carbon stock (16.4 Tg Cyr^{-1} and 17 Tg Cyr^{-1} during PI and PII respectively). Arunachal Pradesh, Orissa, Maharashtra and Uttar Pradesh were the other main contributors to the increase in biomass carbon stocks due to biomass growth. The total annual loss of carbon due to reductions in the biomass as a result of logging and fuel wood extraction was estimated as 74.41 Tg C and 77.21 Tg C for PI and PII, respectively. The results indicate a net annual uptake of 3.41 Tg C (or 12517 Gg CO_2) and 2.44 Tg C (or 8929 Gg CO_2) in PI and PII, respectively.

Under Tier 1, it was assumed that for forest land that remained forest, the carbon stock in soil organic matter does not change, regardless of any change of forest management, types and disturbance regimes. Moreover, the Tier I assumption for both dead wood and litter pools is that their stocks do not change over time if the land remains in the same category, i.e., forest land that stays forest land. Thus, for the purpose of this study, the changes in carbon stocks or emissions from these pools were assumed to be zero.

4.3.2. Net C flux due to land conversion to forest land

Land is converted to forest land by afforestation and reforestation, either by natural or by artificial regeneration (including plantations). This conversion mainly entails the establishment of fast-growing short rotation plantations on degraded lands or previously unmanaged forest lands, or the abandonment of croplands or pastures, which grow to forests. The state level annual above- and below-ground biomass growth, soil carbon density and afforestation rates were the primary data used for estimating net carbon flux in the land converted to forest land. The net C accumulation varies widely due to species, density, location and soil management. The total area of land afforested annually was 0.2 Mha and 0.5 Mha during PI and PII, respectively. Afforestation programmes have been taken up all over India to meet the increasing demand for fuel and pulp wood. Short rotation plantations of specific species (like Eucalyptus, deodar, poplar etc) are frequently established by foresters and farmers to yield wood in quick cycles to meet the urban/industrial demand of fuel and pulp wood. The species are planted under the afforestation /reforestation programmes on the basis of their end uses, and grouped on the basis of their average productivity and rotation ages. The annual biomass productivity was as low as 1.1 and 1.28 Mg $ha^{-1}yr^{-1}$ in Punjab and Gujarat respectively, and maximum of 2.73 Mg $ha^{-1}yr^{-1}$ in Andaman & Nicobar Islands. The total annual increase in biomass C stocks due to biomass growth was estimated as 0.28 Tg C and 0.62 Tg C for PI and PII, respectively. The state annual increase in biomass C stocks due to biomass growth ranged from 1.5 Gg C in Karnataka to 96 Gg C in Arunachal Pradesh during 1982-1992 and from 0.1 Gg C in Dadra & Nagar Haveli to 93 Gg C in West Bengal during 1992-2002. Land conversions on mineral soils generally increase soil C stocks (particularly in land previously managed for annual crops) (Post and Kwon, 2000). The annual change in C stocks in mineral soils was estimated as 0.58 Tg C for PI and 1.85 Tg C for PII. The soil C stocks contributed 70% in PI and 66% in PII to the total C uptake. The total C uptake (i.e., biomass & soil) due to this land use change was estimated as 0.83 Tg C for PI and 1.85 Tg C for PII.

4.3.3. Net C flux due to forest land conversion to another land use

Deforestation and other changes in land use cause significant exchanges of C between the land and the atmosphere. The decline in the forest area in each state or union territory between the years 1982 and 1992 for PI and 1992 and 2002 for PII was considered for the present study. The deforestation rate estimate was based on the aggregate decrease in forest area at the state level separately for two periods (1982-1992) and (1992-2002). The annual area of forest land converted to cropland and waste land was estimated as 0.14 Mha and 0.08 Mha respectively in PI and 0.04 Mha and 0.03 Mha in PII i.e., a total deforestation of 0.22 Mha and 0.07 Mha in PI and PII respectively. The annual change in C stocks in biomass was estimated as 9.4 Tg C during PI and 3.02 Tg C during PII. Orissa (27%), Maharashtra (16%) and Andhra Pradesh (14%) were the states where forest area was reduced the most between 1982 and 1992, whereas Madhya Pradesh (40%) and Andhra Pradesh (34%) accounted for the biggest decline in forest land between 1992 and 2002. The state-level annual change in C stocks in biomass between 1992 and 2002 ranged from 7 Gg C in Haryana to 2127 Gg C in Assam, and from 38 Gg C in Mizoram to 1064 Gg C in Arunachal Pradesh.

The annual change in C stocks in mineral soils was estimated as 0.52 Tg C in PI and 0.18 Tg C in PII. The annual net C emission due to conversion of existing forest lands to cropland and waste lands was estimated as 9.92 Tg C in PI and 3.20 Tg C in PII. The woody biomass left to decay after conversion was assumed to be nil as it is collected by the local inhabitants to be used as fuel wood.

Given the available data and underlying assumptions, the results indicated that the Indian forest sector acted as a small source of carbon during the period 1982-1992 and as a small carbon sink during the period 1992-2002. The annual net C flux due to land use changes was estimated as 5.65 Tg C yr^{-1} or 20717 Gg CO_2 yr^{-1} and 1.09 Tg C yr^{-1} or 3997 Gg CO_2 yr^{-1} during 1982-1992 and 1992-2002 respectively. Thus, the cumulative net carbon flux from Indian forests due to land use change between 1982 to 2002 was estimated as 45.6 Tg C.

4.4. Discussion

Estimation of GHG emission inventories in India started on a limited scale in 1991. These estimates were further revised using the updated methodologies, country specific emission factors and activity data and several papers and reports were published (Mitra, 1992; ALGAS, 1998; Garg *et al*. 2001). The studies on net carbon release due to land use changes in Indian forests are summarized in Table 4.4.

The net carbon balance estimates depend on the methodology adopted as well as on the values of major parameters used for estimation. Each study adopted a different approach based on different methods, different sources of data, different carbon pools and for different years, resulting in a net forest carbon flux that ranges from 0.4 Tg Cyr^{-1} (ALGAS, 1999) to a sink value of 5 Tg Cyr^{-1} (Ravindranath *et al*. 1997). Ravindranath *et al*. (1997) reported that a total of 27.6 Tg C is emitted from Indian forests annually as a result of deforestation and 12.87 Tg C from degraded forests.

Chhabra *et al*. (2002b) computed district level forest phytomass C for 1988 and 1994 and concluded that district level changes in forest cover resulted in better estimates than the results from the aggregated national estimates. As part of India's

TABLE 4.4 **Estimates of C emissions/removal due to deforestation and land use changes in India**

Period	Net C release (Tg C yr^{-1})	Deforestation (Mha yr^{-1})	Remarks	Reference
1980	(-) 3.98	-	Volume based biomass estimates using net C flux model	Hall & Uhlig (1991)
1985	42.52	0.05	Estimates from fires, firewood, shifting cultivation and deforestation	Mitra (1992)
1986	(-) 5.00	0.49	Net difference between emissions (63.6 Tg C) and removals (68.9 Tg C)	Ravindranath et al. (1997)
1987	38.21	1.50	Net emission from deforestation and logging	WRI (1990)
1990	0.40	0.06	IPCC revised 1996 guidelines	ALGAS (1998)
1991	5.73	0.34	IPCC revised 1996 guidelines	WRI (1994)
1994	12.8	-	Estimates based on fluxes between forest biomass (live or dead), soils, forest products and atmosphere	Haripriya (2003)
1985-1996	9.00	-	Using a simple book-keeping MBL model, estimates from deforestation, afforestation and phytomass degradation	Chhabra and Dadhwal (2004)
1994	3.86	-	IPCC revised 1996 guidelines	NATCOM (2004)
1982-1992	5.65	0.22		
1992-2002	(-)1.09	0.07	IPCC 2006 guidelines	This study

Note: − (removal) / + (addition) to atmosphere

National Communication to the UNFCCC, the most comprehensive GHG inventory was reported for the year 1994 based on IPCC 1996 guidelines (NATCOM, 2004). According to this inventory, the net emissions from the LULUCF sector were estimated to be 3.86 Tg C for the inventory year 1994. It is pertinent to mention that LULUCF sector in India contributed only 1.78% of the total CO_2 emissions according to the NATCOM.

The Ministry of Environment and Forests estimates total plantation area, i.e., as forests, wastelands, village commons, and road/canal side and farmers lands. The road/canal side and farmers land plantation is reflected in trees outside forests. Many studies have indicated 60-70% success rate. In addition due to short rotation plantation (7-10 years), species are clear felled and the area is replanted. In cumulative area of plantations, replanted areas are counted doubly and areas of failed plantations are also included. Uncertainty therefore exists in the actual area of plantations. Our estimates for plantation figures were obtained independently for positive forest cover change at the state level. If similar estimates are obtained at district level/ grid wise, more refined numbers would be generated (Chhabra et al. 2002b). Direct use of plantation area would give rise to larger overestimates and we aim to produce conservative estimate in this study.

The results are also dependent upon the quality of input data and one of the areas of concern is fuel wood extraction from Indian forests. As many have pointed out (FSI, 1987; Ravindranath *et al*. 1997; Pandey, 2002; Haripriya, 2003), the recorded extraction is much lower than the actual consumption. Forests become degraded because of illicit felling of trees for timber and fuel wood that exceeds the carrying capacity of the forests. Due to land use change, an area can change from source to sink or vice versa, depending upon the data and the methodology used. The fluxes of carbon attributed to logging include the losses of carbon from slash burning and wood products, as well as the accumulation of carbon in trees re-growing after harvest. Estimating the net C balance from harvest requires accurate information on the available biomass before harvest, the fraction of biomass harvested or damaged, and the fraction removed from the forests and used as fuel wood and wood products. Estimates of rates of deforestation in India vary widely. The annual deforestation rates were estimated as 0.49 Mha during 1982-1986 (Ravindranath *et al*. 1997), 0.09 Mha for the period 1988-1994 (Chhabra *et al*. 2002b) and 0.27 Mha (Manhas *et al*. 2006). In the present study the annual rate of deforestation was estimated as 0.22 Mha for PI and 0.07 Mha for PII showing the reduction in the rate of deforestation. Since the implementation of social forestry and large-scale afforestation programmes, fuel wood production has gradually shifted from forests towards non-forests areas. A lot of fuel wood extraction now takes place along roadside, canals and farm forestry regions, gradually decreasing pressure on forests for wood removal. Thus, varying figures for the consumption and production of wood from the forests give different estimates of the net C flux. It is also possible that fulfilling the wood demands from outside the forests can reduce the pressure within the forests thereby increasing the biomass C within the forests.

Land use can have a large effect on the size of soil pool through activities like conversion from forest land to cropland or grassland, where 20-40% of original soil carbon stock can be lost. Within a land use type, a variety of management practices also can influence soil organic C storage, particularly in cropland and grassland (Ogle *et al*. 2005). The time dependence (D) (i.e., default as 20 years) determines the number of years over which the majority of soil organic C stock change occurs, following a management regime. It is possible to use the default time dependence (D) for the land use sector, (e.g. 20 years for cropland) but the dependence can be changed if sufficient data are available to justify a different time period. With a 30 year (T) time dependence (where T exceeds D) for soil organic carbon to reach equilibrium, the carbon uptake can be reduced from 0.5 to 0.3 Mg C ha^{-1} during PI and from 0.2 to 0.1 Mg C ha^{-1} during PII.

A few studies estimating carbon flux due to litter and harvest are available from India but not enough to estimate the net carbon flux due to land use changes (Haripriya, 2003; Chhabra & Dadhwal, 2004). The total litter fall carbon flux was estimated as 210 ± 20 Tg Cyr^{-1} for 1980-82 (Chhabra & Dadhwal, 2004). And Haripriya (2003) estimated that during 1993-94, disturbances released 11.5 Tg C into the atmosphere (of which fires accounted for 10.8 Tg C, 0.02 Tg C was due to mortality and 0.7 Tg C was due to clear-cut logging and slash burning). Recent studies with detailed spatial analysis for India looked at district level C emissions (Garg *et al*. 2002), district use of phytomass carbon stocks (Chhabra *et al*. 2002b), and carbon stock in biomass and soil for parts of Peninsular India (Ramachandran *et al*. 2007).

4.5. Conclusion

The present study was an attempt to study long-term pattern of emissions from land use change using the latest methodology based on IPCC 2006 guidelines. This approach was intended to improve consistency and completeness in the estimation and reporting of greenhouse gas emissions and removals. The study builds on previous studies that have investigated forest C fluxes in India by adopting three hierarchical tiers of methods that range from default emission factors and simple equations to the use of country-specific data to accommodate natural Indian conditions.

In order to accurately estimate the net C flux from land use changes, there is a need to include all carbon stocks and flows from wood debris, litter, dead trees and wood products. Thus, both the uptake of C in forest land and the sequestration by afforestation / plantations are important. Also, the very small net flux, resulting from various causes, suggests the need for reliable data about the component fluxes. Thus, while area, density etc are based on India-specific data, most of conversion factors are regional/climatic/global averages. There is therefore an urgent need for India-specific parameters in order to obtain reliable figures. Estimates could be improved by applying the IPCC 2006 methodology to subcategories based on forest type and/or climate to districts rather than to states, as was done in this study. Land use change in India is currently not a major contributor to the atmospheric CO_2 increase. This is due to an increase in the area under dense forests, a reduction in the deforestation rates through policy measures and high rates of annual plantation, and the effective implementation of measures to protect our forests from deforestation and degradation. Indian's energy related emissions are projected to increase in future and it is perceived that various environment friendly initiatives like enhancing the use of renewable energy sources, halting deforestation, enhancement of afforestation programmes on large scale, and reporting of GHG inventory by sources and sinks will address climate change issues effectively. Although there are some uncertainties associated with the emission and removal estimates, ongoing efforts will continue to improve these estimates, reducing the uncertainties associated both with the quality of data and the methodologies adopted, thereby producing transparent, comprehensive, comparable and accurate results in future.

CHAPTER 5

Carbon storage versus fossil fuel substitution: a climate change mitigation option for two different land use categories based on short and long rotation forestry in India.

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ABSTRACT

Short rotation bioenergy crops for energy production are considered an effective means to mitigate the greenhouse effect, mainly due to their ability to substitute fossil fuels. Alternatively, carbon can be sequestered and stored in the living biomass. This paper compares the two land use categories (forest land and non-forest land) for two management practices (short rotation vs. long rotation) to study mitigation potential of afforestation and fossil fuel substitution as compared to carbon storage. Significant carbon benefit can be obtained in the long run from using lands for growing short rotation energy crops and substituting fossil fuels by the biomass thus produced, as opposed to sequestering carbon in the biomass of the trees. When growth rates are high and harvest is used in a sustainable manner (i.e., replanting after every harvest), the opportunities for net carbon reductions appear to be fossil fuel substitution, rather than storage in ecosystem biomass. Our results suggest that at year 100 a total of 216 Mg C ha^{-1} is sequestered for afforestation/reforestation using long rotation sal (*Shorea robusta* Gaertn. f.) species, as opposed to offset of 412 Mg C ha^{-1} for carbon storage and fossil fuel substitution for short rotation poplar (*Populus deltoides* Marsh) plantations. The bioenergy option results in a continuous stream of about 3 Mg C $ha^{-1}yr^{-1}$ of carbon benefits per year on forest land and 4 Mg C $ha^{-1}yr^{-1}$ on non-forest land. Earlier studies have shown that in India waste land availability for establishing energy plantations is in the range of 9.6 to 36.5 Mha. Thus, using the 758 Tg biomass per year generated from 9.6 Mha waste land gives a mitigation potential in the range of 227 to 303 Tg C per year for carbon storage and fossil fuel substitution from poplar plantation for substituting coal based power generation. Depending upon the land availability for plantation, the potential for energy generation is in the range of 11370 PJ, possibly amounting to a bioenergy supply of 43% of the total projected energy consumption in 2015. Further studies are needed to estimate the mitigation potential of other species with different productivities for overall estimation of the economic feasibility and social acceptability in a tropical country like India.

Key words: Bioenergy, Fossil fuel substitution, Mitigation, Short rotation crops, Afforestation.

5.1. Introduction

Evidence of climate change linked to with human-induced increase in greenhouse gas (GHG) concentrations is well documented in supported by a number of international studies (IPCC, 2001; 2007). Due to rapid economic growth and large population size, energy consumption is projected to increase at the highest rates in developing countries, largely in China and India. This increase in energy consumption will result in higher greenhouse gas emissions (GCP, 2008; Takeshita, 2009), associated with fossil fuel use. Additional greenhouse gas emissions originate mostly from land-use change, with deforestation in tropical countries accounting for roughly 20% of the anthropogenic carbon emissions (IPCC, 2007). To contribute to extend the worldwide task of reduction of GHG emissions, and or to partly offset the deforestation, the Kyoto protocol (KP) explicitly considers reforestation and afforestation activities for carbon sequestration accounting (IPCC, 2007). Terrestrial carbon dynamics are typically characterized by long periods of slow mall rates of carbon uptake, interrupted by short periods of rapid and large carbon releases during disturbances or harvest. Depending on the stage of stand development, individual stands can be are either carbon sources or carbon sinks. Theoretically, maximum carbon storage (saturation) in a forested landscape is attained when all stands are in old-growth state, but this rarely occurs as natural or human disturbances maintain stands of various ages within the forest landscape. For an average hectare of forested land worldwide, between 50 and 120 Mg (1 Mg = 10^6 g) of carbon are accumulated in aboveground biomass vegetation (IPCC, 2000). The total aboveground forest C stock in the biosphere is estimated to be around 320–360 Pg (1 Pg = 10^{15} g; Dixon *et al*. 1994; FAO/FRA 2006; IPCC, 2000).

Forest mitigation options include reducing emissions from deforestation and forest degradation, enhancing the sequestration rate in existing and new forests, providing wood fuels as a substitute for fossil fuels, and providing wood products for more energy-intensive materials (IPCC, 2007). The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) concludes that for mitigation of climate change several types of measures need to be considered simultaneously (IPCC, 2007). One of the measures that are receiving increased attention from scientists, policymakers and governments is land management to protect and reforest forest land either by direct forest management, or by establishment of fast growing plantations to produce biomass that can be substituted for fossil fuels in energy production. Both these mitigation options are likely to enhance the competitive advantage of woody biomass energy over fossil fuels as they may store carbon while at the same time replace emissions from fossil fuel use (Marland and Schlamadinger, 1997; Berndes *et al*. 2003; Walker *et al*. 2009). Marland and Schlamadinger (1997) suggested that direct carbon sequestration is favoured under low growth and low conversion efficiency (slow growing, long-lived trees), while fossil fuel substitution is favoured under high growth and high conversion efficiency (high production, short-rotation plantations). In line with this, Baral and Guha (2004) showed that significant carbon benefit can be obtained by substituting for coal or gasoline by biomass derived from short rotation woody crops, as compared to sequestering carbon in standing trees. Baral & Guha (2004) indicate that the use of tree biomass for fossil fuel substitution can be a longer-term measure because harvesting and replanting in a given piece of land can be carried out in perpetuity, while storage of carbon in biomass through photosynthetic uptake is limited to the build up of biomass in the forest, which approaches a maximum at high forest age, when natural decomposition equals biomass formation. Although both the approaches i.e., carbon storage through accumulated tree growth and biomass use by substituting fossil fuels, seem to be conflicting, both offer the prospect of substantially contributing to overall net carbon dioxide (CO_2) emissions reduction, by different mechanisms.

Biomass from forestry can contribute 12-74 EJ (1 EJ = 10^{18} J) per year to energy consumption, with mitigation potential roughly equal to 0.4-4.4 Pg CO_2 per year depending on the assumption whether biomass replaces coal or gas in power plants (IPCC, 2007). Biomass in India already accounts for 31% of the total primary energy use, while fossil fuels account for about 67% (Gupta and Ravindranath, 1997), with solar power and wind energy accounting for the remainder. Biomass energy includes fuel wood, crop residues and cow dung, accounting for 63%, 28% and 9% of the total, respectively (Gupta and Ravindranath, 1997).

Forest plantations established exclusively for the purpose of energy production are becoming more common, and plantations with multiple end uses may provide wood both for generating fuel and for other purposes (FAO, 2008). A recent FAO study by Carle and Holmgren (2008) surveyed 61 countries representing 95% of all the planted forests; they indicated that potential industrial wood production from planted forests in 2005 was 1.2 billion m^3 or two-thirds of the overall industrial wood production in that year. Establishment of plantations on degraded and waste lands is one of the best and most promising options for halting deforestation and increasing carbon storage in trees. Reforestation of non-forest lands will prevent further land degradation and can provide a continuous supply of biomass for energy use, replacing fossil fuels and reducing net C emissions.

Since the implementation of social forestry and large-scale afforestation programmes, fuel wood production has gradually shifted from forests towards non-forests areas. A lot of fuel wood extraction now takes place along roadside, canals and farm forestry, gradually decreasing pressure on forests for wood removal in India. In India, trees outside forests have a major contribution in meeting timber and fuel wood needs. The total growing stock of wood in India is estimated to be 6.4 billion m^3, of which 4.8 billion m^3 are found in forests and 1.6 billion m^3 outside the officially recorded forest area (FSI, 2003). This information highlights the need to consider both forest areas and non-forest areas in models of carbon mitigation studies. The objective of this study is to compare the C mitigation potential of afforestation and fossil fuel substitution for two land use categories (forest land and non-forest land) and two management practices (short vs. long rotation).

5.2 Methods and Materials

The CO2FIX v. 3.1 stand level simulation model is a tool which quantifies the carbon stocks and fluxes in forest biomass, the soil organic matter and the wood products chain, essentially using a simple bookkeeping approach (Masera *et al*. 2003; Schelhaas *et al*. 2004). The CO2FIX model consists of four modules, i.e. biomass, soil carbon, wood products and bioenergy (the latter being new to CO2FIX v. 3.1) (Figure 1). The biomass module converts volumetric net annual increment data to the annual carbon stock of the biomass compartment. Turnover and harvest parameters drive the fluxes from biomass to soil. The soil module of CO2FIX takes litter material generated in the biomass module including natural mortality, management mortality, and logging slash and separates it into non-woody litter (foliage and fine roots), fine woody litter (branches and coarse roots) and coarse woody litter (stems and stumps). Each of these litter compartments is decomposed in two steps. In the first step a fractionation rate determines the proportion of each component released to the decomposition compartments in a time step. For the compartment of non-woody litter, this rate is equal to 1 which means that all of its contents are released in one time step, whereas for the woody litter compartments this rate is smaller than 1. In the second

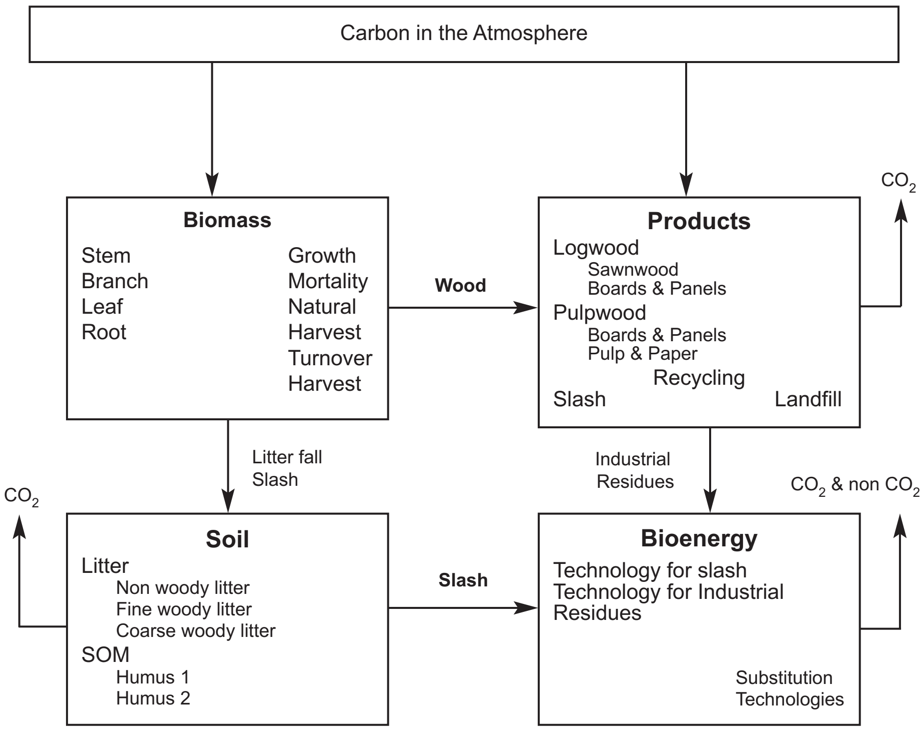


FIGURE 5.1 **Structure of CO2FIX v. 3.1model, including major compartments used in each module, processes affecting the compartments (right hand side in the boxes), major flows between modules and fluxes of CO_2 from modules to the atmosphere.**

step, the model uses assumed chemical compositions (i.e., extractives, cellulose, or lignin) of each component to assign a specific decomposition rate, which determines the proportional loss of its contents in a time step (Liski et al. 2005). Default values are available for the chemical composition of components in the soil module. The soil module uses climate data about precipitation, evapotranspiration and mean monthly temperatures. Initial soil and carbon data were derived from the procedure as reported by Masera et al. (2003). The model is user friendly and provides a number of examples of required input data for a variety of forest management scenarios.

Climate data was used from http://www.indiastat.com. CO2FIX can calculate degree days (above zero, 0^0) and potential evapotranspiration from mean monthly temperatures.

Previously, we used the CO2FIX model for estimating the carbon stocks and carbon sequestration potential of some short and long rotation species under different management scenarios for India (Kaul *et al*. 2010c). For the purpose of this paper, we use the bioenergy module of CO2FIX model, which calculates the carbon mitigation achieved by substituting biomass for fossil fuels. The model simulations were calibrated with inventory data for sal (*Shorea robusta* Gaertn. f.) as representative of long rotation forests and poplar (*Populus deltoides* Marsh) as short rotation plantation forests. For further details on the CO2FIX model, see Masera *et al*. (2003); Schelhaas *et al*. (2004); for a more detailed representation of the parameter values for the above mentioned species in India, see Kaul *et al*. (2010c) The full CO2FIX model is freely available from the web at http://www.efi.int/projects/casfor, together with a large number of examples and case studies. The bioenergy module calculates C-equivalent greenhouse gas flow differences between biomass generated energy and energy derived from fossil fuel. Two subroutines are included in the model: slash biomass substitution technologies and industrial residue substitution technologies. The slash biomass routine uses the part of the slash that remains in the forest after thinning or harvesting short plantations aimed at replacing fossil fuel-based energy production. The industrial residues routine uses industrial woody residues generated from the production of other wood products. For each technology, either traditional (fossil fuel) or substitution (slash and industrial residues), defaults values for efficiency, emission factors, heating values, technology emission factors, and global warming potential of the greenhouse gases are available in the model. The specific values used for the parameterization of the bioenergy module are shown in Table 5.1.

TABLE 5.1 **Main parameters of the bioenergy module to compare current technologies using coal power plant with biomass combustion power plant.**

	Current technology	**Alternative technology**
	(Coal based power plant)	(Biomass combustion power plant)
Energy content (MJ/Kg)	28	15
Efficiency (%)	33	24
CO2 emissions (Kg gas/Kg fuel)	2.425	0
N2O emissions (g/Kg fuel)	.04	.06
CH4 emissions (g/Kg fuel)	.02	.48
CO emissions (g/Kg fuel)	.24	3.6
TNMOC emissions (g/Kg fuel)	0.00	.72

It is worth mentioning that the bioenergy module does not calculate the carbon stock per se; it calculates the effect of using wood or wood waste for the generation of energy. Thus, fossil fuels are replaced by CO_2 neutral fuels, and can thus be regarded as avoided emission. When replanting follows harvesting, the net CO_2 emissions from bioenergy technologies are zero. Therefore their associated CO_2 emissions factors should also be zero. The substitution of fossil fuels by biomass leads to a permanent green house gas mitigation.

We have defined four scenarios in order to draw comparisons among alternative forest management strategies. These scenarios are as follows:

(a) establishment of long-rotation species on forest lands;

(b) short rotation forestry starting on forest lands

(c) establishment of long-rotation species on non-forest lands;

(d) short rotation forestry starting on non-forest lands;

In the scenarios (a) and (b), we assume that forestry is initiated by harvest at time 0 of one ha of forest which contained biomass carbon of 156 Mg ha^{-1} before the final cut. In scenarios (c) and (d), we assume that the forestry is initiated on a non-forest land which was without vegetation or barren for the last 20-30 years. The present study employs the soil and litter carbon uptakes as prescribed by the CO2FIX model run for 20 years without biomass. The scenarios (a) and (c) refer to establishment of trees on forest- and non-forest land, in which trees are planted, protected and allowed to grow without final cut or harvesting, resulting in accumulation of carbon stock in standing trees over the rotation. Thinning is performed at regular intervals as per the prescribed management practices (Tewari, 1995a). The forest is left to its natural dynamics and the biomass removed from the thinning is assumed to be collected and used as fuel wood by local villagers.

The scenarios (b) and (d) refer to planting of short rotation species on forest and non-forest lands with harvesting and replanting on regular basis and using harvested wood to substitute for fossil fuels. A constant growth rate of 8 Mg C $ha^{-1}yr^{-1}$ is considered until the time of harvest for poplar (Kaul *et al*. 2009c). Under fossil fuel substitution, mitigation occurs through the use of slash and industrial wood residues to replace electricity generated by coal fired plant, which is the most commonly used electricity power plant in rural India. The CO2FIX model was run for all four scenarios and the amount of carbon sequestered *versus* the avoided emission via substitution of fossil fuel use was compared over a period of 100 years.

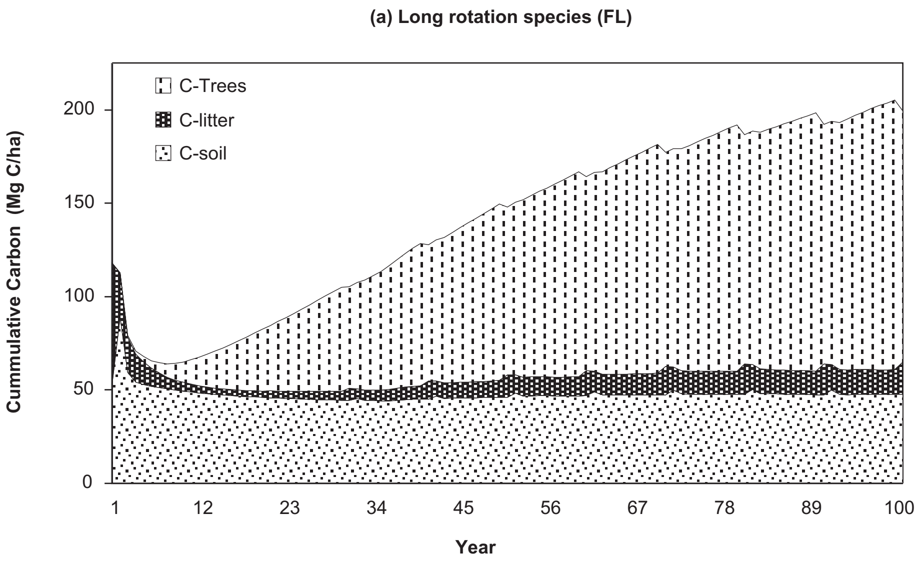
5.3. Results

Figures 5.2 and 5.3 show the cumulative increase in C stocks in various pools over 100 years for carbon sequestration and fossil fuel substitution in forest and non-forest lands. The comparison of simulations for each scenario is presented below in detail.

The carbon storage in forest ecosystem (trees + soil) on forest and non-forest lands varied depending on the species and on the management scenario (Figures 5.2 & 5.3). The long-term (100 years) average carbon stock in tree biomass was higher for long rotation forests as compared to short rotation plantations, irrespective of land use type. The long-term average carbon storage for long rotation species was highest (141 Mg C ha^{-1}) on forest lands as compared to non-forest lands (106 Mg C ha^{-1}) (Figures 5.2a & 5.2b).

Carbon sequestration in soil and litter on forest lands, as simulated by the model, is higher both for short as well as long rotation forests (Figures 5.2a & 5.2b). The long term average carbon stock in tree biomass and soil including litter was 81 Mg C ha^{-1} and 45 Mg C ha^{-1} on forest and non-forest lands for poplar plantations. On forest lands, the soil carbon displayed a rapid decrease in the initial 10 years from 118 Mg Cha^{-1} followed by a slow recovery and later stabilized at 60 Mg C ha^{-1}. This could be due to rapid decomposition of litter and soil resulting in net carbon loss to the atmosphere for initial 10 years and slowly stabilizes with subsequent re-growth. Carbon sequestration in soil and litter through afforestation is higher for long rotation as compared to short rotation species. One possible explanation is that a disturbance due to repeated site preparation and harvesting at regular intervals enhances decomposition of soil and litter resulting in low carbon content when short rotation crops are used.

The Figures 5.2a & 5.2b for long rotation species suggests that the carbon accumulation rate in above ground biomass is linear but declines due to saturation effect. This saturation effect could be avoided if the forest is harvested periodically and a young, fast growing forest is maintained. The net C mitigation potential is strongly dependent on the multitude of parameters that ultimately define the displacement efficiency of bio fuels. Figures 5.4a & 5.4b show the net yearly carbon benefit for short and long rotation species, respectively on forest and non-forest lands since the start of simulation till 100 year period. For short rotation species, the amount of carbon offset increases linearly with time since biomass is continuously harvested and replanted and used to generate energy, and hence under suitable conditions the



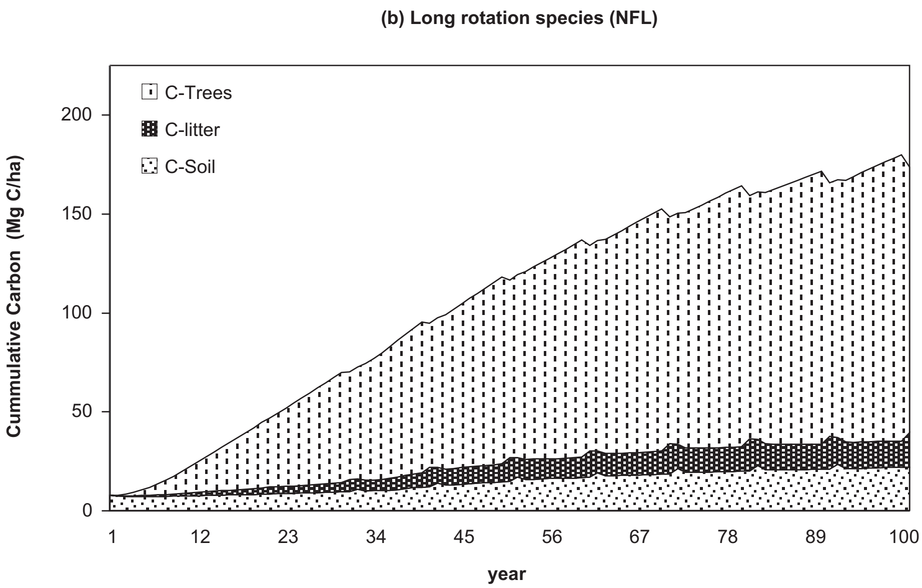


FIGURE 5.2 **Cumulative carbon sequestered in tree, soil and product pools for (a) Forest land and (b) Non-forest land.**

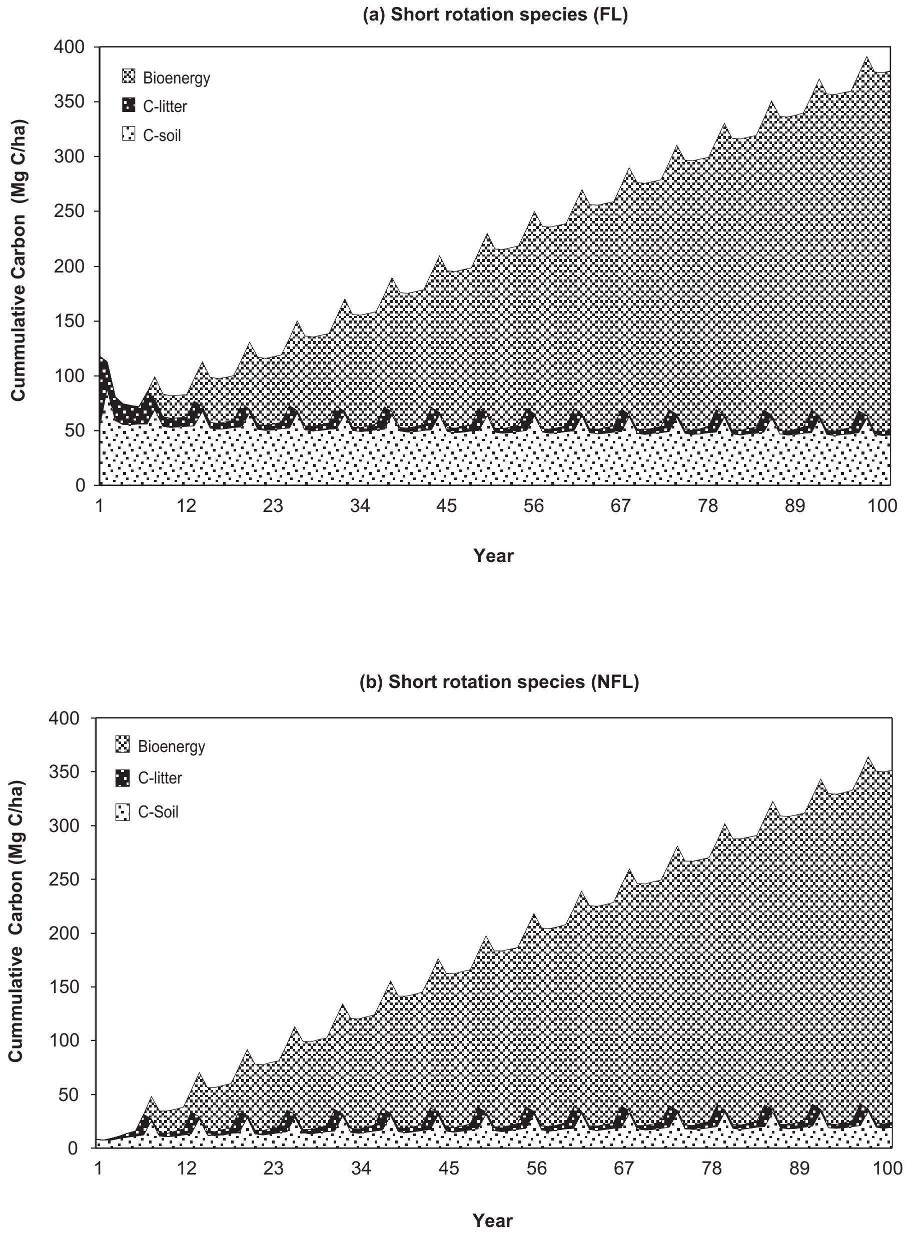


FIGURE 5.3 **Cumulative carbon offset for bio fuel/coal substitution for poplar for (a) Forest Land and (b) Non-forest land.**

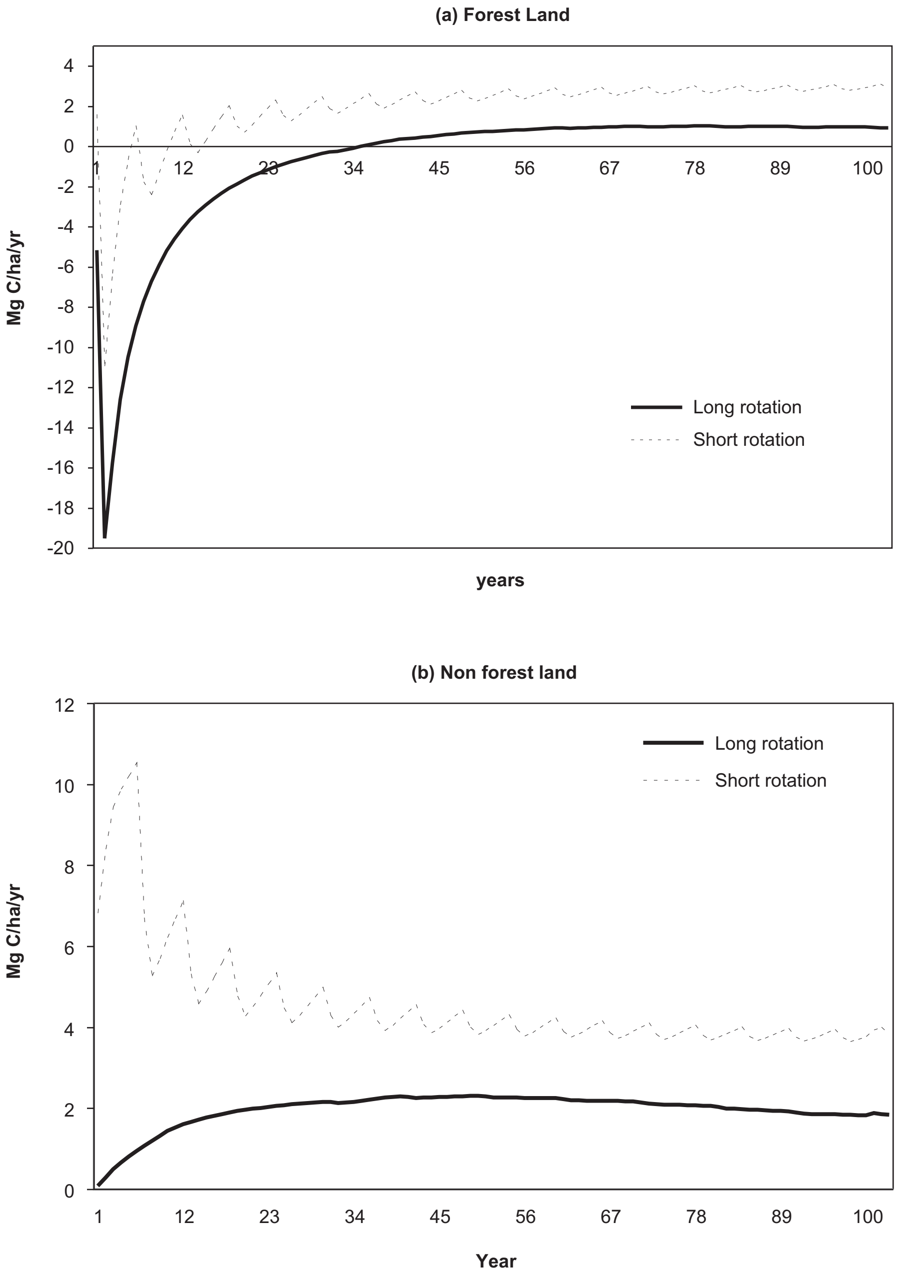


FIGURE 5.4 **Net yearly C mitigation potential (Mg C/ha/yr) of sal afforestation and short rotation bioenergy on (a) Forest land and (b) Non-forest land.**

substitution of fossil fuel can continue forever. On forest lands, the carbon balance is negative in the beginning (due to enhanced decomposition) but it turns positive after about 34 and 14 years respectively, for long rotation sal forests and short rotation poplar species (Figure 5.4a). On non-forest lands however, there is no initial decrease in soil carbon associated with decomposition and emission of carbon in both the species. At 6 years, the carbon sink attains a maximum value of 11 Mg C $ha^{-1}yr^{-1}$ for short rotation poplar plantation on non-forest lands (Figure 5.4b). After a transient period, the bioenergy option mitigates around 1 Mg C $ha^{-1}yr^{-1}$ and 3 Mg C $ha^{-1}yr^{-1}$ on forest land whereas it stabilizes at 2 Mg C $ha^{-1}yr^{-1}$ and 4 Mg C $ha^{-1}yr^{-1}$ on non-forest land, respectively for long rotation sal forests and short rotation poplar plantations.

Figure 5.5 compares the total carbon sequestered vs. the total carbon offset through emission avoidance for short and long rotation forests for the period of 100 years. The carbon benefit at any time is highest for short rotation poplar plantation

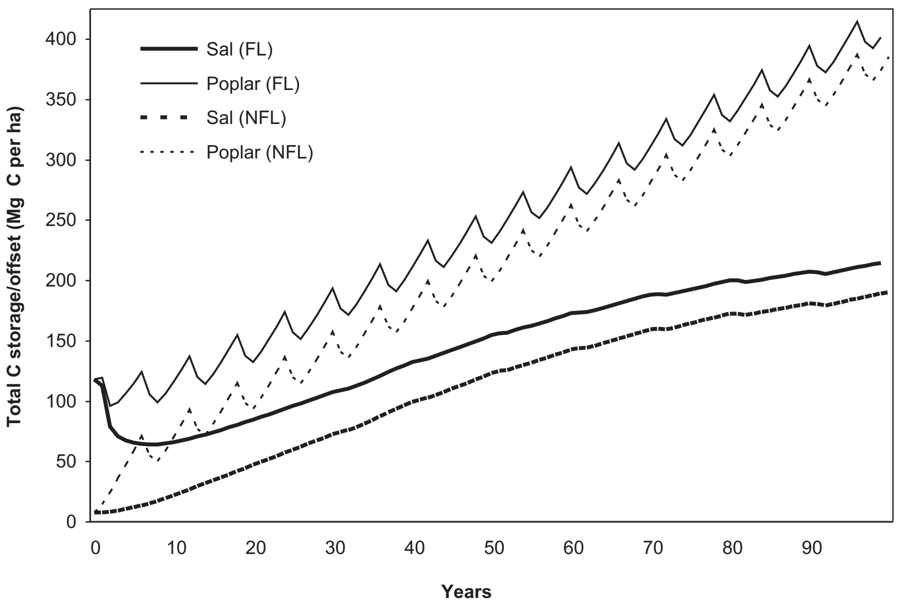


FIGURE 5.5 **Total Carbon sequestered/offset for different scenarios (a) Long rotation Sal afforestation, (b & c) Short rotation energy plantation for fossil fuel substitution.**

involving substitution of coal. This may be attributed to the high carbon sequestration rate and high energy conversion efficiencies. At any time the carbon benefit from land used only for carbon storage is lower compared to fossil fuel substitution scenarios. At year 100 a total of 216 Mg C ha^{-1} is sequestered for afforestation/reforestation using long rotation sal species, as opposed to offset of 412 Mg C ha^{-1} for carbon storage and fossil fuel substitution for short rotation poplar plantations.

As mentioned earlier, we assume that biomass from short rotation poplar plantations is used for electric power generation, substituting coal based electricity generation. Biomass based electricity generated from a sustainable wood supply is a carbon neutral option for power generation leading to zero net emissions. Given that 1 dry Mg of wood replaces 0.67 Mg of coal (Hooda & Rawat, 2006), our model results suggest that 79 Mg $ha^{-1}yr^{-1}$ of wood biomass is available from short rotation plantation, which could replace 53 Mg of coal. Sudha *et al*. (2003) estimated that under different biomass demand scenarios, the total land available in India for biomass production ranges between 9.6 to 36.5 Mha. Thus, the potential biomass that can be acquired for generating bioenergy from 9.6 Mha land would be 758 Tg (1 Tg = 10^{12} g) per year. The annual electricity generation potential (1 Tg = 1 TWh of electrical power) would be 758 TWh. Hence every megawatt hour (MWh) of bioelectricity generated from biomass leads to a C emission reduction of 0.3 to 0.4 Mg as compared to the use of fossil fuel (Hooda & Rawat, 2006; Rawat & Kishan, 2008). Thus, using short rotation plantations for electric power generation gives a mitigation potential in the range of 227 to 303 Tg C per year from carbon storage and fossil fuel substitution. The energy content of wood is considered as 15 GJ Mg^{-1} and thus the energy generation potential of poplar plantation generating 758 Tg wood annually, would be 11370 PJ. It is projected that the energy consumption in 2015 will be 26,527 PJ; thus plantation biomass could supply about 43% of the total projected energy consumption in India in 2015.

5.4. Discussion

Several researchers have pointed out the relative carbon benefit of using land for growing short rotation plantations in addition to afforestation projects. Forest management integrated with bioenergy options has the potential for carbon mitigation in the land use sector. When short rotation plantations are used to produce biofuels to substitute fossil fuels, they can make an ongoing contribution to reducing net CO_2 emissions. In addition, production of biomass for energy production in newly established short rotation plantations may take away pressure from existing forest land in which currently fuel wood is collected. Hence bioenergy plantations may contribute to forest and biodiversity conservation. Conversion of agricultural lands to forest can result in much higher rates of sequestration due to increases in tree carbon in addition to soil C increases (Adams *et al*. 1999; Alig *et al*. 1997; Stavins, 1999). IPCC special report on land use, land use change and forestry states that the potential for additional C sequestration on agricultural soils is related to how depleted the C stocks in the soil are at the start of a new carbon sequestering project (IPCC, 2000). Our study results show that the soil carbon on forest lands displayed a rapid decrease in the initial 10 years from 118 Mg C ha^{-1} followed by a slow recovery and later stabilized at 60 Mg C ha^{-1}. The slow increase could be mainly due to litter fall and other dead organic matter. Paul *et al*. (2003) suggested that soil organic carbon decreased at an average rate of 0.79 Mg C $ha^{-1}yr^{-1}$during the first 10 years following afforestation and to increase at a rate of 0.46 Mg C $ha^{-1}yr^{-1}$ from 10 to 40 years. The average rate of soil organic carbon after 40 years was predicted to be 0.06 Mg C $ha^{-1}yr^{-1}$. Paul *et al*. (2003) claimed that the initial decrease of soil organic carbon after afforestation was mainly due to soil disturbance by site preparation and low organic C input from a young forest stand. Findings from other studies also suggest that soils with high initial soil organic carbon contents generally showed losses in carbon immediately following afforestation (the first 5–10 years, Paul *et al*. 2002; Vesterdal *et al*. 2002), while soils with low initial soil organic carbon contents often exhibited gains of soil organic carbon (Bouwman and Leemans, 1995; Garten, 2002).

An earlier study by Hooda *et al*. (2007) estimated the C mitigation potential of Eucalyptus under agroforestry system in the Uttarakhand state of India. The comparison of Eucalyptus for bioenergy at 6 year rotation and for C sink at 10 year rotation showed higher mitigation potential in bioenergy case. The net C abatement thus was 3.1 Mg C $ha^{-1}yr^{-1}$ under the bioenergy scenario and 1.96 Mg C $ha^{-1}yr^{-1}$ under the agroforestry system even though mean annual increment (MAI) of Eucalyptus in the latter case was 11.25 Mg $ha^{-1}yr^{-1}$. Our results are also comparable with the mitigation potential estimates from earlier studies in India. Hooda & Rawat (2006) estimated the C mitigation potential by 2010 in the range of 25 Tg C to 124.5 Tg C if plantation energy were substituted for fossil fuels. In case of marginal soils / wastelands, not currently under productive use, different species have been suggested to offer good prospects for energy plantations (Goel & Behl, 1996; Baral & Guha, 2004; Niu and Duiker, 2006). Goel & Behl (1996) investigated Prosopis juliflora (Sw.) and Acacia nilotica (L.) for afforestation on alkaline soils in relation to tree age for establishing harvest rotation cycles. They suggested that these species were most suitable for short rotation fuel wood forestry programmes because of their high wood density, biomass yield, low ash and moisture content, and good heat of combustion at the juvenile stage. Coal is the mainstay of Indian energy sector and the rate of coal consumption in production of electricity, overall for India, is of the order of 0.77 – 0.85 Kg per KWh (Raghuwanshi *et al*. 2006). For every Mg of fossil fuel burned, at least three quarters of a Mg of carbon is released as CO_2 and it has been found that 0.8 – 0.9 Kg per KWh CO_2 is emitted in the Indian power sector (Raghuwanshi *et al*. 2006). Dependence on coal-based electric power plants (accounting for 70% of power generation) is leading to environmental degradation; local (land degradation), regional (air, water and soil pollution) and global (greenhouse gas build-up leading to climate change) (Ravindranath *et al*. 2004). Among the renewable energy options, bioenergy technologies have been promoted for meeting rural electricity needs.

Van der Voet (in: Nabuurs and Mohren, 1993) carried out an uncertainty analysis of the model CO2FIX for the Norway spruce forest type in central Europe. For the 32 independent inputs to the model, he found that for the total carbon stock, the average amounted to 316 Mg C ha^{-1}, whereas the 95% confidence interval for the long term average (after 300 years simulation) ranged from 254 to 403 Mg C ha^{-1} which was found to be reasonable. The main uncertainty was caused by uncertainty over the soil organic matter dynamics and the carbon content of dry matter. Since the main input in our study was based on widely accepted growth and yield tables, the present study would probably give a comparable span in results. Although, the growth and yield tables are known to be based on rather old monitoring data which do not represent current site conditions, there are chances of carbon sequestration potential being underestimated. But on the other hand, yield tables also represent fully stocked forests which do not occur very often in practice (Nabuurs and Schelhaas 2002).

5.5. Conclusion

The most suitable option for a developing country like India lies in the use of non-forest lands for fast growing short rotation plantations for bioenergy. Reforestation of non-forest lands will prevent further degradation and also may provide continuous supply of biomass for energy use thereby replacing fossil fuels and reducing net C emissions. Among the two mitigation options i.e., storage and substitution, the best option to be adopted depends upon various factors. Substituting sustainably produced bioenergy for fossil fuels is a continuous way of mitigating greenhouse gas emissions. Based on the land use pattern in India, about 40 Mha of degraded and wasteland land (including 5 Mha next to rail tracks and highways) is available for plantation (Ravindranath & Balachandra, 2009). India's wasteland is spread over different regions with different climatic conditions and also falls in the category of rain-fed or irrigated land. To cater to this variety, research is required to determine which particular species and plant variety will give the maximum yield.

In case of already existing natural forests, carbon storage and preservation is the most appropriate method through improved management practices. Old growth natural forests serve as a global carbon sink, not just in the trees but also in the soils and these forests may accumulate large quantities over centuries (Luyssaert *et al*. 2008). When forests are considered only for carbon sequestration, long rotations give greater benefits for carbon storage in forest and product pools (Gercia *et al*. 2005; Kaul *et al*. 2009c). Although there can be a net carbon storage in trees, soil, forest litter and wood products, all of these carbon pools achieve equilibrium and provide no carbon sequestration after a maximum value (Schlamadinger & Marland, 1996). Evidently, clearing of old growth natural forests for plantation of short rotation crops for fossil fuel substitution is not advisable because the net effect is negative for a long period of time as most of the carbon will be lost to the atmosphere and it may take a long period to compensate this loss through substitution of fossil fuel use. However, in long run, energy plantations on the non-forest lands (referred to as agricultural and waste lands) may give higher net carbon benefit annually. The magnitude of the carbon benefit in the afforestation scenario is lowest at any time, as compared to fossil fuel substitution scenarios. Balancing the short and long-term carbon benefits of two approaches i.e., sequestration and substitution depend on different parameters like growth rate, site conditions, substitution efficiency of bio-fuels etc. The difference in carbon balance is thus not only a matter of the management strategy but also reflects a difference in species selection and rates of forest growth. Our results suggest that short rotation plantations with higher growth rates result in greater net carbon benefit at the end of 100 year as compared to long rotation forests used for permanent carbon storage. At year 100, a total of 216 Mg C ha^{-1} is sequestered for afforestation, as opposed to offset of 412 Mg C ha^{-1} from carbon storage and fossil fuel substitution from short rotation poplar plantations. After a transient period, the bioenergy option mitigates around 3 Mg $Cha^{-1}yr^{-1}$ on forest land whereas it stabilizes at 4 Mg C $ha^{-1}yr^{-1}$ on non-forest land, for poplar plantations.

Improvements in productivity will enhance benefits further. Also, in long run accumulated large stock is vulnerable to disturbances, pests etc, which might increase under projected climate change. With improved biomass productivity and efficient energy conservation, it is feasible to sustain a significant share of biomass in total energy use in India by utilizing even a small portion of degraded land for biomass plantation. Moreover, this energy plantation option will probably for India provide income to the owner, employment in the rural area, an alternative fuel source for replacing coal and reducing C emissions. It also may take away pressure on remaining forests, as fuel wood may become available from the energy plantations and does not need to be collected from the existing forests. The aim should be to take the short-term benefit and long-term view of the economics of bio-fuel plantation and provide a facilitating environment to the farmer, bio-fuel enterprises and researchers, so eventually, India may move forward towards energy independent nation.

CHAPTER 6

General discussion and synthesis

6.1. Introduction

Forests play an important role in the global carbon cycle. They store large quantities of carbon in vegetation and soil, exchange carbon with the atmosphere through photosynthesis and respiration, releasing carbon into the atmosphere when they are disturbed and becoming atmospheric carbon sinks while they are growing. It has been estimated that measures such as forestation, agroforestry, regeneration and slowing deforestation, could sequester and conserve approximately 60-87 Pg C globally between 1995 and 2050. India is one of the world's largest tropical countries and has extremely large and diverse forest resources. At the same time nearly 200,000 villages in India are classified as forest fringe villages, and these communities are usually highly dependent on forest resources for their livelihoods. Thus, there are possibilities to develop and implement strategies that fulfil several goals, including the conservation and protection of biodiversity, the safeguarding of the livelihoods of people who depend on the forests, the production of round wood for industrial and commercial needs and the sequestration of carbon.

Indian forests are classified into five major groups, based on climatic factors. These major groups are further divided into 16 types based on temperature and moisture contents. These forest types differ in their species composition and species diversity. Forest cover in India accounts for 20.6% (67.83 Mha) of the total area of the country, and trees outside forests account for an additional 3% (9.9 Mha) (FSI, 2003).

The degradation of forests (and particularly tropical forests) and their conversion to other land uses is a major cause of greenhouse gas (GHG) emissions. In 1994 India's total GHG emissions were 1228 Tg, just 3% of the global total. Sixty three percent of India's GHG emissions were CO_2 (NATCOM, 2004). Although the compound annual growth rates of CO_2 equivalent emissions from India rose by 4.2 per cent between 1990 and 2000, the absolute value of these emissions is still one-sixth that of the United States. Moreover, the per capita GHG emissions from India are one of the lowest in the world (Figure 6.1) and remain considerably lower than those of other rapidly developing countries such as China and Brazil, (2.2 and 1.3 times lower respectively) (Table 6.1) (Sharma *et al*. 2006).

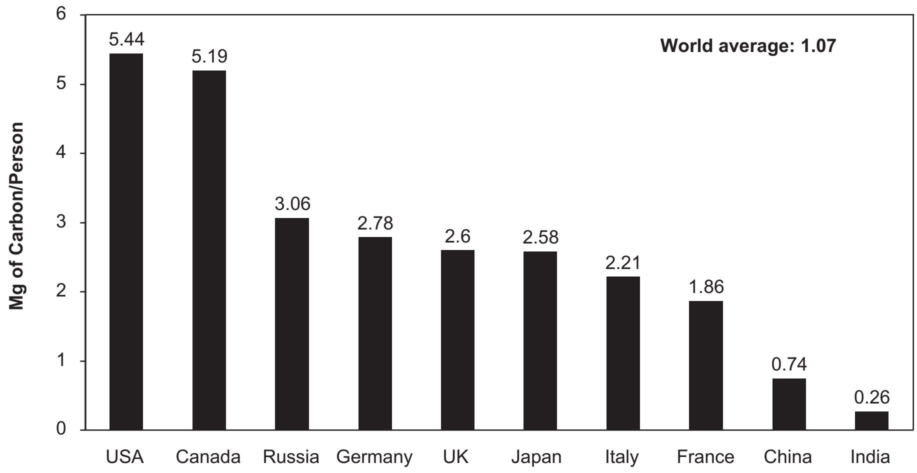


FIGURE 6.1 **Per capita carbon emissions from energy for the year 2003**
Source: International energy Outlook 2005

TABLE 6.1 **Per capita CO_2 equivalent emissions in 2000.**

Country	Per capita CO_2 equivalent emission in 2000 (Mg per capita)	Ratio of per capita emissions compared to Indian emissions	Percentage of Indian emissions
USA	23	15.3	6.5
Germany	12	8	12.5
United Kingdom	11	7.3	13.6
Japan	10	6.7	15.0
India	1.5	1.0	100
Brazil	1.9	1.3	78.9
China	3.3	2.2	45.5
Global	3.9	2.6	38.5

Source: Sharma *et al.* (2006)

The Third Assessment Report of the Intergovernmental Panel of Climate Change (IPCC) indicates that developing countries are likely to be highly vulnerable to climate change, both due to the projected magnitude of these changes and their lack of adaptive capacity. Climate change is one of the most serious global environmental challenges and has the potential to alter terrestrial carbon storage due to changes in temperature, precipitation and carbon dioxide concentrations affecting net primary productivity (NPP), carbon inputs to soil, and soil carbon decomposition rates. India is already experiencing such changes and may have to face a variety of more severe ecological problems in the years and decades to come. These are anticipated to include: drought, disappearing wetlands, eroding soil, the extinction of wild flora and fauna and air and water pollution. Most of these problems today are related to the degradation of land caused by increasing anthropogenic pressures on forests. There is a clear need for global cooperation to arrest the growth of greenhouse gas emissions.

This synthesis summarises the main results of this thesis, which seeks to improve the quantification of carbon pools and fluxes of carbon due to land use, land use change and forestry within India. It uses a calibrated model to estimate the carbon sequestration potential of short and long rotation species and the mitigation potential from bioenergy. In doing so, it addresses the research questions set out in the first chapter.

6.2. Forest conservation, afforestation and reforestation in India: their impact on carbon stocks

India is one of the few developing countries where the rate of deforestation has been reduced and the amount of forest cover has nearly stabilized (FAO, 2005). The main factors contributing to these trends include legislation (such as the Forest Conservation Act -FCA-, 1980), policies (such as the National Forest Policy -NFP-, 1988), and forest conservation and afforestation programs (such as the compensatory regulations included in the FCA 1980). Additionally, the participation of people in the development and protection of forests has been actively promoted by the NFP, 1988 and their role in preserving the forests as a natural heritage has helped to maintain environmental stability. Under the Joint Forest Management (JFM) plan, created in 1990, local communities and the forest department have started to jointly plan and implement forest regeneration programs and the communities are rewarded for their efforts in forest protection and management. So far, more than 100,000 JFM committees cover about 22 Mha of forest area with about 22 million participating members (Rawat and Kishan, 2008). These different policies and actions, taken by the Indian government, have achieved some success in protecting existing forests, regenerating degraded forests, and in establishing forest plantations, with beneficial effects on carbon stocks.

India has a high population density and a low forest cover per capita. Much of the rural population is highly dependent on the forests, and on an agrarian economy. Normally under these conditions, one would expect the forest area to decline, leading to large emissions of CO_2. However, the opposite trends are found. Our results show that between 1992 and 2002 about 0.79 Mha of forests were lost and 4.64 Mha were reforested giving a net increase in the total forest cover of 3.87 Mha (chapter 2). If this current trend continues, the area under forest cover is projected to reach 75 Mha by 2020. Parallel to this the results show that, from 1992 to 2002, the carbon stocks in Indian forests have increased from 2849 Tg C to 2890 Tg C, showing an annual increment of 4 Tg of carbon and an average density of 43 Mg C ha^{-1} (chapter 2). Additionally an estimated 2.68 billion trees outside the forests (FSI, 2003) contribute to an additional national average tree C density of 4 Mg C ha^{-1} (chapter 2). This suggests that trees outside forests are an important resource and should also be considered when carbon stocks are estimated. While it is likely that the Indian forest sector will continue to make positive contributions to global climate change and sustainable development there is also a potential to create more carbon sinks by expanding carbon storage capacities. Increasing the area and carbon density of native forests, plantations and agroforestry can do this. The extent to which this can be achieved depends on the varieties of species used and whether site conditions permit marginal lands to be used for forest plantations.

6.3. The carbon sequestration potential of Indian forests and management options for sustainable increase in carbon stocks

There are a few location-specific studies on productivity of forest plantations. These show that the range of productivity varies between 1.2 and 8.2 Mg ha^{-1} yr^{-1}, with the national mean being about 3.1 Mg ha^{-1} yr^{-1}. This wide variation is not surprising since the location-specific case studies ranged from farm forestry in semi-arid regions to plantations on degraded forestlands in high rainfall zones. Our results indicate that other factors, such as the species used and the management applied, also influence the productivity of forest plantations. The net annual carbon sequestration rates were higher for fast growing short rotation plantations (6 to 8 Mg C ha^{-1}yr^{-1}), followed by moderate (2 Mg C ha^{-1} yr^{-1}) growing plantation forests, and slow growing (1 Mg C ha^{-1} yr^{-1}) natural forests (Chapter 3). However, the long rotation species store the largest carbon stock in living biomass, in the order of 82 Mg C ha^{-1} in the long run. Soil organic carbon (SOC) also plays a very significant role in the carbon balance in the global terrestrial ecosystem. Based on the national and regional soil carbon densities, the SOC stored within Indian forests is estimated between 6.7 and 9.8 Pg C (Dadhwal *et al*. 1998; Jha *et al*. 2003). To assess the potential of additional carbon sequestration through forest management, it is necessary to understand the C storage in forest biomass, soil and wood products, and the interactions between these different compartments. Forest management influences carbon storage through choice over rotation length, thinning intensity, stand density and spacing, and silvicultural practices such as coppicing and soil preparation etc. These choices can cause both increases and decreases in forest carbon stocks. The results from chapter 3 indicate that extended rotation lengths and reduced thinning intensity could enhance the long-term capacity of forest ecosystems to sequester carbon. The goal of simultaneously maximizing carbon storage and producing more valuable saw logs can be achieved from longer rotation lengths. It is expected that a combination of matching species to sites, genetic improvement and proper management practices can be used to improve the growth rate of native tree species. India, with a vast range of forest types, weather and soil conditions, there will be no single forest type that is most suitable for carbon sequestration. When short-term results are desired, short rotation plantations best balance wood demand and carbon storage criteria. When forests are solely considered for long-term carbon storage, long rotation species give greater benefits. Parameters such as soil characteristics, climate conditions and ecological status, should be used as the basis for management practices that maximize productivity and carbon storage and pay attention to maintaining a good soil status. Increases in annual productivity are directly related to an increase in the total standing biomass, which can contribute to higher carbon sequestration.

6.4. The effects of land use change on carbon stocks within Indian forests

Land use change can involve the conversion of forestlands to another land use or vice versa. The emissions and removal of CO_2 resulting from land use change falls within three categories, a) a reduction in forest cover resulting from industrial logging, fuel wood harvesting and shifting cultivation, b) clearing forests for conversion to permanent cropland/ waste lands, and c) clearing land for conversion to forest lands (including plantations). Indian forests are mainly exploited to extract timber, fuel wood and green fodder. Statistics on the volume harvested (legally) are available but the estimates of the volume extracted for timber and fuel wood from forests is much lower than the actual consumption (Haripriya, 2003). Chhabra & Dadhwal (2004) estimated the mean annual flux due to land use changes between 1985 and 1996 as being 9 Tg C yr^{-1}. India's Initial National Communication to the UNFCCC (NATCOM, 2004) estimated the net emissions from the Land Use, Land Use Change and Forestry (LULUCF) sector to be 3.86 Tg C for the inventory year 1994. Further, it was estimated that the LULUCF sector in India contributed only 1.78% of the country's total CO_2 emissions. Our results from chapter 4 suggest that the annual net flux of carbon attributable to land use change has decreased from being a source of 0.09 Mg $Cha^{-1}yr^{-1}$ during 1982-1992 to becoming a sink of 0.02 Mg $Cha^{-1}yr^{-1}$ during 1992-2002. Thus, over recent years, Indian forests have acted as a carbon sink and CO_2 emissions from forest conversion or losses are being more than offset by carbon uptake due to forest increment and afforestation. The cumulative net carbon flux from Indian forests due to land use change between 1982 to 2002 is estimated as 45.9 Tg C (Chapter 4). Thus, we can say that land use change in India is not contributing to atmospheric CO_2 increase. This change from source to sink is largely due to a combination of policies, programs and plans undertaken by the Indian government over the last 30 years. These have resulted in an increase in the area under dense forests, a reduction in deforestation rates, high annual planting rates, and effective implementation of measures to protect India's forests from deforestation and degradation.

6.5. Uncertainties

Uncertainties in carbon stock estimates and stock changes may result from variability in the field, sampling procedures and measurement error. For the analysis of biomass carbon dynamics, and for assessment of policy options, and understanding of uncertainties (related to both accuracy and bias) is required (IPCC, 2000). The uncertainty is normally high in biological and land-use sectors given the large variation in factors contributing to carbon stocks and changes. The uncertainty in estimated carbon stock and changes in land use sectors is often estimated to be 25–70% of the actual values, which has to be considered high. Several reports by IPCC have referred to published estimates ranging from 352 to 536 x 10^9 Mg for the global pool of carbon in forest vegetation. Based on literature reviews, IPCC concludes that the stock of carbon in the global forest vegetation is overestimated. Achard *et al*. (2002) suggest uncertainty for forest carbon estimates of between ±30% and ±60%. As a consequence, assessing the reliability and accuracy of the estimated carbon stocks and changes becomes critical, and the goal of any carbon inventory programme should be to minimize such uncertainty. A recent IPCC report also indicates that it is often necessary to use expert judgement in evaluating uncertainty when measured data are not available (IPCC, 2000). Uncertainty may arise from various parameters required for estimating carbon stocks and changes including; (a) above-ground and below-ground biomass stocks and growth rates, litter, deadwood stocks and soil carbon density; (b) biomass expansion factors for converting commercial biomass to total tree biomass; (c) wood density and (d) model or equation coefficients.

The Ministry of Environment and Forests (MoEF, 1999) estimates total plantation area, i.e., as forests, wastelands, village commons, and road/canal side and farmers lands. The road/canal side and farmers land plantation will be reflected in trees outside forests. In addition due to short rotation plantation (7-10 years), species are clear felled and the area is replanted. In cumulative area of plantations, replanted areas are counted double and areas of failed plantations may also be included. This leads to some unknown bias and hence uncertainty in the actual area of plantations. Plantations are known to have higher biomass increment i.e., estimated national average being 3.2 Mg per ha per year (Lal and Singh, 2000), Since we aim to provide an exact and unbiased estimate, the national C-pool was corrected by proportionate correction of increment to the plantation area of 10 Mha. The plantation rate was corrected for short rotation species only where plantation area of 10 Mha (for the study period 1992-2002) was used with the success rate of 0.70. Young forests or plantations tend to accumulate more carbon than the mature forests, but due to the paucity of data, earlier studies have not taken into consideration this issue while accounting for carbon storage in forests. An important aspect of this study is the separate treatment of natural forests and plantation forestry for estimation of carbon accumulation and also estimation of carbon pool of trees outside forests. Forest cover consists of all lands having tree canopy density of more than 10 percent that can be interpreted from satellite data. Forest cover has been taken to comprise of all the woody and perennial tree species (e.g., palms, bamboos, mango, coconut, apple etc.). Since, NFP has set a goal for having 33 percent of the country's geographical area under forest and tree cover, irrespective of tree species and land use, there is no reason to exclude these areas from forest cover. Substantial tree wealth exists in the country in the form of linear plantation along roads, canals, etc. Thus, the FSI lumps together all forest types, i.e., native as well as exotic plantations for assessing the total tree and tree cover. Local studies reveal that although the plantations in India have expanded rapidly, but the native forests have actually declined due to fuel wood consumption (Puyravaud *et al*. 2010). Uncertainty therefore lies in the actual area of native and plantation forests in India. For C-pool estimation at the national level, we therefore calculate the biomass increment separately for native and plantation forests, thus producing more accurate and reliable estimates. Because of the technological and methodological developments, especially after 1999, the area figures of forest cover of different assessments are difficult to compare. In order to improve forest cover figures for better comparison, a recent attempt has been made by the FSI (FSI, 2009) to reduce (normalise) and modify these types of errors (at the national level) so that an estimate of the real change in forest cover can be elicited and the results can be taken as best approximations. Thus, any variation in the forest cover noted when comparing forest cover assessed at different scales would consist of, besides actual change on the ground, difference due to technical factors also. If differences on account of these technical factors could be separated out, only then the change in forest cover on the ground during the intervening period can be estimated and some scale errors can be reduced.

Uncertainty surrounding BEF is the greatest potential source of error in estimating carbon stock change in natural and plantation forests (Lehtonen *et al*. 2007). Results indicate that use of common BEF's can underestimate the above ground biomass as BEF is related to growing stock volume density (Brown et al. 1989). Using separate BEF's based on species, could go a long way towards reducing this uncertainty (Sasaki & Kim, 2009). Thus, the biomass expansion factors used in our study relate to growing stock volume density and are based on different species in dense and open density classes of Indian forest types giving more realistic estimate and thereby reducing the scope of uncertainty. The IPCC Guidelines (IPCC, 2003) suggest the use of a 95% confidence interval, which is the interval that has a 95% probability of containing the unknown true value. The IPCC Good Practice Guidance (IPCC, 2003) proposed two methodological tiers for uncertainty analysis; (1) error propagation equation and (2) Monte Carlo Simulation. To assess overall uncertainty related to estimates for the year 1992 and 2002, we followed the GPG Tier 1 approach. In this study, the data has been taken from FSI on growing stock and forest area under three crown density classes and from literature and published research papers and reports. In many cases, available data had to be complemented with expert judgement and in some cases, estimates had to rely entirely on expert judgement. Uncertainty is estimated for parameters such as area, growing stock volume, biomass, carbon stock and wood density, which can be assessed from the standard deviation of measured sample values. The volume of growing stock estimated by the FSI was used as a basis for forest biomass estimation. IPCC presents a default carbon concentration in the range from 0.43 to 0.55 (IPCC 2006, Table 4.3). Here, the biomass data are converted to carbon values by assigning a carbon content of 0.5 Mg C per Mg oven dry biomass. The uncertainty is expressed as ± standard error over mean estimates. The uncertainty of carbon stock was estimated using simple error propagation through the root of the sum of the squares of the component errors. We present the uncertainty analysis of the forest C sink that was calculated on the basis of forest inventory data. Approximate 95% confidence interval for growing stock volume was 4741 ± 190 (4%) Mm^3 and 4781 ± 170 (3%) Mm^3 for the year 1992 and 2002, respectively. According to the results, the relative error was 0.01 (1.58 ± 0.02) and 0.13 (0.72 ± 0.09 Mg/m^3) for BEF and wood density respectively. The relative error in growing stock volume was 0.04 and 0.03 for the year 1992 and 2002 respectively. The biomass estimates were around 5423 ± 976 (18%) Tg for 1992 and 5469 ± 711 (13%) Tg for 2002. Since the uncertainty is largely associated with the bias due to parameters like BEF and growing stock, the error is likely to be of the same sign (i.e., positive or negative) for 1992 and 2002 estimates. Hence, the error of the difference is likely to be much less than the error of addition calculated from 1992 and 2002 estimates. The uncertainties in forest sink estimates in 2002 were lower as compared to 1992 estimates, due to better availability of data. The reduction of uncertainty from 18% to 13% indicates an improvement in forestry data and the methodology used for C stock estimation. This also gives an indication that the C-sink estimates for 2002 are more improved and reliable estimates. The uncertainties not taken into account were disturbances like fire, insect damage, storm, climate change, and other environmental changes to be expected in the future. Such external factors are hard to assess and their effects on the total forestry sector carbon balance uncertainty exceed the scope of this study.

6.6. The potential of bioenergy as a substitute for fossil fuels and to reduce emissions

One of the measures currently receiving increased attention from scientists, policymakers and governments is land management to protect and reforest forestland. This can involve direct management of existing forests, or establishing fast growing plantations to produce biomass that can be substituted for fossil fuels. India's high level of dependence on fuel wood, its increasing population, increasing energy demand and the recognition of the contribution that fossil fuels make to the country's GHG emissions all provide strong arguments for seeking to expand use of energy from biomass. This has potential environmental and social benefits. There are several options available to do this: importing timber, which is purely a short-term measure, or generating tree resources within the country which can help both meet energy demand and act as carbon sink. India is both a major producer and consumer of fuel wood. Felling of trees and lopping of twigs and branches in the natural forests have long been the major sources of fuel wood. India's total fuel wood requirements were estimated at 225 million m^3 in 2000. The total industrial demand for round wood equivalents (RWE) is predicted to rise from 58 million m^3 in 2000 to 153 million m^3 in 2020 (Pandey and Rangaraju, 2008). Plantation timbers from non-forest areas (agro-forestry and farm-forestry, etc.) have played a large role in meeting this increasing demand in the recent past, but India's timber imports have also significantly increased. According to FAO (2003b) statistics India was the fourth largest importer of tropical logs in the world, with slightly over 2 million m^3 in 2001 (up 19% from 2000). These figures have continued to dramatically increase and were most recently estimated to be around 3.06 million m^3 (2005 figures, see Pandey and Rangaraju, 2008). Major exporters to India include Malaysia and Myanmar as well as Gabon, Indonesia, Ivory Coast, Nigeria and Togo.

In India, nearly 400 million people (40% of the total population) live in urban areas. Nationally, households energy accounts for about 40-45% of the total energy consumed. Since 1980, substitution of traditional fuels (like firewood, charcoal, dung cake etc) by modern fuels such as Liquefied Petroleum Gas (LPG) and kerosene has gained momentum. In urban areas, fuel preferences become an important determinant of fuel wood use because households are offered a variety of fuels that differ in price, efficiency and convenience of use, accessibility and availability (FAO, 2002). In particular, the effects of these factors on the choice of fuel are more important in urban households, which have better access to modern fuel substitutes. In recent years, serious environmental concerns like global climate change related to the use of fossil fuels, have revived the interest in wood energy as a renewable, sustainable and environmentally benign energy source. Wood energy is renewable, and if sustainably used and produced it is carbon neutral, unlike coal and oil. Therefore, wood energy can be used to reduce greenhouse gas emissions related to energy use, by replacing fossil fuels. For this reason, modern wood energy applications are becoming more and more competitive with conventional applications. Although the consumption of electricity and LPG is increasing at a higher rate than traditional fuel, but the use of wood and biomass energy continues to increase and still remains an important source of energy in urban areas in India.

The quality of life of rural Indian households depends greatly on the availability and access to biomass, particularly woody biomass, which is used for fuel and construction. This demand places the country's forests under immense pressure. Yet there is also substantial scope for expanding plantations to meet this demand, provide biomass generation and increase the country's standing carbon stock. Short rotation plantations have a very high annual productivity. The results from chapter 5 suggest that at year 100, a total of 216 Mg C ha^{-1} can be sequestered and stored by afforestation with sal species, as opposed to an offset of 412 Mg C ha^{-1} from carbon storage and fossil fuel substitution by short rotation poplar plantations. Under the full biomass demand scenario, the minimum land available for plantation in India is estimated as 9.6 Mha. Our estimates suggest that using this land for short rotation poplar plantation has the potential to generate 758 Tg of bioenergy per year. The annual electricity generation potential (1 Mt = 1 TWh of electrical power) would be 758 TWh. The results conclude that short rotation poplar plantations for electricity production would give a mitigation potential of between 227 and 303 Tg C per year by substituting coal based power generation. Ravindranath *et al.* (2007a) suggest that, the mitigation potential on a per-hectare basis for the period 2000-2030 would be lowest for short-rotation forestry (at 25 Mg C ha^{-1}) and highest for forest protection (at 176 Mg C ha^{-1}). At a regional level, Sudha *et al*. (2007) estimated the baseline carbon stock as 39 Mg per ha within land categorized as wasteland and 35 Mg C per ha on fallow land.

Depending upon the land availability for plantation, the potential for energy generation from short rotation forestry could be as much as 11370 PJ, which would represent a potential 43% contribution from bioenergy to total projected energy consumption in 2015 (Chapter 5). Evidently, clearing natural forests in order to plant short rotation plantations is not advisable, especially as the net carbon storage effect would be negative for a long period of time. It would lead to a large loss of C to the atmosphere, which would take a long period to compensate for through the substitution of fossil fuels and have other damaging environmental effects. However, planting bioenergy plantations on degraded land is environmentally beneficial and this could increase India's total forest area to up 108 Mha (nearly 32.8% of the total land cover of India). There are multiple environmental benefits of using bioenergy including:

- reduced pressure on finite natural resources
- reduced landfill waste and associated issues
- protection of ground water supplies and reduced dry land salinity and erosion
- increased terrestrial carbon sinks and reservoirs
- reduced GHG emissions from fossil fuels.

The extent to which one or more of these benefits occurs depends on the specific system design and location. While there are various constraints, including institutional barriers, investment requirements and technological barriers, on establishing new plantations on degraded and wastelands biomass plantations remain one of the best and most promising options for halting degradation and increasing carbon storage in India. They are most effective when harvested periodically and when some of them are retained as a long-term source of timber. Reforestation of non-forest lands will prevent further land degradation and can provide a continuous supply of biomass for energy use, replacing fossil fuels and reducing net C emissions. India's wastelands are spread over different regions with different climatic conditions and include both rain-fed and irrigated land. Given this variety, research is required to determine which particular species and plant varieties will give the maximum yield under different conditions.

6.7. Climate change problem and its impact on Indian forests

The relationship between climate change and tropical forests has received considerable scientific and political attention over recent decades. Observed changes in temperature, precipitation, snow cover, sea level and extreme weather conditions confirm that global warming is a reality. Ravindranath *et al*. (2006) have taken data from the climate projections of the Regional Climate Model of the Hadley Centre (HadRM3) and the BIOME 4 vegetation response model and applied this to India.

They reported predictions under two scenarios as outlined by IPCC i.e., medium-high emissions (A2) and medium-low emissions (B2) scenarios. They projected that a shift towards wetter forest types in the northeast of the country and towards drier forest types in the northwestern region is likely, in the absence of any other human influence. This projected shift in vegetation type may lead to large-scale forest dieback and loss of biodiversity especially in the transition between forest types. However, the NPP, a measure of the amount of vegetation matter produced, is likely to increase in the majority of locations due to carbon fertilisation. Although the projected increase in NPP may lead to increased timber and fuel wood supply in the medium term, benefiting dependent communities, but this increase will not be sustainable: forest dieback and loss of biodiversity will limit forest resources in the longer term, adversely impacting the communities and economies depending on these resources. Increased atmospheric CO_2 levels increase carbon sequestration due to increased photosynthesis however increases in temperature may increase the rate of respiration both in plants and soil. Some climate models predict that this process may turn forests into carbon source.

Falloon *et al*. (2007) suggest that under climate change, precipitation rather than temperature would appear to control the sign of predicted changes in soil carbon, largely through the influence of precipitation on litter inputs to soil. For India, they predicted increase in rainfall and from 2000-2100 an increase in soil C stocks. Under the climate change, wetter conditions would result in higher soil C stocks and drier conditions in lower soil C stocks. Pandey (2002) projected that India may experience a decline in wintertime rainfall between 5 and 25%, leading to droughts during the dry summer months. Prolonged drought may result in population dislocation and redistribution, the abandonment of dwelling, and even the collapse of the state (Pandey, 2002). The drying out may result in turning large areas of carbon sink into a major carbon source.

The analysis of forest cover, afforestation and reforestation (chapter 4) shows that India's forest cover has stabilized over the past 15 years (64–67 Mha). Projections under the current trend scenario indicate that the forest cover is likely to increase in the period 2006–30. Further, model-based projections of carbon stocks in the Indian forest sector show a likely increase, from 8.79 Pg C in 2005 to 9.75 Pg C in 2030 (Ravindranath *et al*. 2008). It is estimated that the carbon uptake in forests, degraded forests, and plantations will more than offset the gross carbon emissions from the forests.

For many developing countries including India, carbon sequestration through afforestation or reduced deforestation may be a cost-effective way for reducing CO_2 emissions. Linking tree growing in waste lands, with bioenergy options and the Clean Development Mechanism (CDM)[1] can further increase the benefits to be obtained from terrestrial carbon sinks. Earning carbon credits through forestry is a promising option for India (Lohmann, 2006). Afforestation and reforestation are both accepted as mitigation measures by the CDM. Using forests as carbon sinks combined with bioenergy, either directly by establishing energy plantations or through the use of forest and industrial residues, has substantial potential for additional carbon mitigation.

The National Environmental Policy Draft, circulated by Ministry of Environment and Forests (MoEF) in 2004, envisages an environmental policy that promotes trading carbon and other environmental services. Carbon sequestered through afforestation projects in India can be bought by other countries to earn carbon credits to meet their carbon reduction targets established under the Kyoto mechanisms. Degraded land or wasteland in India is suitable for growing trees and qualifies for LULUCF activities under the CDM. India has about 40 Mha of degraded and wasteland which could be available for plantation (Ravindranath and Balachandra, 2009). The available area includes degraded forestland, pasture land, marginal cropland and other privately owned non-crop land. It excludes forest land and the area under roads, settlement, water bodies, sand, snow, etc, but includes some 5 Mha next to rail tracks and highways. There is an immense potential for establishing forest plantations on such land and sequestering carbon in aboveground vegetation and even more efficiently in the soil.

Serious and urgent policy decisions are needed at regional and national and international levels over the strategies required to abate greenhouse gas emissions

[1] CDM is a mechanism established within the UNFCCC that allows countries who have committed to making GHG reductions between 2008 and 2012 to purchase credits in non-committed countries (mostly in the tropics).

and to arrest future climate change. However, in most developing countries, environmental conservation is not given the same priority as economic and social development. In India, one-third of the total population is still below poverty line and the government has the primary responsibility to provide them with at least their basic needs e.g., water, food, shelter and healthy environmental conditions. Short rotation plantations could help provide bioenergy to rural areas through decentralized power generation. The leftover treetops, twigs and branches of the energy plantations, which are not used in gasification, could meet fuel wood needs in these rural areas. A shift in government policy, that sought to include sustainable bioenergy plantations within its afforestation programme, could help provide India's rural population with employment opportunities, which would in turn improve their social and economic conditions.

India has adopted a long term and sustainable development perspective, and already introduced measures to increase afforestation and reduce pressure on existing forests. It can further increase the area of forests by targeting wastelands and marginal lands for future reforestation. These measures, together with plans to make more use of renewable energy sources and improve reporting on GHG inventories (including sources and sinks), can all contribute to effectively addressing climate change. India's growing population will inevitably exert mounting pressure on its natural resources. However people in India have come to see the value of trees outside its forests and are seeking to expand this resource. Forests play a multifunctional role that includes biodiversity conservation and maintenance of ecosystem functions that provide goods and services to society at large. They enhance carbon storage in trees, woody vegetation and soils and contribute to the social and economic well being of people. India's existing forests currently fall short of meeting future demands for biomass, yet there is plenty of land potentially available for plantation forestry. Given that land availability is not a constraint in the immediate future, the establishment of forests outside the current forest area should be strongly encouraged.

REFERENCES

Achanta, A. N., and Kanetkar, R., (1996) Impact of climate change on forest productivity: a case study of Kerala, India. Paper presented at the Asian and Pacific Workshop on Climate Change Vulnerability and Adaptation Assessment, January 15-19, 1996, Manila, Philippines.

Achard, F., Eva. H.D., Stibig, H.-J., Mayaux, P., Gallego, J., Richards, T. & Malingreau, J. P., (2002). Determination of deforestation rates of the world´s humid tropical forests. Science 297: 999–1002.

Achard, F., Eva, H. D., Mayaux, P., (2004) Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. Global Biogeochemical Cycles Vol 18, GB2008, doi: 10.1029/2003GB002142.

Adams, D., R. Alig, B. McCarl, J.M. Callaway, and S. Winnett. (1999). "Minimum Cost Strategies for Sequestering Carbon in Forests." Land Economics 75(3): 360-374.

Agarwal, A. (1998). False predictions, Down to Earth 7(1): 3–10.

Alig, R., D. Adams, B. McCarl, J.M. Callaway, and S. Winnett. (1997). "Assessing Effects of Mitigation Strategies for Global Climate Change with an Inter temporal Model of the U.S. Forest and Agriculture Sectors." Environmental and Resource Economics 9: 259-274.

(ALGAS) Asia Least-cost Greenhouse Gas Abatement Strategy. (1998). India Country Report. Asian Development Bank. Global Environment Facility, United Nations Development Programme, Manila, Philippines.

Baishya, R., Barik, S.K., and Upadhaya, K., (2009) Distribution pattern of aboveground biomass in natural and plantation forests of humid tropics in northeast India. Tropical Ecology, 50(2): 295-304.

Ball, J. B., Pandey, D., Hirai, S., (1999). Global overview of Teak plantations. Paper presented to the Regional Seminar, Site, Technology and Productivity of Teak plantations. Chiang Mai, Thailand 26-29 January 1999.

Bargali, S. S., Singh, S.S., Singh, R. P., (1992). Structure and function of an age series of Eucalyptus Plantations in Central Himalaya, Dry matter dynamics. Annals of Botany 69, 405-411.

Baral, A., Guha, G.S., (2004). Trees for carbon sequestration or fossil fuel substitution: the issue of cost vs. carbon benefit. Biomass and Bioenergy 27, 41– 55.

Bebarta, K.C., (1999). Teak: ecology, silviculture, management and profitability. Dehradun, India, International book distributors.

Berndes, G., Hoogwijk, M., Van er Broek, R., (2003). The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy. 25, 1–28.

Bhadwal, S., Singh, R., (2002). Carbon sequestration estimates for forestry options under different land-use scenarios in India. Current Science 83, 11): 1380-1386.

Bhattacharya, P. and Joshi, B. (1999). A case study on forest and displaced people wood fuel collection and sales as a "first step survival strategy" (Study in West Bengal, India). Report submitted to RWEDPA/FAO (GCO/RAS/154/NET). Indian Institute of Forest Management, Bhopal, India.

Bouwman, A.F., Leemans, R., (1995). The role of forest soils in the global carbon cycle. In: Mcfee, W.F., Kelly, F.M. (Eds.), Carbon Forms and Functions in Forest Soils. Soil Science Society of America, Masison, WI, pp. 503–525.

Brown, S., Gillespie, A.J.R., Lugo, A.E., (1989) Biomass estimation methods for tropical forests with application to forest inventory data. Forest Science 35:881-902

Brown, S.L., Schroeder, P., Kern, J.S., (1999) spatial distribution of biomass in forests of the eastern USA. Forest Ecology and Management 123: 81-90.

Buekering, P.V., and Sharma, V.K., (eds.) (1998). Waste Paper Trade and Recycling in India, Jodhpur, India, Scientific publishers.

Burshel, P., Kursten, E., Larson, B.C., and Weber, M., (1993). Present role of German forests and forestry in the national carbon budget and options to its increase. Water, Air, and Soil Pollution 70: 325–349.

Carle, J., and Holmgren, P., (2008). Wood from planted forests – A global outlook 2005-2030. Forest Prod. J. 58(12): 6-18.

Chhabra A, S, Palria., and Dadhwal, V. K., (2002a). Growing stock based forest biomass estimate for India. Biomass and Bioenergy 22: 187-194.

Chhabra, A., S, Palria. and Dadhwal, V. K., (2002b). Spatial distribution of phytomass carbon in Indian forests. Global Change Biology 8: 1230-1239.

Chhabra, A. S. Palria and V.K. Dadhwal., (2002c). Soil Organic carbon pool in Indian forests, Forest Ecology & Management. 5877, 1-13.

Chhabra, A., Dadhwal, V.K., (2004). Assessment of Major Pools and Fluxes of Carbon in Indian Forests. Climatic Change 64, 341–360.

Champion, H.G., and Seth, S.K., (1968). A revised forest types of India. Manager of Publications, Government of India, Delhi.

Chaturvedi, O.P., (1983). Biomass structure, productivity and nutrient cycling in Pinus forest. Ph.D. Thesis. Kumaun University, Nanital, India, 347pp.

Dadhwal, V.K., and Nayak, S. R., (1993) A Preliminary estimate of biogeochemical cycle of carbon for India. Science. & Culture 59: 9-13.

Dadhwal, V. K., and Shah, A. K., (1997) Recent changes (1982-1991) in forest Phytomass Carbon Pool in India estimated using Growing Stock and Remote Sensing Based Forest Inventories J. Tropical Forestry 13: 182-188.

Dadhwal, V. K., Shukla, N., and Vora, A. B., (1997) Forest Litter fall in India: a review and estimate of litter fall carbon flux. Indian Forester 123 (1): 45-52.

Dadhwal, V.K., Pandya, N., Vora, A.B., (1998). Carbon cycle for Indian forest ecosystem: a preliminary estimate. In: Subbaraya BH, Rao DP, Desai PS, Manikiam, Rajaratnam P, editors. Global change studies: scienti6c results from

ISRO-GBP, ISRO Bangalore, pp. 411–430.

DeFries, R.S., Houghton, R.A., Hansen, M.C., (2002) Carbon emissions from tropical deforestation and re-growth based on satellite observations for the 1980s and 90s. Proceedings of the National Academy of Sciences, 99, 14256–14261.

De Jong, B.H.J., Ochoa-Gaona, S., Castillo-Santiago, M.A., Ramı´rez-Marcial, N., Cairns, M., (2000), Land use/land-cover change and carbon flux in the Selva Lacandona, Mexico. Ambio 29(8), 504–511

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C.,Wisniewski J., (1994). Carbon pools and flux of global forest ecosystems. Science 263, 185– 190.

Dwivedi, A.P., (1994). Forests: The ecological ramifications. Dehradun. International book distributors.

Eggers, T., (2002). The Impacts of Manufacturing and Utilisation of Wood Products on the European Carbon Budget. European Forest Institute. Internal Report 9.

Erikson, E. (2006). Thinning operations and their impact on biomass production in stands of Norway spruce and Scots pine. Biomass and Bioenergy 30, 848-854.

Fang, S., Xue, J., Tang, L., (2007). Biomass production and carbon sequestration potential in poplar plantations with different management patterns. Journal of Environmental Management 85, 672-679.

FAO forest products Yearbook database (2002). Role of Wood Energy in Asia (www.fao.org/docrep/w7519e)

FAO. (2003a) State of the World's Forests. Food and Agriculture Organisation of the United Nations. Rome, Italy, 126pp.

FAO. (2003b) Global Forest Resources Assessment update 2005 – FRA 2005 - pilot study for country reporting: India. Forest Resources Assessment Working Paper 78. Rome.

FAO. (2005) State of the World's Forests 2005. Rome (also available at www.fao.org).

FAO/FRA, (2006). Global Forest Resources Assessment 2005. Progress Towards Sustainable Forest Management. FAO, Rome.

FAO. (2008) Food and Agricultural Organization. Forests and Energy, Key Issues. Working Paper No. 154. Rome.

Falloon, P., Jones, Chris. D., Cerri, C.E., Al-Adamat, R., Kamoni, P., Bhattacharyya, T., Easter, M., Paustian, K., Killian, K., Coleman, K., and Milne, E., (2007). Climate change and its impact on soil and vegetation carbon storage in Kenya, Jordan, India and Brazil, Agriculture, Ecosystems and Environment 122 (2007) 114–124

Forests and Wildlife Statistics of India (2004) National Afforestation and Eco-Development Board, Ministry of Environment and Forest, Govt. of India

FSI (1987). State of the Forest Report 1987. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun.

FSI (1995a). State of the Forest Report 1995. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun.

FSI (1995b). Extent, Composition, Density of Growing Stock and annual Increment of India's Forests, Dehradun: .

FSI (1997). State of the forest Report 1997. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun.

FSI (1999), The State of the Forest Report. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun.

FSI (2001). State of the forest Report 2001. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun.

FSI (2003). State of the forest Report 2003. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun.

FSI (2005). State of the forest Report 2005. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun.

FSI (2009). State of the forest Report 2009. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun.

Garg, A., Bhattacharya, S., Shukla, P. R. and Dadhwal, V. K., (2001). Regional and sectoral assessment of greenhouse gases, Atmospheric Environment. 35(15), 2679-2695.

Garg, A., Kapshe, M., Shukla, P. R., Ghosh, D., 2(002). Large point source (LPS) emissions from India: regional and sectoral analysis. Atmospheric Environment 36, 213-224.

Garten, Jr., C.T., (2002). Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA. Biomass and Bioenergy 23, 93–102.

Gercia, J. P., Lippke, B., Comnick, J., Manriquez., (2005). An assessment of carbon pools, storage, and wood products market substitution using life cycle analysis results. Wood and Fibre Science, 37 Corrim special issue, 2005, pp. 140-148.

Global Carbon Project (GCP) (2008) Carbon budget and trends 2007, www.globalcarbonproject.org.

Goel, V.L., Behl, H.M., (1996) Fuel wood quality of promising tree species for alkaline soil sites in relation to tree age. Biomass and Bioenergy; 10:57–61.

Gupta, S., Ravindranath, N. H., (1997). Financial analysis of cooking energy options for India. Energy Conservation and Management, vol. 38, No. 18, pp. 1869-1876.

Gupta, H. S., (2009) Forest as carbon sink-Temporal analysis for Ranchi district. Indian Journal of Forestry, vol. 32(1): 7-11.

Gullison, R. E., et al. (2007) Tropical forests and climate policy. Science, 316, 985–6

Hall, C.A.S. & Uhlig, J., (1991). Refining estimates of carbon release from tropical land use change. Canadian Journal of Forestry Research 21, 118-131.

Haripriya, G.S., (2000). Estimate of biomass in Indian forests. Biomass and Bioenergy 19, 245-258.

Haripriya, G. S. (2001). A framework for carbon stored in Indian Wood Products, Environment, Development and Sustainability, vol. 3, pp.229-251.

Haripriya, G.S. (2003) Carbon budget of the Indian forest ecosystem. Climatic Change, vol. 56, pp.291-319.

Haripriya, G. S., and Atkinson, G., (2006) Accounting for India's forest wealth. Ecological Economics, vol 59, 462-476.

Harmon, M.E., Harmon, J.M., Ferrell, W.K. and Brooks, D., (1996). Modelling carbon stores in Oregon and Washington forest products: 1900–1992. Climatic Change 33, 521–550.

Hooda, N., and Rawat, V. R. S., (2006). Role of bioenergy plantation for carbon dioxide mitigation with special reference to India. Mitigation and Adaptation Strategies for Global Change, 11, 445-467.

Hooda, N., M. Gera, K. Andrasko, J.A. Sathaye, M.K. Gupta, H.B. Vasistha, M. Chandran, and S.S. Rassaily, (2007): Community and farm forestry climate mitigation projects: case studies from Uttaranchal, India. Mitigation and Adaptation Strategies for Global Change. 12(6) pp. 1099-1130.

Houghton, R.A., (2008). Carbon Flux to the Atmosphere from Land-Use Changes: 1850-2005. In TRENDS: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Indian Institute of Science (IISc) (2006). Forest conservation and afforestation/reforestation in India: implications of forest carbon stocks and sustainable development. Report of project No. 6/2/2006-CCC. Indian Institute of Science, Bangalore, 560 012, India.

Indian Council of Forestry Research & Education (ICFRE). Forestry Statistics India, 1995, 2000, 2001 & 2003, Dehradun.

International Energy Outlook (2005), US Department of Energy, Energy Information Administration of Government of United States of America, 2005.

International Energy Outlook (2006), US Department of Energy, Energy Information Administration of Government of United States of America, 2006.

International Energy Outlook (2007), US Department of Energy, Energy Information Administration of Government of United States of America, 2007.

IPCC (Intergovernmental Panel of Climate Change) (1995). Guidelines for greenhouse gas inventory workbook, Volume 2, Module 5 – Land Use Change and Forestry, Report prepared by UNEP, OECD, IEA and IPCC, 5.1-5.45.

IPCC (1997). Revised 1996 IPCC Guidelines for National Greenhouse Inventories. Houghton J.T., Meira Filho L.G., Lim B., Tréanton K., Mamaty I., Bonduki Y., Griggs D.J. Callander B.A. (Eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/OECD/IEA, Paris, France.

IPCC (2000). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Penman J., Kruger D., Galbally I., Hiraishi T., Nyenzi B., Emmanuel S., Buendia L., Hoppaus R., Martinsen T., Meijer J., Miwa K., Tanabe K. (Eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/OECD/IEA/IGES, Hayama, Japan.

IPCC (2001). Climate Change 2001: The Scientific Basis. IPCC third assessment report, Working group I, Technical Summary, Cambridge University Press, Cambridge,UK.

IPCC (2003). Good Practice Guidance for Land Use, Land-Use Change and Forestry. Penman J., Gytarsky M., Hiraishi T., Krug, T., Kruger D., Pipatti R., Buendia L., Miwa K., Ngara T., Tanabe K., Wagner F. (Eds).Intergovernmental Panel on

Climate Change (IPCC), IPCC/IGES, Hayama, Japan.

IPCC (2006). Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

IPCC (2007). Synthesis Report. In: Climate Change 2007, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Jha, K.K., (1995). Structure and functioning of an age series of Teak (Tectona Grandis Linn. f.) plantations in Kumaon Himalayan Terai. Ph.D. Thesis. Kumaon University, Nainital.

Jha, K.K., and Singh, J.S., (1999). Temporal Patterns of Bole Volume and Biomass of Young Teak Plantations Raised in Moist Deciduous Forest Region, India. Int. Jour. Ecol. Env. Sci. 25, 77-184

Jha, M.N., Gupta, M.K., Saxena, Alok., Kumar, Rajesh., (2003). Soil organic carbon store in different forests in India. Indian Forester 129, no.6, 714-724.

Karjalainen, T., Kellomäki, S., Pussinen, A., (1994). Role of wood-based products in absorbing atmospheric carbon. Silva Fennica 28 (2), 67–80.

Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.J., Eherd, M., Eggers, T., Sonntag, M, Mohren, G.M.J., (2002). An approach towards an estimate of the impact of forest management and climate change on the European forest sector budget: Germany as a case study. Forest Ecology and Management 162(1): 87-103.

Karjalainen T, Pussinen A, Liski J, Nabuurs GJ, Eggers T, Lapvetelainen T, Kaipainen T (2003) Scenario analysis of the impact of forest management and climate change on the European forest sector carbon budget. Forest Policy and Economics 5, 141–155.

Kaul, M., Dadhwal, V.K., Mohren, G.M.J., (2009). Land use change and net C flux in Indian forests. Forest Ecology and Management. 258, 100-108.

Kaul, M., Mohren, G.M.J., Dadhwal, V.K. (2010a) Phytomass carbon pool of Indian forests and trees outside forests. (Submitted to Climatic Change).

Kaul, M, Mohren G.M.J., Dadhwal, V.K., (2010b). Carbon storage versus fossil fuel substitution: a climate change mitigation option for two different land use categories based on long and short rotation forestry in India. Mitigation and Adaptation Strategies for Global Change, 15:395-409.

Kaul, M., Mohren, G.M.J., Dadhwal, V.K. (2010c) Carbon storage and sequestration potential of selected tree species in India. Mitigation and Adaptation Strategies for Global Change, 15: 489-510.

Kauppi, P.E., Ausubel, J.H., Fang. J., Mather, A.S., Sedjo, R.A., and Waggoner, P.E., (2006) Returning forests analysed with the forest identity. PNAS, Vol 103, no.46, 17574-17579.

Kanninen, M., Perez, D., Montero, M., Viquez, E., (2004). Intensity and timing of the first thinning of Tectona grandis plantation in Costa Rica: results of a thinning trial. Forest Ecology and Management 203, 89-99.

Kimmins, J. P., Mailly, D. and Seely, B. (1999). Modelling forest ecosystem net primary production: the hybrid simulation approach used in FORECAST. Ecol. Model. 122: 195–224.

Kishwan, J. (2007). Reducing emission from deforestation in developing countries: Indian proposal. Presented at 2nd UNFCCC Workshop on REDD: 7–9 March 2007, Cairns, (Australia) available at: http://unfccc.int/files/methods_and_science/lulucf/application/pdf/070307kishwan.pdf.

Kurz, W. A., Apps, M. J., Webb, T. M. and McNamee, P. J. (1992). The carbon budget of the Canadian forest sector: Phase I. Forestry Canada, Northw. Reg., North. For. Cent., Edmonton, AB. Inf. Rep. NOR-X-326.

Lal, J.B., (1989) Indian Forests, Myth and Reality, Nataraj Publishers, Dehradun.

Lal, R., (1999) Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. Prog. Environ. Sci. 1 (4), 307-326.

Lal, M., Singh, R., (2000) Carbon sequestration potential of Indian forests. Environmental Monitoring and Assessment 60: 315-327.

Lasco, R.D. and Pulhin, F.B., (2000). Forest land use change in Philippines and climate change mitigation, Mitigation and Adaptation Strategies for Global Change 5, 81-97.

Lehtonen, A., Cienciala, E., Tatarinov, F. and Makipaa, (2007). Uncertainty estimation of biomass expansion factors for Norway spruce in the Czech Republic . Ann. For. Sci. **64**, 133 – 140.

Liski, J., Nissinen, A., Erhard, M., Taskinen, O., (2003). Climatic effects on litter decomposition from arctic tundra to tropical rainforest. Global Change Biology 9, 575-584.

Liski, J., Palosuo, T., Sieva¨nen, R., (2005). Carbon and decomposition model Yasso for forest soils. Ecol. Model. 189, 168–182.

Lohmann, L., (2006). Carbon Trading—A Critical Conversation on Climate Change, Privatization and Power. What Next Project Publications, Sweden Development Dialogue No. 48.

Luyssaert, S., Schulze. E. D., Borner, A., Knohl, A., Hessenmoller, D., Law, B. E., Ciais, P., Grace, J., (2008). Old growth forests as global carbon sinks. Nature, Vol 455, 213-215.

Lodhiyal, L. S., Singh, R. P., Singh, S. P., (1995). Structure and function of an age series of Poplar plantations in Central Himalaya: I. Dry matter dynamics. Annals of Botany 76: 191-199.

Lodhiyal, L.S., Lodhiyal, N., (1997). Variation in Biomass and Net primary productivity in short rotation high density central Himalayan poplar plantations. Forest Ecology & Management 98, 167-179.

Manhas, R.K., Negi, J.D.S., Kumar, R. and Chauhan, P.S. (2006) Temporal

Assessment of Growing Stock, Biomass and Carbon Stock of Indian Forests. Climatic Change 74: 191-221.

Masera, O. R., Garza-Caligaris, J. F., Kanninen, M. Karjalainen, T., Liski, J., Nabuurs, G. J., Pussinen, A., de Jong, B. H. J. and Mohren, G. M. J. (2003). Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. Ecological Modelling 164: 177–199.

Marland, G., and Schlamadinger, B., (1997), "Forests for Carbon Sequestration or Fossil Fuel Substitution? A Sensitivity Analysis," Biomass and Bioenergy vol 13, No. 6, 389-397.

Mitra, A. P. (ed.), Greenhouse Gas Emissions in India: 1992 Update, Scientific Report No. 4, Centre for Global Change, National Physical Laboratory, New Delhi, 1992.

Ministry of Environment and Forests (1999) National Forestry Action Programme in India. Government of India, New Delhi.

Ministry of Environment and Forests (MoEF) (2002) Agenda 21: An Assessment. Prepared by Tata Energy Research Institute (TERI) on behalf of Ministry of Environment and Forests, Government of India, New Delhi

Nabuurs, G. J,, Mohren, G.M.J., (1993) Carbon fixation through forestation activities: a study of the carbon sequestering potential of selected forest types, commissioned by the Foundation Face. Institute for Forestry and Nature Research, Wageningen. IBN Research Report 93/4.

Nabuurs, G. J,, Schelhaas, M. J., (2002) Carbon profiles of forest types across Europe assessed with CO2FIX. Ecological Indicators 1: 213-223.

National Commission Of Agriculture (NCA), (1976). National Commission of Agriculture, volume 9, New Delhi, India.

Natarajan, I. (1996). Trends in firewood consumption in rural India. National Council of Applied Economic Research (NCAER), New Delhi, India.

(NATCOM) (2004) India's Initial National Communication to the United Nations Framework Convention on Climate Change (UNFCCC), Ministry of Environment and Forests, Government of India. New Delhi.

Negi, K.S., Rawat, Y.S., Singh, J.S., (1983). Estimation of biomass and nurient storage in a Himalayan temperate forest. Can. J. For. Res. 13: 1185-1196.

Negi, J.D.S., (1984). Biological Productivity and Cycling of Nutrients in Managed and. Man Made Ecosystems. Ph.D Thesis, Garhwal Uni. Srinagar India.

Negi, J.D.S., and Sharma, S.C., (1985). Biomass production and nutrient distribution in an age series of Eucalyptus hybrid plantation in Tamil Nadu. Indian Forester 111 (12), 1111-1122.

Negi, S.S., (1996). Teak (Tectona grandis). Book

Negi, J.D.S., Chauhan, P.S., (2002). Green house gases mitigation potential by Sal (Shorea robusta Gaertn. f.) forest in Doon Valley. Indian Forester 128 (7), 771-778.

Negi, J.D.S., Manhas, R.K., Chauhan, P.S., (2003). Carbon allocation in different components of tree species of India: A new approach for carbon estimation. Current Science 85, (11), 1528-1531.

Niu, X., Duiker, S. W., (2006). Carbon sequestration potential by afforestation of marginal agricultural land in the Midwestern U.S., Forest Ecology and Management 223, 415-427.

Nilson, P., Strand, L.T. (2008). Thinning intensity effects on carbon and nitrogen stores and fluxes in a Norway Spruce (Picea abies (L.) Karst.) stand after 33 years. Forest Ecology and Management 256, 201-208.

Ogle, S.M., Breidt, F.J. and Paustian, K (2005). Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72:87-121.

Pandey, D., (2002). Fuel wood studies in India, Myth and Reality, Centre for

International Forestry Research, Indonesia.

Pandey, D. (2008). India's forest resource base. International Forestry Review Vol. 10(2). 116-124.

Pandey, M.C., Tandon, V.N., Rawat, H.S., (1987). Organic matter production and distribution of nutrient in Eucalyptus hybrid plantation ecosystem in Karnataka. Indian Forester 114 (11), 713-724.

Pandey, C.N., and Rangaraju, T.S., (2008). India's Industrial wood balance. International Forestry Review Vol. 10(2): 173-189.

Parton, W. J., Schimel, D. S., Cole, C. V. and Ojima, D. S. (1987). Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51: 1173–1179.

Paul, K.I., Polglase, P.J., Nyakuengama, J.G., Khanna, P.K., (2002). Change in soil carbon following afforestation. Forest Ecology and Management. 168, 241–257.

Paul, K.I., Polglase, P.J., Richards, G.P., (2003). Predicted change in soil carbon following afforestation or reforestation, and analysis of controlling factors by linking a C accounting model (CAMFor) to models of forest growth (3PG), litter decomposition (GENDEC) and soil C turnover (RothC). For. Ecol. Manage. 177, 485–501.

Peng, C., Liu, J., Dang, Q., Apps, M. J. and Jiang, H. (2002). TRIPLEX: a generic hybrid model for predicting forest growth and carbon and nitrogen dynamics. Ecol. Model. 153: 109–130.

Perez D, Kanninen M (2005) Effect of Thinning on stem form and wood characteristics of teak (Tectona Grandis) in a humid tropical site in Costa Rica. Silva Fennica 39(2): 217-225.

Pingoud, K., Perälä, A.-L. and Pussinen, A. (2001). Carbon dynamics in wood products. Mitigation and Adaptation Strategies for Global Change, Vol. 6, No.

2, pp. 91-111.

Pitto, D., Montagnini, F., Ugalde, L., Kanninen, M. (2003). Growth and effects of thinning of mixed and pure plantations with native trees in humid tropical Costa Rica. Forest Ecology and Management 177, 427-439.

Post, W.M. and Kwon, K.C., (2000). Soil carbon sequestration and land-use change: processes and potential. Global Change Biology 6, 317-327.

Post, W. M., Pengh, T. H., Emanuel, W., King, A. W., Dale, V. H. and Delnglis., (1990). The global carbon cycle. Atmospheric. Science 78, 310–326.

Poffenberger, M., Ravindranath, N.H., Pandey, D.N., Murthy, I.K., Bist, R., Jain, D., (2001). Communities and climate change: The clean development mechanism and village based restoration in Central India – a case study from Harda forest Division, Madhya Pradesh, India.

Prasad, R., Majumdar, N.B., Bhattacharya, P., Phukan, B.R. and Singh, S.P. (1999). Wood fuel trade in India. Paper presented to the National Training Workshop on Woodfuel Trade in India, 17–19 February (1999). Indian Institute of Forest Management, Bhopal, India.

Price, D. T., Peng, C. H., Apps, M. J. and Halliwell, D. H. (1999). Simulating effects of climate change on boreal ecosystem carbon pools in central Canada. J. Biogeogr. 26: 1237–1248.

Pussinen A, Karjalainen T, M¨akip¨a¨a R, Valsta L, Kellom¨aki S (2002) Forest carbon sequestration and harvests in Scots pine stand under different climate and nitrogen deposition scenarios. Forest Ecology and Management 158(1–3):103–115.

Puyravaud, J. P., Davidar, P., Laurance, William. F., (2010). Cryptic loss of India's native forests. Science, vol. 329, p-32.

Rai, S.N. and Chakrabarty, S.K. (1996). Demand and supply of fuel wood, timber and fodder in India. Forest Survey of India, Ministry of Environment and

Forests, Dehradun, India.

Ramachandran, A., Jayakumar, S., Haroon, R.M., Bhaskaran, A. and Arockiasamy, D.I., (2007). Carbon sequestration: estimation of carbon stock in natural forests using geospatial technology in the Eastern Ghats of Tamil Nadu, India, Current Science 92 (3), 323-331.

Ravindranath, N.H., Somasekhar, B.S., Gadgil, M., (1997). Carbon flows in Indian forest. Climatic Change 35, (3),297-320.

Ravindranath, N.H., Sudha, P., Rao, Sandhya., (2002) Forestry for Sustainable Biomass Production and Carbon Sequestration in India, Mitigation and Adaptation Strategies for Global Change, 6: 233:256.

Ravindranath, N.H.; Rajiv Kumar Chaturvedi and Murthy, I.K. (2008). Forest conservation, afforestation and reforestation in India: Implications for forest carbon stocks. Current Science: 216 95 (2): 216-222.

Ravindranath, N. H., Balachandra, P., (2009), Sustainable bioenergy for India: Technical, economic and policy analysis, Energy, doi:10.1016/j.energy.2008.12.012

Raghuvanshi, S.P., Chandra, A., Raghav, A.K., (2006). Carbon dioxide emissions from coal based power generation in India. Energy Conservation and Management 47, 427-441.

Ravindranath, N.H., Somashekar, H.I., Dasappa, S., and Reddy, J.C.N., (2004). Sustainable biomass power for rural India: Case study of biomass gasifier for village electrification, Current Science, VOL. 87, NO. 7.

Ravindranath, N.H., Joshi, N.V., Sukumar, R., Saxena, A., (2006). Impacts of climate change on forests in India. Current Science, VOL. 90. NO. 3.

Ravindranath, N.H., Murthy, I.K., Chaturvedi, R.K., Andrasko, K., Sathaye, J.A., (2007a). Carbon forestry economic mitigation potential in India. Mitigation and Adaptation Strategies for Global Change. 12: 1027-1050.

Richards, J. F. and Flint, E. P. (1994). Historic land use and carbon estimates for South and Southeast Asia 1880–1980. ORNL/CDIAC-61, NDP-046, Oak Ridge National Laboratory, Tennessee, USA.

Rawat, V. R. S., Kishan, J., (2008). Forest conservation-based, climate change-mitigation approach for India. International Forestry Review Vol. 10(2), 269-280.

Sasaki, N. and Kim, S. (2009). Biomass carbon sinks in Japanese forests: 1966 – 2012. Forestry, Vol. 82, No. 1. doi:10.1093/forestry/cpn049

Sathaye, J., Shukla, P. R., and Ravindranath, N. H., (2006). Climate change, sustainable development and India: Global and national concerns. Current Science, Vol. 90, No. 3, 314-325

Saxena, N.C. (1997). The woodfuel scenario and policy issues in India. RWEDP Field Document No.49, Food and Agriculture Organization, Bangkok, Thailand, April.

Seely, B., Welham, C. and Kimmins, H. (2002). Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. For. Ecol. Manage. 169: 123–135.

Schelhaas, M.J., Esch, P.W. Van., Groen, T.A., De Jong, B.H.J., Kanninen, M., Liski, J., Masera, O., Mohren, G.M.J., Nabuurs, G.J., Palosuo, T., Pedroni, L., Vallejo, A., & Vilen, T., (2004). CO2FIX V 3.1 – A framework for quantifying carbon sequestration in forest ecosystems. Wageningen, Alterra, Alterra rapport 1068.

Schlamadinger, B., and Marland, G., (1996). The role of forest and bioenergy strategies in the global carbon cycle. Biomass and Bioenergy. 10:275–300

Sharma, S., Bhattacharya, S., Garg, A., (2006). Greenhouse gas emissions from India: A perspective. Current Science, Vol.. 90, NO. 3.

Singh, B., (1979). Ecology of Pinus Patula planted in Darjeeling Himalaya. Ph.D. Thesis. Banaras Hindu University, Varanasi, India.

Singh, T.P., (2003). Potential of farm forestry in carbon sequestration. Indian Forester 129 (7), 839-843.

Skog, K.E. and Nicholson, G.A., (1998), 'Carbon cycling through wood products: the role of wood and paper products in carbon sequestration', Forest products Journal 48(7/8), 75–83.

Smith, F.W., Resh, S.C., (1999). Age-related changes in production and below-ground carbon allocation in Pinus Contorta forests. Forest Sci. 45 (3), 333–341.

Stavins, R.N. (1999). "The Costs of Carbon Sequestration: A Revealed-Preference Approach." American Economic Review 89: 994-1009.

State of Environment Report (2009) Ministry of Environment and Forests, Government of India. (http:www.moef.gov.in; http://envfor.nic.in).

Sudha, P., Somashekhar, H.I., Rao, S., and Ravindranath, N.H., (2003). Sustainable biomass production for energy in India. Biomass and Bioenergy 25: 501-515.

Sudha, P., Subhashree, D., Khan, H., Hedge, G.T., Murthy, I.K., Shreedhara, V., Ravindranath, N.H., (2007), Development of regional climate mitigation baseline for a dominant agro-ecological zone of Karnataka, India Mitigation and Adaptation Strategies for Global Change 12:1051–1075.

Takeshita, T., (2009). A strategy for introducing modern bioenergy into developing Asia to avoid dangerous climate change. Applied Energy, 86, s222 –s232.

Tewari, D.N., (1995a). A Monograph on Sal. Vedam Publications, India.

Tewari, D.N., (1995b). A Monograph on Teak. Vedam Publications, India.

Updegraff, K., Baughman, M.J., Taff, S.J., (2004). Environmental benefits of cropland conversion to hybrids poplar: economic and policy considerations. Biomass and Bioenergy 27, 411–428.

Vesterdal, L., Ritter, E., Gundersen, P., (2002). Change in soil organic carbon following afforestation of former arable land. Forest Ecology and Management 169, 137– 147.

Vucetich, J. A., Reed, D. D., Breymeyer, A., Deg´orski, M., Mroz, G. D., Solon, J., Roo-Zielinska, E., Noble, R., (2000). Carbon pools and ecosystem properties along a latitudinal gradient in northern Scots pine (Pinus sylvestris) forests. Forest Ecology and Management 136:135–145.

Walker, N., Bazilian, M., Buckley, P. (2009). Possibilities of reducing CO2 emissions from energy-intensive industries by the increased use of forest derived fuels in Ireland. Biomass & Bioenergy 33, 1229-1238.

Winjum, J. K., Brown, S., and Schlamadinger, B. (1998). Forest harvest and wood products: Sources and sinks of atmospheric carbon dioxide. For. Sci. 44(2):272–284.

Woomer, P.L., Tieszen, L.L., Tappan, G., Tour!e, A., Sall, M., (2004). Land Use change and terrestrial carbon stocks in Senegal. Journal of Arid Environments 59 (3) 625-642.

World Resources Institute, WRI, (1990). World Resources 1990–91, NY, 383 pp.

World Resources Institute, WRI, (1994). World Resources 1994–95, NY, 366 pp.

APPENDICES

APPENDIX I

Standard definition of various categories of land use adopted in land utilization statistics:

(i) Forests

Area under forests includes all lands classed as forest under any legal enactment dealing with forest or administered as forests, whether state owned or private, & whether wooded or maintained as potential forest land. The area under a raised or open for grazing within the forest should remain included under the forest area.

(ii) Barren & unculturable land

This category consists of all barren & unculturable land like mountains, deserts, etc. Land which cannot be brought under cultivation unless at a high cost, shall be classed as unculturable, whether such land is in isolated blocks or within cultivated holdings.

(iii) Land put to non-agricultural use

This includes all lands occupied by buildings, roads & railways, graveyards, cremation grounds, or under water, for example rivers & canals, and other land put to use other than agricultural use.

(iv) Permanent pastures and other grazing land

This covers all grazing lands whether or not they are permanent pastures or meadows. Village common grazing lands are also included under this category.

(v) Land under miscellaneous tree crops and groves, not included in net sown area

This category includes all culturable lands which are not included under the net area sown, but are put to some agricultural use. Lands under casuarina trees, thatching bamboo bushes and other groves for fuel, etc. shall be classified under this category.

(vi) Culturable wasteland

This includes lands available for cultivation but not cultivated during the current year and last five years or more in succession. Such lands may be either fallow or covered with shrubs and jungles which are not put to any use. They may be assessed or un assessed and may be in isolation blocks or within cultivated holdings. Land once cultivated, but not cultivated for five years in succession, shall also be included in this category after five years.

(vii) Current fallows

These are the lands which are kept fallow during the current years only. For example, if any seedling area is not cropped again in the same year, it may be treated as current fallow.

(viii) Other fallow land

These include all lands which were taken up for cultivation but are temporarily out of cultivation for a period of not less than one year and not more than five years.

(ix) Net area sown

This term denotes the net area sown counting areas sown more than once in the same year only once.

APPENDIX II

1. ANNUAL CARBON STOCK CHANGE IN A GIVEN POOL AS A FUNCTION OF GAINS AND LOSSES (GAIN-LOSS METHOD)

$$\Delta C_B = \Delta C_G - \Delta C_L \quad \text{...........} \quad \textbf{Eq.1}$$

2. ANNUAL INCREASE IN BIOMASS CARBON STOCKS DUE TO BIOMASS INCREMENT IN LAND REMAINING IN THE SAME LAND-USE CATEGORY

$$\Delta C_G = \sum_{i.j} [A_{i,j} * \{G_W * (1+R)\} * CF_{i.j}] \quad \text{...........} \quad \textbf{Eq.1.1}$$

3. ANNUAL DECREASE IN CARBON STOCKS DUE TO BIOMASS LOSSES IN LAND REMAINING IN THE SAME LAND-USE CATEGORY

$$\Delta C_L = L_{wood-removals} + L_{fuelwood} \quad \text{...........} \quad \textbf{Eq.1.2}$$

Where:

$$L_{wood-removals} = \{H * BCEF_R * (1+R) * CF\} \quad \text{...........} \quad \textbf{Eq.1.2a}$$

$$L_{fuelwood} = [\{FG_{Trees} * BCEF_R * (1+R)\} + FG_{part} * D] * CF \quad \text{...} \quad \textbf{Eq.1.2b}$$

4. ANNUAL CHANGE IN BIOMASS CARBON STOCKS ON LAND CONVERTED TO ANOTHER LAND-USE CATEGORY (TIER 2)

$$\Delta C_B = \Delta C_G + \Delta C_{conversion} - \Delta C_L \quad \text{...........} \quad \textbf{Eq.2}$$

5. INITIAL CHANGE IN BIOMASS CARBON STOCKS ON LAND CONVERTED TO ANOTHER LAND CATEGORY

$$\Delta C_{CONVERSION} = \sum_i \{(B_{After} - B_{Before}) * \Delta A_{To\_Others}\} * CF\} \quad \text{......} \quad \textbf{Eq.2.1}$$

6. ANNUAL CHANGE IN ORGANIC CARBON STOCKS IN MINERAL SOILS

$$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D} \quad \text{............} \quad \textbf{Eq.3}$$

$$SOC = \sum_{C,S,i} (SOC_{REF_{c,s,i}} * F_{L,U_{c,s,i}} * F_{M,G_{c,s,i}} * F_{I_{c,s,i}} * A_{c,s,i}) \quad \text{.........} \quad \textbf{Eq.3.1}$$

Where:

ΔC_B = annual change in carbon stocks in biomass (the sum of above-ground and below-ground biomass) for each land sub-category, considering the total area, Mg C yr^{-1}

ΔC_G = annual increase in carbon stocks due to biomass growth for each land sub-category, considering the total area, Mg C yr^{-1}

ΔC_L = annual decrease in carbon stocks due to biomass loss for each land sub-category, considering the total area, Mg C yr^{-1}

A = area of land remaining in the same land-use category, ha

G_W = average annual above-ground biomass growth for a specific woody vegetation type, Mg d. m.ha^{-1} yr^{-1}
i = ecological zone (*i* = 1 to *n*)
j = climate domain (*j* = 1 to *m)*

CF = carbon fraction of dry matter, tonne C (tonne d.m.)-

Lwood-removals = annual carbon loss due to wood removals, Mg C yr^{-1}

Lfuel wood = annual biomass carbon loss due to fuel wood removals, Mg C yr^{-1}

Lwood-removals = annual carbon loss due to biomass removals, Mg C yr^{-1}

H = annual wood removals, roundwood, m^3 yr^{-1}

R = ratio of below-ground biomass to above-ground biomass, in tonne d.m. below-ground biomass (tonne d.m. above-ground biomass)-1. R must be set to zero if assuming no changes of below-ground biomass allocation patterns (Tier 1).

BCEFR = biomass conversion and expansion factor for conversion of removals in merchantable volume to total biomass removals (including bark), Mg biomass removal (m3 of removals)-1. However, if BCEFR values are not available and if the biomass expansion factor for wood removals (BEFR) and basic wood density (D) values are separately estimated, then multiplication of both conversion can be used:

FGtrees = annual volume of fuel wood removal of whole trees, m^3 yr^{-1}

FGpart = annual volume of fuel wood removal as tree parts, m^3 yr^{-1}

$\Delta C_{CONVERSION}$ = initial change in carbon stocks in biomass on land converted to other land-use category, in Mg C yr^{-1}

$B_{AFTER}i$ = biomass stocks on land type *i* immediately after the conversion, Mg d.m. ha^{-1}

$B_{BEFORE}i$ = biomass stocks on land type *i* before the conversion, Mg d.m. ha^{-1}

ΔA_{To_Others} = area of land use *i* converted to another land-use category in a certain year, ha^{-1}

$\Delta C_{MINERAL}$ = annual change in carbon stocks in mineral soils, Mg C yr^{-1}

SOC_0 = soil organic carbon stock in the last year of an inventory time period, Mg C

$SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory time period, Mg C

SOC_0 and $SOC_{(0\text{-}T)}$ are calculated using the SOC equation in the box where the reference carbon stocks and stock change factors are assigned according to the land-use and management activities and corresponding areas at each of the points in time (time = 0 and time = 0-T)

T = number of years over a single inventory time period, yr

D = time dependence of stock change factors which is the default time period for transition between equilibrium SOC values, yr. Commonly 20 years, but depends on assumptions made in computing the factors FLU, FMG and FI. If T exceeds D, use the value for T to obtain an annual rate of change over the inventory time period (0-T years).

c = represents the climate zones, *s* the soil types, and *i* the set of management systems that are present in a country.

SOC_{REF} = the reference carbon stock, Mg C ha^{-1}

FLU = stock change factor for land-use systems or sub-system for a particular land-use, dimensionless

[Note: FND is substituted for FLU in forest soil C calculation to estimate the influence of natural disturbance regimes.

FMG = stock change factor for management regime, dimensionless

FI = stock change factor for input of organic matter, dimensionless

A = land area of the stratum being estimated, ha. All land in the stratum should have common biophysical conditions (i.e., climate and soil type) and management history over the inventory time period to be treated together for analytical purposes.

SUMMARY

Widespread concern about global climate change has led to interest in reducing emissions of carbon dioxide (CO_2) and, under certain circumstances, in accounting for carbon absorbed in soils and vegetation as part of the emissions reductions. Forests are a significant part of the global carbon cycle and have been identified as potential major contributors to mitigation of climate warming through their carbon sequestration capacity. Forests contain a large part of the carbon stored in the terrestrial biosphere, in the form of biomass (trunks, branches, foliage, roots, etc.) and in the form of soil organic carbon. In order for forests to contribute significantly to a reduction in the rate of increase in atmospheric carbon, two things must happen: deforestation must be slowed and the biotic reservoirs of carbon must be enhanced through forest management.

Fossil fuel burning and deforestation have emerged as the major contributor of carbon dioxide to the atmosphere. Forest management refers to a broad range of activities, including forest protection, afforestation, reforestation, and slowing down deforestation. An option for mitigating the accumulation of CO_2 in the atmosphere is the enhanced sequestration of carbon by the biosphere through massive reforestation or sustainable afforestation programme. Reducing the rate of forest clearing reduces carbon losses from terrestrial ecosystems. Furthermore, establishing plantations on former agricultural land may have less of an impact on increasing carbon sequestration than restoring natural forests. Of course, plantations also provide forest products to society and have been making a major contribution in meeting the needs of timber and fuelwood. Ecosystem conservation and appropriate management practices can restore, maintain, and enlarge soil carbon stocks. This study attempts to estimate the carbon budgets and carbon sequestration potential of Indian forests, assessing the possible impacts of land-use changes and climate change on carbon stocks of Indian forests and the mitigation potential of using bioenergy for fossil fuel substitution.

India is one of the few developing countries where deforestation rate has been reduced and the forest cover has nearly stabilized. This study reports in chapter 2 the estimates of above-ground phytomass carbon pools in Indian forests for the year 1992 and 2002 using two different methodologies. The estimated total biomass increment

was about 458 Tg biomass over the period 1992-2002 (approximately 8% of the total biomass). Removals from forests include mainly timber and fuel wood, whereby the latter includes large uncertainty, as reported extraction is lower than actual consumption. Both approaches indicate Indian forests to be sequestering carbon, in agreement with other recent studies. A major uncertainty in phytomass carbon pool dynamics is associated with trees outside forests and with soil organic carbon dynamics. Using recent remote-sensing based estimates of tree cover and growing stock outside forests, the estimated national average tree C density is 4 Mg C ha^{-1} in non-forest area, in comparison to an average density of 43 Mg C ha^{-1} in forests. In India the deforestation rate has reduced and forests nearly stabilized. The main factors contributing to these trends include legislations (such as the Forest Conservation Act -FCA-, 1980), policies (such as the National Forest Policy -NFP-, of 1988), and forest conservation and afforestation programmes (such as the compensatory regulations included in the Forest conservation Act of 1988). Additionally, the participation of people in the development and protection of forests has been actively promoted by the NFP, 1988. Future studies will have to consider dynamics in both trees outside forests and soil for total terrestrial carbon dynamics.

Existing studies show that the above ground woody biomass productivity of forest plantations at different locations in India range from 1.2 to 8.2 Mg ha^{-1} $yr^{-1,}$ with the national mean productivity being around 3.1 Mg ha^{-1} yr^{-1}. A dynamic carbon balance model (CO2FIX) was used for estimating the carbon sequestration potential of natural sal (*Shorea robusta* Gaertn. f.), Eucalyptus (*Eucalyptus tereticornis* Sm.), poplar (*Populus deltoides* Marsh), and teak (*Tectona grandis* Linn. f.) forests in India. The results in chapter 3 indicate that the highest net annual carbon sequestration rates were achieved with fast growing short rotation poplar (8 Mg C $ha^{-1}yr^{-1}$) and Eucalyptus (6 Mg C ha^{-1} yr^{-1}) plantations, followed by moderately growing teak forests (2 Mg C ha^{-1} yr^{-1}) and slow growing long rotation sal forests (1 Mg C ha^{-1} yr^{-1}). Long rotation forests give greater benefits for long term carbon storage in forest and product pools; whereas short rotation forests, in addition to carbon storage, rapidly produce biomass for meeting the demand for fibre and fuel. Choice of rotation length and thinning intensity are commonly used to manage timber yield and carbon stocks of forests. These management practices affect all forms of carbon stocks (i.e., tree, soil and wood products). Our results in chapter 3 show that the estimated total carbon stock in forest biomass and wood products ranged from 123 to 168 Mg C ha^{-1} indicating that increased rotation length yielded higher total carbon storage. For sal species, the carbon stock in soil and product was less sensitive to the increase or decrease in rotation length from recommended 120 years as compared to the carbon stock in tree biomass. In sal forests, the net primary productivity (i.e. the carbon flux to the system) was highest (3.7 Mg $ha^{-1}yr^{-1}$) at 60-year rotation length and minimum (i.e., 1.7 Mg $ha^{-1}yr^{-1}$) at 150 years. An increased rotation length from recommended 120 to 150 years in sal species increased the carbon sequestration of trees by 18% from 82 to 97 Mg C ha^{-1}. High carbon storage and production of more valuable saw logs can be achieved from longer rotation lengths. Extended rotation lengths and reduced thinning intensity could enhance the long-term capacity of forest ecosystems to sequester carbon.

Land use changes such as reduction in forest cover resulting from industrial logging, fuel wood harvest or shifting cultivation, clearing of forests for conversion to permanent cropland or to waste lands, and conversion of crop lands or waste lands to forest lands by afforestation or reforestation, either by natural or artificial regeneration (including plantations) result in emissions and removal of CO_2 from the terrestrial biosphere. Chapter 4 reports on the net carbon flux caused by deforestation and afforestation in India over the period from 1982 to 2002, using the IPCC 2006 guidelines for greenhouse gas inventories. The approach accounts for forest and soil C pool changes for forest areas remaining as forests, afforested areas and deforested areas. In the 1982 to 2002 period, the forest cover changed from 64.20 Mha in 1982 to 63.96 Mha and 67.83 Mha in 1992 and 2002 respectively. During the 1982-1992 and 1992-2002 periods, plantations were established at a rate of 0.2 and 0.5 Mha per year, while the annual deforestation rate was reduced from 0.22 to 0.07 Mha in these successive periods.

The average net flux of carbon attributable to land use change decreased from a source of 5.65 Tg C yr^{-1} (or 0.09 Mg C $ha^{-1}yr^{-1}$) during 1982-1992 to a sink of 1.09

Tg C yr^{-1} (or 0.02 Mg C $ha^{-1}yr^{-1}$) during 1992-2002. Thus, over the 10-year period from 1992-2002, Indian forests have acted as a small carbon sink. The cumulative net carbon flux from Indian forests to the atmosphere, due to land use change between 1982 to 2002 was estimated as 45.9 Tg C in total. The largest fluxes result from the conversion of forest land to cropland deforestation leading to waste lands. Because of the uncertainties in input variables (resulting from very large spatial heterogeneity) that affect net C flux from land use change, there is an urgent need for more reliable district - based data to facilitate accurate and refined estimates in future.

Nowadays, land management for establishment of fast growing energy crops for biomass production is receiving increasing attention from scientists, policymakers and governments. Short rotation bioenergy crops for energy production are considered an effective means to mitigate the greenhouse effect, mainly due to their ability to substitute fossil fuels. Alternatively, carbon can be sequestered and stored in the living biomass. Chapter 5 compares two land use categories (forest land and non-forest land) for two management practices (short rotation vs. long rotation) to study mitigation potential of afforestation while separating fossil fuel substitution using bioenergy for emission reduction as compared to carbon storage in the biomass to compensate for emissions from fossil fuel use. Significant carbon benefit can be obtained in the long run from using lands for growing short rotation energy crops and substituting fossil fuels by the biomass thus produced, as compared to sequestering carbon in the biomass of the trees. When growth rates are high and harvest is used in a sustainable manner (i.e., replanting after every harvest), the opportunities for net carbon reductions appear to be fossil fuel substitution, rather than storage in ecosystem biomass. Substitution of fossil fuels by bioenergy is potentially a continuous process, whereas carbon storage can occur only once. Our results suggest that at year 100 a total of 216 Mg C ha^{-1} can be sequestered and stored by afforestation using long rotation sal forests, as opposed to a total offset of 412 Mg C ha^{-1} from carbon storage and fossil fuel substitution from short rotation poplar plantations. The bioenergy option results in a continuous stream of about 3 Mg C $ha^{-1}yr^{-1}$ of carbon benefits per year on forest land and 4 Mg C $ha^{-1}yr^{-1}$ on non-forest land. Sudha *et al*. (2003) estimated that under different biomass demand scenarios, the total land available in

India for biomass production ranges between 9.6 to 36.5 Mha. Thus, the potential biomass that can be acquired for generating bioenergy from 9.6 Mha land would be 758 Tg per year. Thus, giving a mitigation potential in the range of 227 to 303 Tg C per year for electricity generation from poplar plantation for substituting coal based power generation. Further studies are needed to estimate the mitigation potential of other species with different productivities for overall estimation of the economic feasibility and social acceptability in a tropical country like India. Finally, we conclude that India with high population density, low forest cover per capita, high dependence of a large part of human population on forests, and a predominantly agrarian economy, has been able to reduce deforestation rate and increase its forest cover and carbon sink in the terrestrial biosphere. India is projected to make further positive contributions to global change mitigation and has the potential to create additional carbon sinks by using marginal lands, while at the same time balancing economic development and environmental concerns.

SAMENVATTING

Wijdverbreide bezorgdheid over mondiale klimaatverandering heeft geleid tot de behoefte om de uitstoot van kooldioxide (CO_2) te reduceren en, onder bepaalde omstandigheden, de koolstof die is opgenomen in de bodem en vegetatie als onderdeel van de emissiereducties te beschouwen. Bossen vormen een belangrijk onderdeel van de mondiale koolstofcyclus en kunnen, vanwege hun capaciteit om koolstof vast te leggen, potentieel een belangrijke bijdrage leveren aan de terugdringing van de opwarming van het klimaat. Bossen bevatten een groot deel van de koolstof die opgeslagen is in de terrestrische biosfeer, in de vorm van biomassa (van stammen, takken, bladeren, en wortels) en in de vorm van organische koolstof in de bodem. Er moeten twee dingen gebeuren om bossen significant te laten bijdragen aan een vermindering van de snelheid waarmee CO_2 in de atmosfeer stijgt; de ontbossing moet worden afgeremd en de biotische koolstofreservoirs moet toenemen door middel van bosbeheer.

Verbranding van fossiele brandstoffen en ontbossing leveren nu de belangrijkste bijdrage aan kooldioxide in de atmosfeer. Bosbeheer omvat een breed scala aan activiteiten, waaronder bosbescherming, bebossing, herbebossing, en het terugdringen van ontbossing. Een verhoogde vastlegging van koolstof in de biosfeer door middel van grootschalige herbebossing of duurzame bebossingprogramma's kan bijdragen aan een vermindering van de stijging van atmosferisch CO_2. Daarnaast kan een verlaging van de ontbossingssnelheid de koolstofemissie door terrestrische ecosystemen reduceren. Verder heeft het vestigen van plantages op voormalige landbouwgronden minder effect op de verhoging van koolstofopslag dan het herstel van natuurlijke bossen. Natuurlijk leveren plantages ook bosproducten aan de samenleving, en zij hebben een belangrijke bijdrage geleverd om aan de behoefte aan (brand)hout te voldoen. Het behoud van ecosystemen en doelmatig beheerspraktijken kunnen de koolstofvoorraden in de bodem herstellen, handhaven, en vergroten. In deze studie wordt getracht om een schatting te maken van het koolstofbudget van Indiase bossen en van hun potentieel om koolstof vast te leggen, door het effect van landgebruiks- en klimaatsveranderingen op Indiase bossen te bepalen, evenals de mogelijkheden van het gebruik van bio-energie om fossiele brandstoffen te vervangen.

India is een van de weinige ontwikkelingslanden waar de ontbossingssnelheid is afgenomen en de bosbedekking bijna is gestabiliseerd. In hoofdstuk 2 wordt, met behulp van twee verschillende methodes, een schatting gemaakt van de bovengrondse koolstofvoorraad in de biomassa van Indiase bossen in 1992 en in 2002. De geschatte totale biomassatoename was ongeveer 458 Tg over de periode 1992-2002 (ongeveer 8% van de totale biomassa). De oogst van biomassa uit het bos was voornamelijk het gevolg van de exploitatie voor (brand)hout. De schatting voor brandhout is erg onzeker, omdat de gerapporteerde extractie lager is dan het daadwerkelijke brandhoutverbruik. Beide benaderingen geven aan dat Indiase bossen koolstof vastleggen, wat overeenkomt met de resultaten van andere recente studies.

Bomen buiten het bos, en de dynamiek van de organische koolstof in de bodem zijn belangrijke bronnen van onzekerheid in de schatting van de koolstofvoorraad in de biomassa. Recente teledetectie schattingen van boombedekking en biomassavoorraad buiten het bos zijn gebruikt om een betere schatting te maken van de landelijke gemiddelde koolstofvoorraad van de bomen buiten het bos. Deze voorraad wordt geschat op 4 Mg C ha^{-1} voor niet-bosgebieden, en op 43 Mg C ha^{-1} voor bosgebieden. In India is de ontbossingssnelheid afgenomen and is het bosoppervlak bijna gestabiliseerd. De belangrijkste factoren die bijdragen aan deze trends zijn boswetten (zoals de Forest Conservation Act -FCA- uit 1980), beleid (zoals het Nationaal Bosbeleid-NFP- uit 1988), en programma's voor bosbescherming en bebossing (zoals de compenserende voorschriften die zijn opgenomen in de Forest Conservation Act van 1988). Daarnaast wordt de deelname van lokale bevolking in de ontwikkeling en bescherming van bossen actief gestimuleerd door het NFP uit 1988. Toekomstig onderzoek naar de terrestrische koolstofdynamiek zal zowel bomen buiten de bossen, als ook de koolstofvoorraad in de bodem in beschouwing moeten mee nemen.

Eerdere studies laten zien dat de bovengrondse productiviteit van hout in bosplantages op verschillende locaties in India varieert van 1.2 tot 8.2 Mg ha^{-1} jr^{-1}, met een landelijk gemiddelde productiviteit van ongeveer 3.1 Mg ha^{-1} jr^{-1}. Een dynamisch koolstofbalansmodel (CO2FIX) werd gebruikt om het koolstofopslagpotentieel van natuurlijke bossen van sal (*Shorea robusta* Gaertn. F.), eucalyptus (*Eucalyptus* *tereticornis* Sm.), populier (*Populus deltoides* Marsh) en teak (*Tectona grandis* Linn. f.) te schatten. De resultaten in hoofdstuk 3 laten zien dat de hoogste netto jaarlijkse koolstofvastlegging wordt bereikt met snelgroeiende populieren- (8 Mg C ha^{-1} jr^{-1}) en eucalyptusplantages (6 Mg C ha^{-1} jr^{-1}) met korte omlooptijd, gevolgd door matig groeiende teak bossen (2 Mg C ha^{-1} jr^{-1}) en traag groeiende salbossen met lange omlooptijd (1 Mg C ha^{-1} jr^{-1}). Bossen met een lange omlooptijd leveren grotere voordelen voor de langetermijn koolstopslag in bos en bosproducten. Bossen met een korte omlooptijd slaan daarentegen niet alleen koolstof op, maar ze produceren ook heel snel biomassa zodat aan de vraag naar vezels en brandstof kan worden voldaan. Bosbeheerders variëren de omlooptijd en de dunningsintensiteit om de houtopbrengst en koolstofvoorraden van bossen te beheren. Deze beheerspraktijken zijn van invloed op alle vormen van koolstofvoorraden (in bomen, bodem, en houtproducten). Hoofdstuk 3 laat zien dat de geschatte totale koolstofvoorraad in bosbiomassa en houtproducten varieert van 123 tot 168 Mg C ha^{-1}. Dit geeft aan dat de toegenomen omlooptijd voor een hogere totale koolstofopslag zorgt. Voor sal was de voorraad koolstof in de boombiomassa gevoelig voor een toe- of afname van de aanbevolen omlooptijd van 120 jaar, terwijl de koolstofvoorraad in de bodem en bosproducten hiervoor minder gevoelig was. De netto primaire productiviteit (dat wil zeggen,. de koolstofvastlegging door het systeem) van sal bossen was het hoogst (3.7 Mg $ha^{-1}yr^{-1}$) bij een omlooptijd van 60 jaar en het laagst (1.7 Mg $ha^{-1}yr^{-1}$) bij een omlooptijd van 150 jaar. Een toename van de omlooptijd van de aanbevolen 120 jaar tot 150 jaar verhoogde de koolstofvastlegging van bomen met 18%, van 82 tot 97 Mg C ha^{-1}. Een hoge koolstofopslag en een hogere productie van waardevolle stammen kan worden bereikt door een langere omlooptijd. Een langere omlooptijd en een lagere dunningsintensiteit kan de lange termijn capaciteit van koolstofvastlegging door bosecosystemen verhogen.

Veranderingen in landgebruik leiden tot de uitstoot of opname van CO_2 in de terrestrische biosfeer. Voorbeelden van zulke landgebruiksveranderingen zijn de vermindering van bosareaal door commerciële houtkap, brandhoutoogst, of zwerflandbouw, de omzetting van bossen naar permanente landbouw, of de toename van bosareaal door (her)bebossing door natuurlijke en kunstmatige regeneratie (zoals plantages). Hoofdstuk 4 evalueert, gebruik makend van de IPCC 2006 richtlijnen voor de inventarisatie van broeikasgassen, de netto koolstofflux veroorzaakt door ontbossing en bebossing in India over de periode van 1982 tot 2002. De koolstofvoorraad in bos en bosbodem wordt geëvalueerd voor gebieden die bebost werden, ontbost werden, of waar het bos is gebleven. Het bosareaal veranderde van 64.20 Mha in 1982, via 63.96 Mha in 1992 tot 67.83 Mha in 2002. In de periodes van 1982-1992 en 1992-2002, nam het oppervlak aan plantages toe met een snelheid van respectievelijk 0.2 en 0.5 Mha per jaar, terwijl de ontbossingsnelheid afnam van 0.22 tot 0.07 Mha per jaar.

De gemiddelde netto koolstofflux die kan worden toegeschreven aan veranderingen in landgebruik daalde van een netto koolstofproductie van 5.65 Tg C jr^{-1} (0.09 Mg C ha^{-1} jr^{-1}) in de periode 1982-1992 tot een netto koolstoffixatie van 1.09 Tg C jr^{-1} (0.02 Mg C ha^{-1} jr^{-1}) in de periode 1992-2002. Indiase bossen hebben daarom over de 10-jarige periode van 1992-2002 gefunctioneerd als een kleine koolstofput. Landgebruiksveranderingen gedurende de 20-jarige periode van 1982 tot 2002 hebben geleid tot een netto koolstofuitstoot van 45.9 Tg C van bos naar atmosfeer. De grootste koolstofuitstoot was het gevolg van de omzetting van bos naar landbouwgrond, en van ontbossing die tot gedegradeerde bodems geleid heeftt. De zeer grote ruimtelijke heterogeniteit leidt tot onzekere schatting van de variabelen die de netto koolstofstromen beïnvloeden. Er is daarom een dringende behoefte aan meer betrouwbare, op districten gebaseerde gegevens, zodat in de toekomst meer precieze en nauwkeuriger schattingen kunnen worden gemaakt.

Onderzoekers, beleidsmakers en overheden besteden tegenwoordig steeds meer aandacht aan snelgroeiende gewassen voor biomassaproductie. Gewassen met een korte omlooptijd die gebruikt kunnen worden voor energievoorziening kunnen als substituut dienen voor fossiele brandstoffen, en zo op een effectieve wijze het broeikaseffect verminderen, Een andere optie is om de vastgelegde koolstof op te slaan in de levende biomassa. Hoofdstuk 5 evalueert de potentie van bebossing om het broeikaseffect te verminderen, onderscheiden naar koolstofopslag en substitutie van gebruik van fossiele brandstof. Dit wordt gedaan door twee landgebruikstypes (bos en niet-bos) en twee beheermaatregelen (korte vs. lange omloop) met elkaar te vergelijken. Significante emissiereductie kan op de lange termijn worden verkregen, door land te gebruiken voor energiegewassen met een korte omlooptijd, waarbij de biomassa gebruikt wordt ter vervanging van fossiele brandstoffen. Deze koolstofbaten zijn hoger in vergelijking met lange termijn koolstofopslag in boombiomassa omdat de vervanging van fossiele brandstoffen door biobrandstoffen in principe een continu proces is (indien de geoogste gewassen opnieuw worden geplant), terwijl de lange termijn koolstofopslag in de vegetatie slechts eenmaal kan gebeuren.

Bebossing met sal met een lange omlooptijd, resulteert na 100 jaar in een totale koolstofvastlegging en opslag van 216 Mg C ha^{-1}. Populierenplantages met een korte omlooptijd (die gebruikt worden ter substitutie van fossiele brandstoffen) resulteren daarentegen in een totale emissie-vermijding van 412 Mg C ha^{-1}. De bioenergie-optie resulteert in een continue stroom van ca. 3 Mg C ha^{-1} jr^{-1} aan koolstofbaten op bosgrond en 4 Mg C ha^{-1} jr^{-1} op niet-bosgrond. De totale beschikbare grond in India voor biomassaproductie varieert van 9.6 tot 36.5 Mha, afhankelijk van welk scenario wordt gebruikt voor de vraag naar biomassa (Sudha *et al.* 2003). Met 9.6 Mha aan land voor het genereren van bioenergie zou de potentiële koolstofvastlegging 758 Tg C per jaar zijn. Indien biobrandstof van populierenplantages wordt gebruikt als vervanger voor steenkool om electriciteit op te wekken, dan zou de vermindering van koolstofuitstoot 227 tot 303 Tg C per jaar zijn. Verdere studies zijn nodig om het potentieel van andere soorten om het broeikaseffect te verminderen te evalueren. Voor een tropisch land als India zijn er ook studies nodig naar de economische haalbaarheid en maatschappelijke acceptatie hiervan. Tot slot concluderen we dat India er in is geslaagd om de ontbossingsnelheid te verminderen en het bosareaal en de terrestrische koolstofopslag te laten toenemen. Dit ondanks de hoge bevolkingsdichtheid, het lage bosoppervlak per hoofd van de bevolking, een overwegend agrarische economie, en het feit dat een groot deel van de bevolking afhankelijk is van bossen. India zal naar verwachting verder bijdragen aan de broeikasgasvermindering, en heeft de potentie om extra koolstof vast te leggen door marginale gronden te gebruiken, waardoor economische ontwikkeling en de zorg voor het milieu gecombineerd kunnen worden.

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CURRICULUM VITAE

Meenakshi Kaul was born on the 29th of January 1972 at Bangalore, India. She completed her higher secondary school in 1989, with Biology, Chemistry, Physics and Mathematics as major subjects and later on studied Bachelors in Physics at the Delhi University, India. After completing her graduation, she did two years Masters programme in Ecology and Environment from the Institute of Ecology and Environment, New Delhi. In 1993, she started her carrier as a field organiser at "Environment Society of India" an NGO at Chandigarh. Subsequently, she worked as a volunteer and later on as research assistant in the "*Green Rating of Indian Industry Project (GRP)*" funded by United Nations Development Programme (UNDP) and Government of India (GOI) at "Centre for Science and Environment". In 1999, she joined Centre for Atmospheric Sciences (CAS), Indian Institute of Technology, New Delhi as a research assistant and worked till december 2002 .

In April 2002, she was admitted to the Sandwich Fellowship program of Wageningen University and joined the Forest Ecology and Forest Management group for a PhD study that led to this dissertation. While doing her PhD research, she started working at "Quality Software Solutions"as research associate from 2003 to 2005.

LIST OF PUBLICATIONS

Published in peer reviewed international journals

Kaul, M., Dadhwal, V.K., Mohren, G.M.J. 2009. Land use change and net C flux in Indian forests. Forest Ecology and Management, 258, 100-108.

Kaul, M., Mohren, G.M.J., Dadhwal, V.K., 2010. Carbon storage and sequestration potential of selected tree species in India. Mitigation and Adaptation Strategies for Global Change, 15: 489-510.

Kaul, M., Mohren, G.M.J., Dadhwal, V.K., 2010. Carbon storage versus fossil fuel substitution: a climate change mitigation option for two different land use categories based on short and long rotation forestry in India. Mitigation and Adaptation Strategies for Global Change, 15: 395-409.

Submitted

Kaul, M., Mohren, G.M.J., Dadhwal, V.K., 2009. Phytomass carbon pool of trees and forests in India

PE&RC PhD EDUCATION CERTIFICATE

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

The C.T. De Wit Graduate School PE&RC PRODUCTION ECOLOGY & RESOURCE CONSERVATION

Review of Literature (5.6 ECTS)

- Carbon budgets and carbon sequestration of Indian forests (2002)

Writing of Project Proposal (7 ECTS)

- Carbon budgets and carbon sequestration potential of Indian forests (2002)

Post-Graduate Courses (2.8 ECTS)

- How to manage diversity in living systems; PE&RC (2002)
- Application of remote sensing; Indian Institute of Remote Sensing (IIRS), Dehradun (2004)

Deficiency, Refresh, Brush-up Courses (2.3 ECTS)

- GIS Tools and applications; Lab. GIS and Remote Sensing, Wageningen (2002)
- Climate change mitigation and sustainable development; Govt. of India, Ministry of Environment and Forests (2006)
- Introduction to Endnote; Wageningen Library (2002)

Competence Strengthening / Skills Courses (3.8 ECTS)

- Writing and presenting a scientific paper; Mansholt Graduate School of Social Science, Wageningen (2002)
- Workshop on forestry, agriculture and ecosystems; Ministry of Environment & Forests and Indian Institute for Sustainable Development (2003)

- National workshop "GHG emission estimation"; NATCOM PMC (2004)
- Inception workshop on India's second national communication to the UNFCCC; IHC, New Delhi (2007)
- National workshop on "Forestry projects for Climate change mitigation in India: stakeholders dialogue and capacity building" (February' 2007)

Discussion Groups / Local Seminars and Other Scientific Meetings (7.4 ECTS)

- Weekly Chair group presentations (2002, 2004 and 2008/2009)
- Production Ecology and Resource Conservation (PE&RC discussion group) (2002)
- Climate change and GHG effect (presentation: Effect of climate change on Indian forests); Indian Institute of Science, Bangalore (2003)
- Towards a strategic approach to climate change: Indo-Italian seminar on renewable energy and energy conservation; FICCI, New Delhi (2005)
- Presentation on "Land use change effect on C stock of Indian forests (IPCC 2006 methodology)"; Dehradun (2008)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (1.9 ECTS)

- Vulnerability assessment and adaption in India; IIC, New Delhi (2007)
- PE&RC Introduction weekend (2008)

International Symposia, Workshops and Conferences (5.8 ECTS)

- CASFOR II, International Conference, Modelling carbon sequestration at the landscape level: Techniques, models and policy relevance; Palenque, Chiapas, Mexico (2004)
- International Conference on "Bio fuels 2012 – Vision to reality"; Tata Energy Research Institute, New Delhi (2005)