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CARBON FLOW IN INDIAN FORESTS

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Abstract. The present study estimates the net emission of carbon from the forest sector in India. For the reference year (1986), the gross emission from deforestation in that year, plus committed emissions from deforestation in the preceding years, is estimated to be 64×10^6 t of C. The carbon sequestration (or net woody biomass accumulation in trees for long-term storage) from the area brought under tree plantations and the existing forest area under forest succession is estimated to offset the gross carbon emission in India, leading to no net emissions of carbon from the forest sector. Medium-term projections for India (for the year 2011) show that under a 'business as usual' scenario at current rates of afforestation, projected carbon emissions would continue to be balanced by sequestration.

1. Introduction

Tropical deforestation has been responsible in part for the increasing concentration of CO_2 in the atmosphere (Houghton, 1990). Estimates of net release of carbon (C) at the global level are highly uncertain, ranging from 0.4–1.6 Gt (10^9 t or 10^{15} g) of C/year (Detwiler and Hall, 1988) to 1.1–3.6 Gt C/year (Houghton, 1991). According to IPCC (1995) carbon emission from changes in tropical land use is 1.6 ± 1 Gt. The high standard deviation indicates the uncertainties of methodology and data. The net annual carbon emission estimates for India vary from 0.672×10^6 t (Pachauri et al., 1992) to 41×10^6 t (Houghton, 1991). These uncertainties in estimates are due to difficulties in obtaining reliable data on rates of deforestation, extent of conversion of deforested area to different purposes, rates of degradation (and regeneration) of forests, standing biomass and soil carbon in different forest types and the extent of dependence on forests for various end uses in different countries. The definitions and methods used vary greatly.

Studies of carbon flows must take into consideration factors like carbon sequestration from regrowth in degraded forests and in afforested patches, soil carbon, and the nature of end uses of timber (for example, its use as structural members in buildings, or as furniture where carbon is stored for long periods). In this context the present study aims at estimating carbon flows in Indian forests, their contribution to global CO_2 build up, the factors that influence the carbon flows and future emission prospects. The study specifically aims to estimate:

1. standing biomass and carbon storage given the area under different forest types,

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Table I
Land use in India

Land use	Area (10^6 ha)	% of total area
Agriculture/area cropped	154.70	47.0
Forests (area officially recorded as forests)	75.18	22.8
Permanent pastures and other grazing land	12.15	3.7
Land under cultivable tree crop and groves	3.91	1.3
Cultivable wasteland	16.64	5.1
Land under non-agricultural uses (water bodies, settlement, infrastructure, etc.)	17.53	5.3
Barren and wasteland	24.60	7.5
Area for which no records exist	24.09	7.3
TOTAL	328.80	100.0

Source: FSI, 1988.

2. carbon emissions through various conversions given the rates of deforestation as well as forest degradation and the dependence on forests for meeting various biomass needs,
3. accumulation of biomass and carbon in Indian forests,
4. net carbon emissions from forestry, and,
5. net carbon emissions from Indian forests in the future under two scenarios.

Carbon flows from Indian forests are estimated for the reference year (1986). The methodology is based mainly on the CO-PATH model of Makundi et al. (1991).

2. Land Use in India

India has a population of 843 × 10^6 (1991) and a geographic area of 328.8 × 10^6 ha. The land use pattern is given in Table I. Nearly half of India's geographic area is under crops; 22.8% of the country's geographic area is classified as forest land legally. The area under categories other than forests and croplands (excluding 24 × 10^6 ha for which no records exist) accounts for 74.8 × 10^6 ha; most of this land is highly degraded with poor vegetation cover.

'Forest' area in India has traditionally been defined as land controlled by the Forestry Department, rather than as land actually under tree cover. In the past, the area actually under forests has been highly contested. However, with access to satellite imagery data from the Forest Survey of India, area under forests has been estimated (Table II). Satellite assessments carried out during 1981–1983 and 1985–1987 are used in this study. According to 1985–1987 assessment (FSI, 1988), 64.01 × 10^6 ha or 19.5% of the geographic area is under forests with over 10% crown cover. Of this, 37.8 × 10^6 ha or 11.5% of the geographic area is dense forest (with a crown cover of over 40%). The area under forest includes that under natural

Table II
Area under forest (10^3 ha) by state based on satellite imagery

State/union territories	1981–1983 imagery: all forests (crown cover ≥ 10%)	1985–1987 imagery: all forests (crown cover ≥ 10%)	Mean net change in forest area/year: (crown cover ≥ 10%)
Andhra Pradesh	5,019.4	4,791.1	–57.1
Aru. Pradesh	6,050.0	6,876.3	206.6
Assam	2,638.6	2,605.8	–8.2
Bihar	2,874.8	2,693.4	–45.4
Goa	128.5	130.0	0.38
Gujarat	1,357.0	1,167.0	–47.5
Haryana	64.4	56.3	–2.0
Himachal Pradesh	1,288.2	1,337.7	12.4
Jammu and Kashmir	2,088.0	2,042.4	–11.4
Karnataka	3,226.4	3,210.0	–4.1
Kerala	1,040.0	1,014.7	–6.3
Madhya Pradesh	12,774.9	13,319.1	136.1
Maharashtra	4,741.6	4,405.8	–84.0
Manipur	1,767.9	1,788.5	5.2
Meghalaya	1,651.1	1,569.0	–20.5
Mizoram	1,909.2	1,817.8	–22.9
Nagaland	1,435.1	1,435.6	0.1
Orissa	5,316.3	4,713.7	–150.7
Punjab	76.6	116.1	9.9
Rajasthan	1,247.8	1,296.6	12.2
Sikkim	283.9	312.4	7.1
Tamilnadu	1,838.0	1,771.5	–16.6
Tripura	574.3	532.5	–10.5
Uttar Pradesh	3,144.3	3,384.4	60.0
West Bengal	881.1	839.4	–10.5
Andaman and Nicobar	760.3	762.4	–0.8
Other regions	26.2	23.5	0.7
TOTAL AREA	64,203.9	64,013.0	
Change in forest area where the states with declining forest area are considered			498.5

Source: FSI, 1990. 1981–1983 imagery interpreted in 1987 assessment; 1985–1987 imagery interpreted in 1989 assessment.

forests and forest plantations. Woodland or plantation area with a crown cover of less than 10% is not considered as forest in Table II or in the calculations in the present study.

Indian forests have been classified into four major groups based on climate (FSI, 1988) namely: (1) tropical, (2) montane subtropical, (3) montane temperate, and

(4) alpine. Each of these major groups is further classified into sub-types based on vegetation; the area under each of these 14 forest types is given in Table III. Tropical moist deciduous and tropical dry deciduous forests dominate, accounting for 36% and 28.2% of the total forest area, respectively.

3. Area Deforested

A figure commonly quoted for area deforested annually in India is 0.4×10^6 ha (Myers, 1991). It is not clear how this was estimated and whether afforested area is considered. The data from satellite imagery at two periods on which the estimates used in the present study are based include the area brought under silvicultural plantations and the percentages of crown cover. Changes in area under forest (as defined by crown cover) in each state or union territory are given in Table II. Total area under forest (>10% crown cover) declined by 190,900 ha during the period of four years. Thus, when both deforestation and afforestation are considered, the decline in forested area (including plantations) was only 47,725 ha/year. However, considering only the deforestation rates, the area clearfelled is estimated to be 498×10^3 ha for the year 1986, later in the paper (Table II). The reference year for the carbon flow calculation is 1986 (the mid-year of the imagery assessment 1985–1987). For estimating gross carbon emissions the actual area deforested should be used. For estimating the net carbon emission (including carbon uptake), the area afforested or reforested should also be included as the standing carbon is different between clearfelled forest and afforested forest patches. In view of constraints imposed by availability of data, the following procedure was adopted for estimating the area deforested for gross carbon emission calculations.

All the states and union territories where there was a decline in forest area between the years 1982 and 1986 from the two satellite assessments given in Table II are considered. The decline in forest area of only the states where there was a reduction in area between 1982 and 1986 was estimated which was then divided by four years to obtain the annual decline in area in each state. National annual decline in forest area is estimated by considering the states (provinces) where $A\,82_i > A\,86_i$:

$$D = \sum_{i=1}^{27} (A\,82_i - A\,86_i)/4 \text{ years},$$

where

D = Annual decline in forest area (10^3 ha/year)

$A\,82_i$ = Area under forest for 1982 assessment in state 'i'

$A\,86_i$ = Area under forest for 1986 assessment in state 'i'

i = 1 to 27 states and union territories.

Table III

Area under different forest types, area deforested according to forest type, conversion of deforested area for different purposes (percentages) and maximum carbon emission in India

SI no.	Forest type	Area occupied	Area deforested	Conversion rate (% of the total deforested area)				Potential C emission from vegetation of deforested area
				Agri	Pasture	Clearcut	Sel. cut	
1.	Tropical moist evergreen	5,289	7.48	44.8	24.7	19.9	10.6	1.00
2.	Tropical semi evergreen	2,576	16.77	44.4	22.3	22.4	10.9	1.77
3.	Tropical moist deciduous	23,054	240.45	68.0	16.3	12.0	3.7	20.57
4.	Littoral and swamp	384	5.35	89.5	6.2	3.3	1.0	0.25
5.	Tropical dry deciduous	18.083	172.49	67.8	18.1	11.0	3.1	3.43
6.	Tropical thorn	1,573	25.81	29.9	46.0	21.0	3.1	0.20
7.	Tropical dry evergreen	134	1.36	31.4	14.5	52.2	1.9	0.01
8.	Sub tropical broadleaf hill	268	2.57	80.5	8.7	9.1	1.7	0.05
9.	Sub tropical pine	4,567	3.27	34.4	28.7	29.2	7.7	0.15
10.	Sub tropical dry evergreen	1,201	13.68	8.6	85.4	6.0	–	0.32
11.	Montane moist temperate	2,582	0.89	49.9	13.7	19.6	16.8	0.05
12.	Himalayan moist temperate	2,243	6.09	20.8	52.8	22.6	3.8	0.72
13.	Himalayan dry temperate	30	0.17	–	100.0	–	–	0.01
14.	Sup alpine and alpha	2,028	1.87	26.3	57.2	10.7	5.8	0.06
		64,012	498.25	62.8	21.3	12.2	3.7	28.59

Source: FSI, 1988.

The sum of all states where forest area declined is considered as the total decline in forest area for the reference year (1986) for C emission estimation. The area brought under silvicultural plantations in some states is included as forest area along with its crown cover, due to non-availability of disaggregated data. Thus the net area decline in each state is over and above the area planted to silviculture having over 10% crown cover. Standing biomass and consequently carbon storage in afforested areas is different from forests. To overcome this problem, carbon storage is estimated by considering the crown cover of the forests and plantations.

Decline in forest area for each state and the total for all India are given in Table II (last column). The total net decline in forest area in the reference year (1986) is estimated to be 498,250 ha. In the present study, the states where area under forest in 1986 was higher than in 1982 are considered only while estimating carbon uptake.

4. Conversion of Deforested Area for Different Purposes

Information on the conversion of deforested area for different purposes for each state is available only for the 1951–1975 period (Central Forestry Commission, 1981). Using the state-level data, it is possible to obtain the area deforested for different purposes in each forest type. The same proportion of total deforested area converted to each purpose in the 1951–1975 period (Table III) is assumed for 1986. Deforested area is considered as converted to agriculture, conversion to river valley projects (power and irrigation) and roads is considered as clearcutting, conversion to industry as selective cutting, and conversion to other purposes as pasture.

By considering the rates of conversion of deforested area to different uses at the state level and the area under different forest types in each state, the proportion of deforested area converted to each of the four purposes is calculated by forest type and at the national level for input to the CO-PATH model. The values are given in Table IV. At the national level, conversion to agriculture dominates (63% of the area deforested), followed by conversion to pasture, and clearcutting.

5. Biomass Demands on Indian Forests

In accordance with the CO-PATH model, the biomass demands on forests are considered under three headings: combustion, long-term use and short-term use. It is very difficult to estimate the quantities of different types of biomass removed from different forest types. Thus current consumption levels are considered and are given in Table V (combustion of firewood) and Table VI (short-term and long-term use).

Table IV

Diversion of forest area for various purposes in India (Area × 10^3 ha.)

Causes	Conversion considered in the present study	Area lost during 1951–1975 (10^3 ha)	Area lost during 1951–1975 as proportion of total	Area lost annually between 1982 (1981–1983) and 1986 (1985–1987) (10^3 ha)	Annual loss as % of total forest area present in 1982 (1981–1983)
Agriculture	Agriculture	2,520	0.625	313.02	0.4879
– River valley projects (dams)	Clearcutting	479	0.119	60.61	0.0946
– Roads		57	0.014		
Industries	Selective cutting	168	0.042	18.53	0.0289
Miscellaneous purposes	Pasture	803	0.199	106.08	0.1657
TOTAL		4,027	1.000	498.24	0.7783

Source: Since statewise details of deforestation for various purposes were available only for the years 1951–1975, Central Forestry Commission, 1981) the same proportion has been used as the basis while allocating the area deforested for various purposes in different states between 1982 and 1986.

Table V
Firewood, crop residues and dung use as fuel (10^6 t)

Year	Fuelwood (air dry)	Crop residues (air dry)	Dung (fresh – about 87% moisture)
1953–1954[a]	86.3	26.4	46.4
1960–1961[a]	99.6	30.6	54.6
1965–1966[a]	109.3	33.6	59.9
1970–1971[a]	117.9	36.3	64.6
1975–1976[a]	133.1	41.0	73.0
1986[b]	157.0		
2011[c]	191.0		

[a] Ministry of Environment, 1986.
[b] FSI, 1988.
[c] Projected figure.

Table VI
Long-term and short-term wood/timber use and projected demand for India (10^6 m^3)

Type of timber in demand	Year 1986	Projection for year 2011
For long-term use	13.76	25.85
Short-term use		
– Paper	6.57	
– Match industry	0.44	
– Packaging	6.81	
Total short-term use	13.82	25.96
Total timber	27.58	51.81

Source: FSI, 1988.
Long-term use includes: plywood and veneer, agricultural implements, furniture, housing, mining pit props, sporting goods, railway sleepers, etc.
Timber demand for year 2011: Population and demand ratio of 1981 was calculated. This ratio was multiplied with the projected population of 2011 to estimate the projected demand assuming current rate of consumption.

5.1. COMBUSTION (FIREWOOD)

Firewood is the dominant fuel for cooking in rural areas (as 95% of households depend on biomass; firewood, crop residues and dung), and for about 35% of urban households (NCAER, 1985). According to FSI (1988), the total firewood demand in 1987 was 157×10^6 t. This is in addition to crop residues and cattle dung. Combustion is important as it leads to release of CO_2 during the reference year. The different sources of firewood are: forests, village trees, and plantation tree crops like coconut, tea, rubber and *Eucalyptus*. In addition, shrubs and annual weeds are also used. Firewood in the form of twigs and branches or even entire trees, if harvested in a sustainable way, will not make any net CO_2 contribution if one assumes that the system is in equilibrium or if calculations are made with no discounting. However if trees or branches are felled for fuel in a non-sustainable way and burned, there would be net CO_2 emissions. It is difficult to estimate the proportion of, the 157×10^6 t/year, total firewood consumption in India coming from forests, and how much of the forest portion is harvested in a non-sustainable way. Sources of firewood considered in this study are: deforestation, silvicultural production in the current year, biomass removal from existing forests, and cutting of shifting cultivation fallows. Wood harvested for fuel purposes in sustainable as well as non-sustainable modes is considered here. Information on firewood extraction from forests is given in Appendix I.

5.2. SHORT-TERM USE

Wood used for pulp, paper, packaging, the match industry, etc., is considered as short-term use and the demand was officially estimated to be 13.82×10^6 m^3 for the reference year (1986) (FSI, 1988). The sources of timber for short-term uses are forests and plantations of trees like *Eucalyptus*.

5.3. LONG-TERM USE

Long-term use consists of timber for housing, agricultural implements, plywood, mining pit props, railway sleepers, etc. The total long-term use according to FSI (1988) was 13.76×10^6 m^3, and the same value is taken for the reference year (1986). Sources of timber for long-term use are: forests, tree plantations and trees in the village ecosystems. Forest is the dominant source of timber for structural materials, plywood and mining pit props. The actual quantity used may be higher than what is officially recorded as coming from clearfelled areas. This higher quantity is accounted for by considering the source of 'forest degradation'.

6. Standing Biomass in Forests

Standing biomass (above ground) data for different forest types were obtained from various published studies. Standing biomass includes only live woody biomass excluding leaves, reproductive parts and dead wood. Information on standing biomass is given in Appendix II.

The FSI (1988) gives the crown cover of forests in different states. Tiwari and Singh (1987) provide estimates of biomass under five crown cover levels for some forest types. This was extrapolated to other forest types. Using the data on

Table VII
Production and standing biomass (above ground) in forests, 1986

Forest type	Area occupied (10^3 ha)	Standing biomass (t/ha)	Average crown cover[a] (%)	Total standing biomass (10^6 t)
Tropical wet evergreen	5,289.3	607.7	0.4700	1,510.72
Tropical semi evergreen	2,575.7	468.0	0.4782	576.44
Tropical moist deciduous	23,054.7	409.3	0.4259	4,018.92
Littoral and swamp	383.4	213.8	0.4426	36.28
Tropical dry deciduous	18,083.3	93.8	0.4313	731.58
Tropical thorn	1,573.0	40.0	0.3989	25.10
Tropical dry evergreen	134.2	40.0	0.4156	2.23
Subtropical broadleafed hill	267.8	108.7	0.3818	11.11
Subtropical pine	4,567.5	210.8	0.4581	441.07
Subtropical dry evergreen	1,201.0	159.7	0.2901	55.64
Montane wet temperate	2,581.9	237.7	0.4875	299.19
Himalayan moist temperate	2,242.8	562.2	0.4263	537.52
Himalayan dry temperate	30.5	169.1	0.4079	2.10
Subalpine and alpine	2,027.7	127.4	0.4822	124.57
Total	64,013.0	–	–	8,372.47

[a] See explanation in Section 6 for estimating average crown cover.

standing forest biomass under full crown cover (from the literature) and estimating mean crown cover for each forest type, total standing biomass was calculated for each forest type (Table VII). Total above ground standing biomass in Indian forests (>10% crown cover) is estimated to be 8372×10^6 t, with a mean standing biomass of 130.8 t/ha.

7. Carbon Storage in Forests

Carbon storage in vegetation and soil is given in Table VIII. Carbon storage in forests is estimated by taking 50% of the biomass as carbon. Carbon storage in forest soil is considered based on the soil organic carbon content in the top 30 cm soil in different forest types from published studies. Total carbon stored in Indian forests is estimated at 9585×10^6 t C, of which vegetation and soil account for 44% and 56%, respectively. Information on soil carbon is given in Appendix III.

8. Carbon Uptake in Forests

When considering net carbon release, carbon uptake and storage in forests, and tree plantations (e.g., *Eucalyptus, Casuarina equisetifolia*) should be considered.

Table VIII

Carbon flows – current and future scenarios in India (10^6 t)

Carbon flux	1986	2011 business as usual[a]	2011 favorable scenario[b]
Carbon storage			
– Forest			
vegetation	4,178.95	4,178.95	4,186.00
soil	5,399.33	5,399.33	5,399.33
– Plantation	–	850.50	1,181.25
– Perennials	–	75.00	3,000.00
– Natural regeneration	–	–	1,096.87
TOTAL	9,578.28	10,503.78	14,856.40
Carbon emissions			
– Shifting cultivation	1.56	1.56	1.56
– Combustion	31.97	61.66	31.85
– Past long-term use	1.38	4.61	4.61
– Past short-term use	3.10	5.91	5.91
– Current short-term use	2.84	2.95	2.95
– Release from soil	3.91	3.91	3.91
– Biomass decomposition	18.82	18.82	18.82
TOTAL	63.58	99.42	69.61
Carbon uptake			
– Forests	68.87[c]	68.87	68.87
– Natural regeneration	–	0.23	9.38
– Afforestation	–	27.00	37.50
– Reforestation	–	–	75.00
TOTAL	68.87	96.10	190.75

[a] Business as usual: carbon flux in 2011 at current rates (explanation in text).

[b] Favorable scenario: carbon flux under favorable scenario (explanation in text).

[c] Carbon uptake in forests includes: C uptake in tree plantations as well as forests under succession.

Only in mature or climax forests is all gross primary productivity either used up in respiration or returned to soil as litter with no net addition to the standing biomass. At all other stages of forest succession there would be a net addition to the standing biomass leading to carbon storage. The 64.01 × 10^6 ha of forest considered in the present study also includes part of the 11.4 × 10^6 ha of cumulative area afforested from 1952 to 1986 (Ministry of Environment and Forests, 1990). Large tracts of forests in India have been subjected to anthropogenic pressures over centuries and thus are at various stages of succession. Annual carbon accumulation for the reference year is calculated using data on Net Primary Productivity (NPP) and standing biomass from various studies. Accumulation of biomass in the main trunk and large branches is considered for calculating carbon uptake. Leaf litter productivity is not included as it comes from the current year's production and is likely to end up in decomposition. The net accumulation of woody biomass considered for the study is in the range of 1.28 to 2.84% of the standing biomass of forests. The carbon accumulation is estimated using data on standing biomass data and % of standing biomass accumulating as wood in trunk and main branches. Thus the net carbon accumulation in Indian forests is estimated to be 69×10^6 t C for the year 1986 (Table VIII).

9. Carbon Emissions

Carbon emissions from forests can be from deforested areas as well as from degradation in existing forest areas. Carbon emission values are given in Table IX.

9.1. CARBON EMISSION FROM CLEARCUT FOREST

Annually, 27×10^6 t of firewood removed from forests through clearcutting, as given in FSI (1988), is taken to be coming from area deforested during the year. Thus 13.5×10^6 t C is estimated to be released from combustion from deforested areas. When the release of carbon from long-term use (structural timber) is considered, a lifespan of 30 years is taken for the timber used. Accordingly, the quantity of timber used for long-term purposes 30 years prior to the reference year is assumed to decompose and release carbon during the reference year. Due to this factor there is no balance between the total carbon stored in the felled vegetation (of 28.59×10^6 t from Table III) and the total carbon released from deforested area (of 27.6×10^6 t from Table IX). The wood or timber used under the short-term category (like paper) is expected to last for only three years, the stock declining in a straight line fashion to zero at the end of the period. Accordingly, the biomass used for short term purposes during the previous three years, which is assumed to release carbon annually, plus one-third of the reference year's use is taken for carbon release during 1986. Release of carbon from soil was calculated based on Ayanaba et al. (1976), while carbon release from biomass decomposition was calculated based on quantity of litter (largely natural) left for decomposition on forest floor (FRI, 1970). Gross release from various conversions (like combustion, short- and long-term use and decomposition) is estimated to be 27.6×10^6 t C for the reference year (Table IX).

9.2. CARBON EMISSION FROM THE REFERENCE YEAR'S PRIMARY PRODUCTION

Total NPP per year was estimated at 137.7×10^6 t woody biomass on the basis of recorded data from different forest types. Of total NPP, 69% was considered as accumulating in the bole and large branches for long-term storage (Seebauer, 1992).

Table IX
Carbon emission from forests in India – 1986 (10^6 t)

End use	From clearcut area for					From the NPP in the forest	From degradation of existing forests	From shifting cultivation	Total
	Agriculture	Pasture	Clear-cutting	Selective cutting	Total				
Combustion	8.15	2.92	2.03	0.40	13.50	10.75	7.72	1.56	33.53
Past long-term use	–	–	1.38	–	1.38	–	–	–	1.38
Past short-term use	–	–	1.30	0.25	3.10	–	–	–	3.10
Current short-term use	–	–	1.30	0.25	1.55	–	1.29	–	2.84
Root decomposition	–	–	0.16	0.05	0.21	–	–	–	0.21
Soil	2.41	0.83	0.50	0.17	3.91	–	–	–	3.91
Other surface decomposition	–	–	–	–	4.00	10.75	3.86	–	18.61
Total	10.56	3.75	6.67	1.12	27.65	21.50	12.87	1.56	63.58

NPP – Net Primary Productivity.

Of the remaining 31% of NPP, 50% was considered to be used as firewood and the remaining 50% (largely new shoots and micro litter) to be left to decompose. Biomass originating from net primary production in forests is estimated to produce a total carbon release through decomposition and through firewood combustion of 21.5×10^6 t/year.

9.3. CARBON EMISSION FROM FOREST DEGRADATION

In addition to carbon release from deforestation or clearcutting, degradation of existing forests also contributes to carbon release. Degradation can result from grazing, fire, death due to disease and pests, illegal removal of timber, non-sustainable harvest of firewood or timber, etc. Evidence for this is available from several studies (Brown and Lugo, 1991; Houghton, 1991; Flint and Richards, 1991). The analysis carried out by Flint and Richards (1991) and Houghton (1991) for Southern Asia (including northern parts of India) for the period 1950–1980 indicates a degradation ratio of 1.54, which is the ratio of biomass lost to area lost relative to the initial biomass. In other words, for every ton of carbon released to the atmosphere through deforestation, an additional 0.54 t of carbon is released from degradation of standing forests. The total quantity of carbon released due to degradation factors is 15.4×10^6 t C. Of this, about 50% is assumed to be used as firewood, 25% for long-term purposes, and 25% decomposes. The emission due to forest degradation is estimated to be 12.87×10^6 t C for the reference year (1986).

9.4. SHIFTING CULTIVATION

About 0.99×10^6 ha are annually subjected to shifting cultivation (FSI, 1988). The fallow period is getting shorter. Considering the shortened fallow period, a net emission of 1.56×10^6 t C is estimated after accounting for cutting of secondary forests in fallow areas, uptake in the fallow, and degradation or burning of new areas.

The gross annual emission from all natural and anthropogenic factors in the forest is estimated to be 64×10^6 t of C.

10. Net Carbon Release

When the net carbon emission in forest ecosystems is considered (release minus uptake) for India, a marginal net sequestration of 5×10^6 t of C can be observed for the reference year (Table VIII). This estimate differs from the net emission estimates of 41×10^6 t of C by Houghton (1991), 20.2×10^6 t of C by Ahuja (1991) and 0.67×10^6 t of C by Pachauri et al. (1992). The methods used differ among these studies. These studies generally do not consider carbon sequestration in tree plantations and in secondary forests, delayed carbon release from wood used for structural purposes, or use different values for rates of deforestation. The

C uptake in forests is significant as it includes forests subjected to degradation (unlike undisturbed climax forests) and a part of plantations raised on forest lands. A national level study on forest plantations in India has estimated the mean annual productivity (of woody biomass) to be 3.2 t/ha/year, with *Eucalyptus* (the dominant species) plantations recording 6.6 t/ha/year (Seebauer, 1992).

11. Explanation for Balance between Emission and Sequestration

The present study establishes that the carbon flux is nearly balanced in India and the forestry sector may not be making any net contribution to global CO_2 build up. Though this may look surprising, there are strong reasons supporting the case.

1. The Forest Conservation Act, 1980, prescribes that no land should be alienated from control by state forest departments without consent of the central government. Obtaining permission from the central government is an onerous task. This has largely halted all indiscriminate alienation.
   Forest area of 64×10^6 ha includes 41.4×10^6 ha of reserve (primary) forest land (FSI, 1994) which is covered under the Forest Conservation Act. However, the remaining 22.6×10^6 ha consists of plantations and forests dedicated for use by communities. The deforestation rate (of 498×10^3 ha) is likely to be largely from non-reserve forest categories which are meant to meet the biomass needs of communities and industries.
2. Beginning with the Fifth Five Year Plan (1975–1980), it is compulsory for all major development projects to carefully prepare an Environmental Impact Statement and to provide for compensatory afforestation in the event of any loss of forest cover.
3. Beginning in the late 1970s, the high levels of subsidies enjoyed by forest-based industries have been gradually reduced, thereby helping to motivate more careful use of resources.
4. Beginning in the 1970s, farmers have been encouraged to plant tree crops and many industries and farmers have developed links that supply wood to forest-based industries from marginal crop lands.
5. Beginning in the 1970s with the village Forest Protection Committees of West Bengal, local tribal peoples and villagers are being given an economic stake in the well-being of local forest resources. The response has been most encouraging. Other states like Haryana and Gujarat have initiated measures to create village-based management systems involving local people in sustainable use and restoration of degraded forest lands.
6. India has launched a very large afforestation program. The areas afforested in recent years are given in Table X. These data indicate that large areas are being brought under tree plantations in deforested areas or on degraded community land or private land. Studies of tree plantations raised by the forest department

Table X
Areas afforested in India

Years	Area afforested
1985–1986	1.51×10^6 ha
1986–1987	1.76×10^6 ha
1987–1988	1.77×10^6 ha
1988–1989	2.12×10^6 ha

Source: Ministry of Environment and Forests, 1989.

and farmers have shown a biomass productivity in the range of 1.3 to 8.3 t/ha/year (Ravindranath et al., 1992).
However, it should be noted that all the afforested area (of over 1 Mha annually since 1980) will not be reflected as forest area in the satellite assessment. The plantations are raised on farmers land or on community lands on a fraction of a ha or on a few ha annually in a discontinuous manner. Such small plantation patches are not covered in the satellite assessment (Ravindranath and Hall, 1995).

7. Biomass fuel conservation programs for biogas and more efficient stoves are being implemented in all states.

Limitations of the estimates of C emission: The emission estimates are based on the standing biomass determined using the crown cover estimates and a few published studies on standing biomass. Similarly, the C uptake is estimated to be in the range of 1.25 to 2.84% of the standing biomass. Any change in the estimates of crown cover, standing biomass and annual productivity will change the values of net C emissions.

12. Future Scenarios for Carbon Flow

To approximate possible future carbon emissions, a medium-term scenario is considered for the year 2011 (25 years from the reference year). Future scenarios are considered at two levels:

Scenario 1: Current rates of deforestation, afforestation, firewood consumption, productivity, long-term and short-term timber uses, etc., are considered. Area under tree plantations (like *Eucalyptus*) is expected to increase at current rates.

Some of the features of the scenario considered are;

- Short-term (firewood and softwood) and long term (timber) forest plantation area growth rate; 1.51 to 2.12×10^6 ha/year.
- Area allowed for natural regeneration; insignificant area.

- Productivity of forests and plantations: 1.28 to 2.84% of the standing biomass.
- Biogas plants for cooking; 0.22×10^6/year.
- Efficient stove program: 2×10^6/year.
- Rate of deforestation; 497×10^3 ha/year, largely from dedicated plantations raised for harvesting wood.

Scenario 2: A favorable scenario is considered assuming the following changes:

- Short-term forestry (firewood and softwood): 2.5×10^6 ha/year.
- Long-term forestry (fruit and timber trees): 2.0×10^6 ha/year.
- Area allowed to regenerate naturally as secondary forest: 1×10^6 ha/year.
- Productivity of plantations: 3 t/ha/year.
- Productivity of land regenerating naturally as secondary forest: 0.75 t/ha/year.
- Biogas plants for cooking: 0.5×10^6 units/year.
- Efficient stoves for households that can not get gaseous or liquid fuels for cooking and are forced to use biomass fuels (at a fuel saving of 33%).
- Area under forest would remain unchanged.

13. Results

Scenario 1: The 'Business As Usual' (BAU) scenario for the year 2011 shows that with an increase in population, there would be a proportionate increase in demands for biomass from forests and plantations. If the current per capita demands for firewood, short-term and long-term timber (which are being currently met from the forests and to a small extent from imports) are assumed for 2011, the gross emission from forests is estimated to be 99×10^6 t C during 2011. The current rates of afforestation, if continued, would offset the emissions of carbon. Thus even under the BAU scenario, carbon uptake is likely to balance carbon emission. In fact, in the years to come the rates of afforestation on degraded land are likely to increase, along with dissemination of firewood-conserving biogas and more efficient stoves. Such factors would reduce the pressure on forests and expand the carbon sinks.

Scenario 2: The favorable assumptions made for this scenario do not appear unrealistic to these authors. It is possible to bring annually 4.5×10^6 ha under planted tree vegetation and 1×10^6 ha under natural regeneration and to build 0.5×10^6 biogas plants and 2×10^6 fuel-efficient stoves. Under this scenario a net carbon sequestration of 121.1×10^6 t is possible. India has vast tracts of degraded lands of about 66 to 130×10^6 ha (Ravindranath and Hall, 1995) and thus large potential for sequestering carbon.

14. Summary and Conclusions

Net carbon emission from the forest sector in India can be estimated from the 0.498×10^6 ha annual rate of deforestation for the reference year (1986), based on satellite imagery assessments at two dates. In 1986, gross emission of carbon from deforestation and forest degradation was balanced by sequestration in tree plantations installed under afforestation programs and by forest succession taking place in forest land subjected to anthropogenic pressures. In literature there are varying estimates of net carbon emissions for tropical countries. Thus there is a need for standardizing the methodology for estimating carbon emissions from land use change and forest sources. Projections made under a 'business as usual' scenario for the year 2011 show that carbon sequestration (at current rates of afforestation and forest succession) would offset the gross emissions. Projections under a favorable scenario show large potential for net sequestration of carbon in India.

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Appendix I: Sources of Firewood

1. From deforestation

This study assumes that all of the recorded production of firewood (27×10^6 t) came from deforested area, the remaining 130×10^6 t of firewood consumed in the country came from other sources. Of the total recorded fuelwood produced, 17.7×10^6 t came from the area deforested for agriculture, while 5.3×10^6 t, 3.4×10^6 t and 0.6×10^6 t came from the areas deforested for pasture, clearcutting and selective cutting, respectively.

2. From net primary productivity (NPP) of woody biomass in the forest

Biomass accumulated annually in the forest through NPP is 137.7×10^6 t. Studies have shown that about 48–74% of the NPP accumulates in the boles (Rai, 1981; Rana, 1985; Sharma et al., 1990). Thus, about 94.7×10^6 t remains in the bole fraction and about 43×10^6 t is available in the form of small twigs and branches. Out of the latter share, only 50% (21.5×10^6 t) is considered extractable firewood; the remaining fine litter is likely to end up decomposing.

3. From degradation of existing stock

At a degradation ratio of 1.54, the biomass that would come from degraded sources is estimated to be 30.88×10^6 t; of this, 15.44×10^6 t (50%) is available as firewood and the remaining part may end up partly for short-term or long-term use and partly for decomposition.

4. From shifting cultivation

From an annual area of 0.99×10^6 ha under shifting cultivation, wood equivalent to 3.12×10^6 t is considered to be burned.

Altogether, firewood from forests accounts for 67.06×10^6 t. The rest of the firewood (89.94×10^6 t) may come from: (i) trees in village ecosystems, (ii) shrubs like *Prosopis juliflora*, *Lantana camara* and *Cassia auriculata*, (iii) residues of plantation crops like tea, coffee, rubber and coconuts.

Appendix II: Maximum Standing Biomass of Different Forest Types

	Forest Type	Standing biomass (t/ha)	Reference
1.	Tropical wet evergreen	607.7	Rai, 1981
2.	Tropical semi evergreen	468.0	Swamy, 1989
3.	Tropical moist deciduous	409.3	Swamy, 1989
4.	Littoral & swamp	213.8	V.P. Singh, 1989
5.	Tropical dry deciduous	93.8	L. Singh, 1990
6.	Tropical thorn[a]	40.0	
7.	Tropical dry evergreen[b]	40.0	
8.	Subtropical broadleafed hill	108.7	Toky and Ramakrishnan, 1982
9.	Subtropical pine	210.8	Chaturvedi and Singh, 1984
10.	Subtropical dry evergreen[c]	159.7	
11.	Montane wet temperate	237.67	Yadava, 1986
12.	Himalayan moist temperate	562.2	Rana, 1985
13.	Himalayan dry temperate[d]	169.1	
14–16	Subalpine & alpine	127.4	Yoda, 1968, cited by Cannell, 1982

[a] Tropical thorn forests were assumed to have 40% of the crown cover of tropical dry deciduous forests as they appear alongside the tropical dry deciduous forests; 40% of the standing biomass of deciduous forests were assumed to be the standing biomass of tropical thorn forests, which is 37.52 t/ha further rounded off to 40 t/ha.

[b] Same as tropical thorn forests.

[c] Since it occurs between subtropical pine and tropical dry deciduous forests, a mid value between the standing biomass values of these two forest types is used.
[d] Since it occurs between subtropical pine and subalpine forests a mid value between the standing biomass values of these two forest types is used

Appendix III: Soil Carbon in Different Forest Types

Forest type		Soil carbon in top 30 cm (t/ha)	Reference
1.	Tropical wet evergreen	125.19	K. P Singh, 1968
		140 4	Rajamannar and Krishnamoorthy, 1978
	Mean	132.79	
2.	Tropical semi evergreen	152.9	K. P. Singh, 1968
		190.6	Swamy, 1989
	Mean	171.75	
3.	Tropical moist deciduous	40.17	Das, 1975
		42.12	Rajamannar and Krishnamoorthy, 1978
		67.08	Banerjee et al., 1986
		79.17	Jha et al., 1979
	Mean	57.14	
4.	Littoral & swamp	26.52	Sahoo et al , 1989
		29.25	
		34.90	
	Mean	30.22	
5.	Tropical dry deciduous	51.87	Kumar et al., 1987
		54.21	Sachan et al., 1980
		61.16	R. Singh et al., 1990
		64.74	Singhal and Sharman, 1983
	Mean	57.99	
6.	Tropical thorn	44.0	[a]
7.	Tropical dry evergreen	33.0	[b]
8.	Subtropical broadleafed hill	94.37	Mandal et al., 1990
		111.93	Banerjee et al., 1986
		119.70	Mandal et al., 1990
	Mean	108.66	

9	Subtropical pine	73.9	R. Singh et al., 1990
		85.0	Sachan et al. 1981
		88.14	Nair and Chamuah 1988
		114.66	
	Mean	90.43	
10.	Subtropical dry evergreen	33.0	c
11.	Montane wet temperate	170.0	L. Singh 1990
		206.7	Banerjee et al., 1986
	Mean	188.35	
12.	Himalayan moist temperate	132.6	Banerjee and Badola, 1980
		132.6	Sachan et al., 1981
		144.3	Rawat and Kumar, 1989
		152.1	Dhar and Jha, 1983
	Mean	140.4	
13.	Himalayan dry temperate	71.4	Singh and Gupta, 1990
		78.0	Negi and Ghosh, 1980
	Mean	74.7	
14.–16.	Subalpine and alpine	255.0	Das et al., 1988
		259.7	Datta et al., 1989
		259.7	Gangopadhyaya et al., 1990
	Mean	258.13	

[a] Since no studies were available on tropical thorn forest, it was assumed that soil carbon in this forest type would be equivalent to 75% of soil carbon of tropical dry deciduous forests.
[b] Since no studies were available on tropical dry evergreen forest, it was assumed that soil in this forest would contain carbon equivalent to 75% of soil carbon of tropical thorn forest.
[c] Since no studies were available on subtropical dry evergreen forest, it was assumed that soil carbon content would be similar to that of tropical dry evergreen forests.

Appendix IV: NPP (t/ha/year) in Different Forests

Forest type number	Forest type	Standing biomass	NPP of stem, branch and twig	% NPP (% to the standing biomass)	References
1.	Tropical wet evergreen	607.7	7.806	1.28	Rai, 1981
3.	Tropical moist deciduous	588.9	8.59	1.46	Rana, 1985
5.	Tropical dry deciduous	115.5	3.28	2.84	Sharma et al., 1990

9.	Subtropical pine	198 96	4 12	2.07	Rana, 1985
12	Himalayan moist temperate	432.8	8.98	2 07	Rana, 1985

Note: Apart from the above studies data were not available for the remaining forest types.

Thus the above values were used for the other forest types. A value of 1 28% (type 1) was used for forest type 2; 1 46% (type 3) was used for forest type 4; 2.84% (type 5) was used for forest types 6 & 7; 2.07 (from types 9 and 12) was used for forest types 8, 10, 11, 13 and 14–16.

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