TEMPORAL ASSESSMENT OF GROWING STOCK, BIOMASS AND CARBON STOCK OF INDIAN FORESTS

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Abstract. The dynamics of terrestrial ecosystems depends on interactions between carbon, nutrient and hydrological cycles. Terrestrial ecosystems retain carbon in live biomass (aboveground and belowground), decomposing organic matter, and soil. Carbon is exchanged naturally between these systems and the atmosphere through photosynthesis, respiration, decomposition, and combustion. Human activities change carbon stock in these pools and exchanges between them and the atmosphere through land-use, land-use change, and forestry.

In the present study we estimated the wood (stem) biomass, growing stock (GS) and carbon stock of Indian forests for 1984 and 1994. The forest area, wood biomass, GS, and carbon stock were 63.86 Mha, 4327.99 Mm^3, 2398.19 Mt and 1085.06 Mt respectively in 1984 and with the reduction in forest area, 63.34 Mha, in 1994, wood biomass (2395.12 Mt) and carbon stock (1083.69 Mt) also reduced subsequently. The Conifers, of temperate region, stocked maximum carbon in their woods, 28.88 to 65.21 t C ha^{-1}, followed by Mangrove forests, 28.24 t C ha^{-1}, Dipterocarp forests, 28.00 t C ha^{-1}, and *Shorea robusta* forests, 24.07 t C ha^{-1}. *Boswellia serrata,* with 0.22 Mha forest area, stocked only 3.91 t C ha^{-1}. To have an idea of rate of carbon loss the negative changes (loss of forest area) in forest area occurred during 1984–1994 (10yrs) and 1991–1994 (4yrs) were also estimated. In India, land-use changes and fuelwood requirements are the main cause of negative change. Total 24.75 Mt C was lost during 1984–1994 and 21.35 Mt C during 1991–94 at a rate of 2.48 Mt C yr^{-1} and 5.35 Mt C yr^{-1} respectively. While in other parts of India negative change is due to multiple reasons like fuelwood, extraction of non-wood forest products (NWFPs), illicit felling etc., but in the northeastern region of the country shifting cultivation is the only reason for deforestation. Decrease in forest area due to shifting cultivation accounts for 23.0% of the total deforestation in India, with an annual loss of 0.93 Mt C yr^{-1}.

List of Abbreviations

A & N Islands: Andaman and Nicobar Islands; AP: Andhra Pradesh; D & D: Daman and Due; D & N Haveli: Dadar and Nagar Haveli; GS: Growing stock; HP: Himachal Pradesh; J & K: Jammu and Kashmir; Mha: Million hectare; Mm^3: Million cubic meter (10^6); MP: Madhya Pradesh; Mt: Million tones (10^6); Mt C yr^{-1}: Million tones carbon per year; Pg: Peta gram (10^{15}); t C ha^{-1}: tones carbon per hectare; UP: Uttar Pradesh.

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1. Introduction

Forests are natural storehouses for biomass and carbon. They and other terrestrial ecosystems offer significant, if often temporary, mitigation potential. Human activities, particularly energy requirements, agriculture and industries, are reducing the forests world wide, causing increases in atmospheric concentration of CO_2 and other green house gases (GHGs); in turn, these increases are thought to be a primary source for global climate change (Melillo et al., 1996). The average atmospheric CO_2 concentration has increased from pre-industrial concentration of 280 μmol mol^{-1} to 364 μmol mol^{-1} in 1994, and is currently increasing at a rate of about 1.5 μmol mol^{-1}yr^{-1} (Keeling and Whorf, 1998).

Houghton (1996) estimated that the expansion of croplands has been responsible for the largest net carbon release (63 Gt C), followed by logging and regrowth of forests (23 Gt C) and conversion of forests to pasture (10 Gt C). He also stated that changes in land use releases 1.6 ± 0.5 Gt C yr^{-1} and tropical Asia accounts 44% (0.7 ± 0.3 Gt C yr^{-1}) of total carbon released per year. Schimel (1995) estimated that 1.6 ± 1.0 Gt C yr^{-1} was released through tropical deforestation and 5.5 ± 0.50 Gt C yr^{-1} through fossil fuel combustion.

In most of the developing world, fuelwood is used as a main source of energy and this burning releases carbon into the atmosphere. In India, about 95% of the rural households depends upon biomass, firewood, crop residues and dung for cooking whereas in urban areas about 35% households (NCAER, 1985). The estimated demand of fuelwood for the country in 1994 was 224 Mt yr^{-1} and projected demand for 2005 is 350 Mt yr^{-1} (Ravindranath and Hall, 1995).

Change in total carbon stocks in forest stands can be assessed by direct measurement of net source and sinks over periods of one or more years. However, this approach has so far met with little success for estimating the large area and longer term carbon budgets because of lack of data covering all stages in life cycle, as well as lack of data on impact of disturbances such as fire, wind throw, drought, pollution, pests and diseases (Bolin and Sukumar, 2000). Thus forest inventories and ecosystem process models are widely used for broad scale quantification of forest carbon budgets (Dixon et al., 1994; Alexeyev et al., 1995; Isaev et al., 1995; Turner et al., 1995; Brown et al., 1999; Fang et al., 2001; Cohen et al., 1996; Chiba, 1998; Alexandrov et al., 1999). In India biomass, carbon stock and carbon budget estimation is done by various workers (Ravindranath et al., 1997; Lal and Singh, 2000; Chhabra et al., 2002) on the basis of growing stock (GS) volume data of forest inventories and appropriate conversion factor related to both biomass and carbon. In the present study we estimated the biomass and carbon of India by taking GS and specific gravity (SG) of the dominant tree species of various strata.

2. Materials and Methods

2.1. STUDY SITE

India, a union of 25 States and 07 Union Territories (UTs), lies in the Northern Hemisphere between latitude 8°4′ and 37°6′N and longitude 67°7′ and 97°25′E (Kaushal, 1993). In the present study all the states and 02 out of 07 UTs were studied. The UTs of Delhi and Chandigarh were not taken due to the ambiguous and scattered forest strata, in Lakshdweep and Pondicherry forest area was nil, and Daman and Due (UT) was clumped with Goa (State) as the forests of these two lie in the same grid.

2.2. METHODOLOGY

The country's forest carbon stock estimated in this study is based on the forest cover assessments of 1989 and 1997. The satellite data used for 1989 assessment pertained to the period 1983 to 1985 and that for 1997 belonged to the period 1993 to 1995. Thus, the analysis using forest cover assessments of 1989 and 1997 can be safely presumed to provide, respectively, the carbon stock estimates for the year 1984 and 1994 on the ground (Saxena et al., 2003). Following methodologies were used to calculate growing stock (GS), biomass and finally carbon stock of the wood (stem or bole).

The estimation of GS is based on forest inventories, thematic maps and vegetation maps of all the states and Union territories (UTs) of the country, provided by Forest Survey of India (FSI). Toposheets of all the states and UTs of the country were marked with 2.5′ × 2.5′ (latitude × longitude) grids, covering an area of 18 Km^2 (approx.). Data on extent of forest cover, forest stratum density (D1, D2 & D3) and GS (ha^{-1}), extracted from these grids for 22 strata was analyzed for GS estimate. The classification of density is based on crown cover; D1 or very dense forest signifies 70% and above crown cover; D2 or dense forest 40 to 70% crown cover & D3 or open forest with crown cover more than 10% but less than 40% in every grid. The formulas used for calculating growing stock (GS), biomass and carbon are as follows:

$$\text{Growing stock} = \left\{ \begin{array}{l} \text{Total number of Grids in each} \\ \text{map sheet (stratawise)} \end{array} \right\} \times \left\{ \begin{array}{l} \text{Grid volume of the} \\ \text{stratum} \end{array} \right\}$$

Addition of growing stock for all the map sheets falling in a state and UT gives the total growing stock of that State/UT.

Biomass and carbon of different stratum and density class for States and UTs was estimated as

$$\text{Biomass (Mt)} = \text{Growing stock } (Mm^3) \times \text{Specific Gravity (SG)}$$

where

$$SG = \frac{\text{Oven Dry Wt}}{\text{Green Volume}} \quad \text{(Rajput et al., 1996)}$$

Carbon (Mt) = Biomass × carbon % (Annexure – I; Negi et al., 2003).

For miscellaneous forests and forests having no carbon percentage available, 0.45 factor (Carvalho et al., 1998; Lal and Singh, 2000) was used.

3. Results

3.1. FOREST COVER

The total forest area of India was 63.86 Mha in 1984 and 63.34 Mha in 1994. Madhya Pradesh (M.P.) covered maximum, 21.22% (13.55 Mha) and 20.71% (13.12 Mha), of the total forest area in 1984 and 1994 respectively. Western Himalayan region of Jammu and Kashmir (J & K), Himachal Pradesh (H.P.) and Uttar Pradesh (U.P.) constituted 10.43% (6.66 Mha) and 10.58% (6.70 Mha) and Northeastern region (Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland & Tripura) constituted 23.11% and 22.96% of the total forest area for the year 1984 & 1994 respectively (Table I).

Temperate forests with *Abies pindrow*, *Picea smithiana*, *A. pindrow-P. smithiana*, *Pinus wallichiana*, *Cedrus deodara* and mixed conifer species were present in H.P., J & K, U. P., West Bengal and Arunachal Pradesh (Table II). J & K, with 1.50 and 1.51 Mha temperate forests, accounted for 57.69 and 55.11% of the total area covered by temperate forests respectively for 1984 and 1994. The Sunderbans, situated in West Bengal, occupied more than 50% of the total mangrove forests (0.42 Mha) of the country. Andaman and Nicobar Islands (A & N), Gujarat and Andhra Pradesh (A.P.) were the other main states/union territories (UTs) containing mangrove forests. Bamboo forests were present in as many as seventeen states and UTs. Seven states of northeast viz., Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland and Tripura, contributed nearly 60.68 and 61.75% of the total area covered by bamboo forests in 1984 and 1994 respectively. Evergreen forests were present in A & N Islands (0.39 Mha in both 1984 and 1994), Goa, Daman and Due (0.04 and 0.04 Mha) and Maharashtra (0.22 and 0.23 Mha) in 1984 and 1994 respectively.

Miscellaneous forest strata covered 64.63% (41.27 Mha) & 64.30% (40.73 Mha) of the total forest area for 1984 and 1994 respectively. *Shorea robusta* (Sal) forest (7.58 Mha, 1984 & 7.54 Mha, 1994) and *Tectona grandis* forests (6.21 Mha, 1984 & 6.13 Mha, 1994) were the other main forest strata. Tropical forests covered only 5.12% of the total forest area with *Pinus roxburghii* and up-land hardwoods jointly contributed 85.32% (2.79 Mha) and 84.57% (2.74 Mha) of the total area covered by tropical forests in 1984 and 1994 respectively. Temperate forests covered 2.60 Mha (1984) and 2.74 Mha (1994) of the forest area with mixed conifers

TABLE I
Stratawise Forest area, wood biomass growing stock and carbon of various states/union territories of India for the years 1984 and 1994

States	Forest strata/Forest type	1984				1994			
		Area (Km^2)	Volume (Mm^3)	Biomass (Mt)	Carbon (Mt)	Area (Km^2)	Volume (Mm^3)	Biomass (Mt)	Carbon (Mt)
Andaman & Nicobar Islands*	Deciduous	178	3.20	1.85	0.83	178	3.20	1.84	0.83
	Evergreen forest	385	6.93	4.00	1.80	385	6.93	4.00	1.8
	Mangrove	97	1.75	1.20	0.54	97	1.74	1.19	0.54
	Miscellaneous forest	102	1.84	1.06	0.48	102	1.84	1.06	0.48
	Total	762	13.72	8.11	3.65	761	13.70	8.10	3.64
Andhra Pradesh	Bamboo	23	0.66	0.49	0.21	24	0.66	0.50	0.21
	Mangrove	41	4.52	2.53	1.14	38	4.27	2.39	1.08
	Tectona grandis	472	19.23	11.15	4.91	454	18.96	11.00	4.84
	Miscellaneous forest	4193	269.52	204.83	92.18	3813	243.58	185.12	83.31
	Total	4729	293.92	219.01	98.43	4329	267.48	199.01	89.43
Arunachal Pradesh	Bamboo	14	1.33	0.42	0.18	14	1.32	0.41	0.18
	Mixed conifers	311	31.98	14.07	6.47	309	31.55	13.88	6.38
	Pinus roxburghii	18	1.57	0.68	0.31	20	1.67	0.72	0.33
	Upland-Hardwoods	850	86.87	38.22	17.58	849	86.27	37.96	17.46
	Miscellaneous forest	5707	416.42	130.76	58.84	5669	406.69	127.70	57.47
	Total	6900	538.17	184.15	83.39	6860	527.49	180.67	81.82
Assam	Bamboo	109	5.27	3.69	1.58	110	5.44	3.81	1.64
	Shorea robusta	111	16.02	11.22	5.16	105	16.18	11.32	5.21
	Miscellaneous forest	2264	282.96	153.36	69.01	2168	277.71	150.52	67.73
	Total	2483	304.25	168.26	75.76	2382	299.33	165.65	74.58

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TABLE I
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States	Forest strata/Forest type	1984 Area (Km^2)	1984 Volume (Mm^3)	1984 Biomass (Mt)	1984 Carbon (Mt)	1994 Area (Km^2)	1994 Volume (Mm^3)	1994 Biomass (Mt)	1994 Carbon (Mt)
Bihar	*Acacia catechu*	5	0.04	0.02	0.01	5	0.04	0.02	0.01
	Bamboo	95	3.58	2.15	0.92	95	3.59	2.16	0.93
	Boswellia serrata	13	0.12	0.06	0.03	13	0.12	0.06	0.03
	Shorea robusta	1447	74.55	53.67	24.69	1447	68.89	49.60	22.82
	Miscellaneous forest	1107	44.57	25.63	11.53	1093	34.71	19.96	8.98
	Total	2667	122.85	81.53	37.18	2652	107.36	71.81	32.77
Dadara and Nagar Haveli*	*Acacia catechu* forest	5	0.49	0.43	0.19	6	0.51	0.45	0.20
	Tectona grandis	5	0.22	0.12	0.05	4	0.18	0.09	0.04
	Miscellaneous forest	10	0.69	0.37	0.17	11	0.73	0.39	0.18
	Total	21	1.39	0.91	0.41	20	1.42	0.94	0.42
Goa, Daman & Due	Evergreen forest	41	6.44	4.95	2.22	44	6.89	5.29	2.38
	Miscellaneous forest	85	2.11	1.10	0.49	82	2.07	1.08	0.49
	Total	126	8.55	6.05	2.72	125	8.97	6.38	2.87
Gujrat	Mangrove	41	2.93	2.09	0.94	579	27.90	19.87	8.94
	Tectona grandis	572	28.52	15.46	6.80	591	38.15	20.67	9.10
	Miscellaneous forest	579	16.84	11.99	5.40	88	5.89	4.19	1.89
	Total	1192	48.30	29.54	13.14	1258	71.94	44.74	19.92
Haryana	*Shorea robusta*	5	0.05	0.04	0.02	14	0.14	0.10	0.05
	Miscellaneous forest	46	0.33	0.22	0.10	47	0.55	0.36	0.16
	Total	51	0.38	0.25	0.11	60	0.69	0.46	0.21

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States	Forest strata/Forest type	1984 Area (Km^2)	1984 Volume (Mm^3)	1984 Biomass (Mt)	1984 Carbon (Mt)	1994 Area (Km^2)	1994 Volume (Mm^3)	1994 Biomass (Mt)	1994 Carbon (Mt)
Himachal Pradesh	*Abies pindrow*	6	2.41	0.95	0.44	9	3.45	1.36	0.62
	A. pindrow-Picea smithiana	4	0.74	0.29	0.13	6	1.06	0.42	0.19
	Acacia catechu forest	30	0.37	0.26	0.12	18	0.32	0.22	0.10
	Bamboo	23	0.77	0.54	0.23	14	0.47	0.33	0.14
	Cedrus deodara	60	15.81	7.40	3.40	71	19.20	8.99	4.13
	Hardwoods	57	9.61	4.19	1.93	67	13.16	5.74	2.64
	Mixed conifers	457	127.75	53.27	24.51	551	163.99	68.38	31.46
	P. smithiana	8	2.47	0.99	0.45	11	3.54	1.41	0.65
	Pinus roxburghii	258	13.99	6.87	3.16	199	12.38	6.08	2.80
	Pinus wallichiana	14	2.38	0.82	0.38	16	3.03	1.04	0.48
	Upland-Hardwoods	112	13.91	6.07	2.79	119	18.96	8.27	3.80
	Miscellaneous forest	220	8.94	4.75	2.14	170	7.92	4.21	1.89
	Total	1248	199.16	86.39	39.67	1252	247.48	106.44	48.91
Jammu & Kashmir	*A. pindrow*	354	140.89	50.58	23.27	355	143.06	51.36	23.63
	A. pindrow-P. smithiana	111	31.27	11.98	5.51	110	30.55	11.70	5.38
	Acacia catechu forest	2	0.05	0.04	0.02	1	0.03	0.03	0.01
	Cedrus deodara	41	5.62	2.63	1.21	41	5.70	2.67	1.23
	Hardwoods	20	2.19	0.90	0.41	20	2.09	0.86	0.40
	Mixed conifers	607	168.99	69.29	31.87	610	170.94	70.08	32.24
	P. smithiana	18	4.76	1.96	0.90	18	4.85	1.99	0.92

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States	Forest strata/Forest type	1984 Area (Km^2)	1984 Volume (Mm^3)	1984 Biomass (Mt)	1984 Carbon (Mt)	1994 Area (Km^2)	1994 Volume (Mm^3)	1994 Biomass (Mt)	1994 Carbon (Mt)
	Pinus roxburghii	363	31.24	15.34	7.06	363	31.34	15.39	7.08
	Pinus wallichiana	375	68.53	23.50	10.81	377	68.90	23.63	10.87
	Upland-Hardwoods	133	7.82	3.21	1.48	131	7.29	2.99	1.37
	Miscellaneous forest	21	0.44	0.24	0.11	19	0.43	0.24	0.11
	Total	2045	461.79	179.65	82.64	2044	465.19	180.93	83.23
Karnataka	Bamboo	15	0.05	0.03	0.01	15	0.05	0.03	0.01
	Deciduous	58	2.24	1.38	0.62	59	2.25	1.39	0.62
	Tectona grandis	140	9.38	5.27	2.32	141	9.42	5.29	2.33
	Miscellaneous forest	2997	227.64	140.23	63.10	3026	229.14	141.15	63.52
	Total	3210	239.31	146.91	66.05	3240	240.87	147.86	66.48
Kerala	Bamboo	31	1.59	0.93	0.40	31	1.59	0.93	0.40
	Tectona grandis	90	4.34	2.55	1.12	91	4.38	2.57	1.13
	Miscellaneous forest	908	83.31	44.32	19.94	911	83.57	44.46	20.01
	Total	1029	89.24	47.80	21.47	1033	89.53	47.96	21.54
Madhya Pradesh	*Acacia catechu* forest	69	0.97	0.64	0.29	68	0.93	0.61	0.28
	Bamboo	65	3.03	2.00	0.86	62	1.37	0.90	0.39
	Boswellia serrata	7	0.33	0.17	0.07	7	0.32	0.16	0.07
	Shorea robusta	2064	191.07	130.69	60.12	2013	160.42	109.73	50.47
	Tectona grandis	2448	122.77	65.93	29.01	2354	109.03	58.55	25.76
	Miscellaneous forest	8901	390.32	248.24	111.71	8616	424.37	269.90	121.46
	Total	13554	708.49	447.67	202.06	13120	696.44	439.85	198.43

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States	Forest strata/Forest type	1984 Area (Km^2)	1984 Volume (Mm^3)	1984 Biomass (Mt)	1984 Carbon (Mt)	1994 Area (Km^2)	1994 Volume (Mm^3)	1994 Biomass (Mt)	1994 Carbon (Mt)
Maharashtra	Bamboo	79	0.63	0.43	0.18	71	0.68	0.47	0.20
	Boswellia serrata	7	0.28	0.14	0.06	7	0.27	0.13	0.06
	Evergreen forest	221	24.11	15.67	7.05	229	22.94	14.91	6.71
	Mangrove	11	0.23	0.16	0.07	4	0.25	0.17	0.08
	Shorea robusta	4	0.52	0.36	0.16	3	0.46	0.32	0.14
	Tectona grandis	2283	103.56	57.17	25.15	2292	99.31	54.82	24.12
	Miscellaneous forest	1800	80.28	52.91	23.81	2008	83.09	54.75	24.64
	Total	4404	209.61	126.82	56.49	4614	207.02	125.58	55.95
Manipur	Bamboo	62	0.87	0.61	0.26	64	0.88	0.62	0.27
	Depterocarpus	8	1.05	0.62	0.28	7	0.91	0.54	0.24
	Hardwoods	30	1.00	0.54	0.25	30	0.99	0.54	0.25
	Pinus khasiana	28	1.41	0.61	0.28	30	1.64	0.71	0.33
	Pinus roxburghii	5	0.15	0.07	0.03	4	0.14	0.06	0.03
	Shorea robusta	3	0.80	0.56	0.26	3	0.69	0.48	0.22
	Tectona grandis	3	0.80	0.43	0.19	3	0.69	0.37	0.16
	Upland-Hardwoods	140	9.21	4.98	2.29	130	8.47	4.58	2.11
	Miscellaneous forest	1491	64.94	35.00	15.75	1473	67.07	36.15	16.27
	Total	1769	80.21	43.42	19.59	1742	81.47	44.05	19.87

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States	Forest strata/Forest type	1984 Area (Km^2)	1984 Volume (Mm^3)	1984 Biomass (Mt)	1984 Carbon (Mt)	1994 Area (Km^2)	1994 Volume (Mm^3)	1994 Biomass (Mt)	1994 Carbon (Mt)
Meghalaya	Bamboo	177	10.32	7.22	3.11	174	11.34	7.94	3.41
	Hardwoods	29	0.16	0.09	0.04	28	0.29	0.16	0.07
	Pinus khasiana	122	4.69	2.02	0.93	119	4.67	2.01	0.93
	Shorea robusta	94	7.11	4.98	2.29	98	7.28	5.10	2.35
	Tectona grandis	4	0.59	0.35	0.15	4	0.72	0.43	0.19
	Upland-Hardwoods	8	0.05	0.03	0.01	8	0.05	0.02	0.01
	Miscellaneous forest	1132	81.62	53.21	23.95	1135	88.28	57.56	25.90
	Total	1565	104.53	67.90	30.48	1566	112.63	73.22	32.86
Mizoram	Bamboo	185	2.38	1.66	0.72	198	2.58	1.80	0.78
	Miscellaneous forest	1632	60.26	32.48	14.62	1679	63.01	33.96	15.28
	Total	1817	62.64	34.14	15.33	1878	65.59	35.77	16.06
Nagaland	Bamboo	3	0.32	0.22	0.10	2	0.06	0.04	0.02
	Shorea robusta	11	1.21	0.84	0.39	10	1.13	0.79	0.36
	Miscellaneous forest	1427	103.24	55.96	25.18	1410	93.86	50.87	22.89
	Total	1440	104.77	57.03	25.67	1422	95.05	51.70	23.27
Orissa	Bamboo	12	0.68	0.52	0.22	11	0.65	0.50	0.22
	Boswellia serrata	11	0.50	0.25	0.11	11	0.47	0.24	0.11
	Mangrove	19	2.55	1.27	0.57	21	1.68	0.84	0.38
	Shorea robusta	2832	148.43	114.15	52.51	2780	144.15	110.85	50.99
	Tectona grandis	35	0.96	0.55	0.24	30	0.86	0.49	0.22
	Miscellaneous forest	1814	95.37	58.84	26.48	1841	94.93	58.57	26.36
	Total	4723	248.48	175.58	80.14	4694	242.74	171.49	78.26

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States	Forest strata/Forest type	1984 Area (Km^2)	1984 Volume (Mm^3)	1984 Biomass (Mt)	1984 Carbon (Mt)	1994 Area (Km^2)	1994 Volume (Mm^3)	1994 Biomass (Mt)	1994 Carbon (Mt)
Punjab	*Acacia catechu* forest	77	0.20	0.18	0.08	83	0.36	0.31	0.14
	Bamboo	7	0.04	0.02	0.01	10	0.10	0.05	0.02
	Pinus roxburghii	8	0.22	0.11	0.05	6	0.20	0.10	0.05
	Miscellaneous forest	42	0.23	0.16	0.07	39	0.28	0.19	0.08
	Total	134	0.70	0.47	0.21	139	0.93	0.65	0.29
Rajasthan	*Acacia catechu* forest	14	0.02	0.02	0.01	14	0.04	0.03	0.01
	Boswellia serrata	184	2.52	1.26	0.58	187	2.63	1.31	0.60
	Tectona grandis	38	0.26	0.15	0.06	41	0.32	0.18	0.08
	Miscellaneous forest	1053	9.17	5.90	2.65	1094	9.87	6.34	2.85
	Total	1288	11.98	7.32	3.30	1335	12.85	7.86	3.55
Sikkim	Mixed conifers	43	5.23	1.91	0.88	44	5.36	1.96	0.90
	Shorea robusta	4	0.39	0.29	0.13	4	0.38	0.28	0.13
	Miscellaneous forest	257	32.74	16.70	7.51	265	33.80	17.24	7.76
	Total	304	38.35	18.90	8.52	313	39.54	19.48	8.79
Tamilnadu	*Tectona grandis*	2	0.17	0.11	0.05	2	0.16	0.10	0.04
	Miscellaneous forest	1697	67.35	42.90	19.31	1705	65.53	41.75	18.79
	Total	1699	67.52	43.01	19.35	1706	65.69	41.84	18.83
Tripura	Bamboo	75	0.39	0.27	0.12	74	0.40	0.28	0.12
	Shorea robusta	12	0.69	0.49	0.22	13	0.78	0.55	0.25
	Tectona grandis	49	1.34	0.73	0.32	48	1.34	0.73	0.32
	Miscellaneous forest	418	12.46	6.75	3.04	420	12.93	7.01	3.15
	Total	554	14.88	8.24	3.70	555	15.46	8.56	3.85

(*Continued on next page*)

TABLE I
(*Continued*)

States	Forest strata/Forest type	1984 Area (Km^2)	1984 Volume (Mm^3)	1984 Biomass (Mt)	1984 Carbon (Mt)	1994 Area (Km^2)	1994 Volume (Mm^3)	1994 Biomass (Mt)	1994 Carbon (Mt)
Uttar Pradesh	*Abies pindrow*	18	4.74	2.12	0.97	19	4.86	2.17	1.00
	Acacia catechu forest	5	0.20	0.17	0.08	5	0.20	0.17	0.08
	Bamboo	56	0.58	0.41	0.18	53	0.56	0.40	0.17
	Cedrus deodara	25	5.41	2.51	1.15	29	5.46	2.53	1.16
	Hardwoods	333	24.63	14.04	6.46	342	25.19	14.36	6.61
	Mixed conifers	100	24.48	10.67	4.91	102	25.00	10.90	5.01
	Picea smithiana	17	5.16	2.02	0.93	17	5.29	2.07	0.95
	Pinus roxburghii	703	49.02	21.37	9.83	710	49.88	21.75	10.00
	Pinus wallichiana	16	1.79	0.79	0.36	15	1.75	0.78	0.36
	Shorea robusta	704	93.56	67.36	30.99	729	95.71	68.91	31.70
	Tectona grandis	36	1.41	0.81	0.36	35	1.41	0.81	0.36
	Upland-Hardwoods	199	23.86	13.67	6.29	207	24.40	13.98	6.43
	Miscellaneous forest	1144	60.52	33.04	14.87	1130	60.32	32.94	14.82
	Total	3356	295.36	168.98	77.38	3393	300.03	171.77	78.65
West Bengal	*Abies pindrow*	6	0.62	0.23	0.10	6	0.66	0.24	0.11
	A. pindrow-P. smithiana	4	0.41	0.16	0.08	4	0.44	0.18	0.08
	Acacia catechu forest	2	0.21	0.17	0.08	2	0.22	0.18	0.08
	Hardwoods	13	1.70	0.96	0.44	14	1.82	1.03	0.48
	Mangrove	211	25.44	19.11	8.60	212	25.61	19.23	8.65
	Mixed conifers	13	1.44	0.54	0.25	14	1.54	0.58	0.27
	Shorea robusta	293	15.89	11.93	5.49	319	17.91	13.45	6.19
	Tectona grandis	34	1.15	0.65	0.29	36	1.22	0.69	0.30
	Miscellaneous forest	226	12.56	6.41	2.88	228	13.24	6.75	3.04
	Total	802	59.41	40.16	18.20	835	62.66	42.34	19.20

TABLE II
Forest area, growing stock, biomass and carbon of various forest strata in 1984 and 1994

	Forest area (Mha)		Growing stock (Mm^3)		Biomass (Mt)		Carbon (Mt)		Carbon (t C ha^{-1})	
Forest strata/Forest type	1984	1994	1984	1994	1984	1994	1984	1994	1984	1994
Temperate forests										
Abies pindrow (Fir)	0.38	0.39	148.66	152.04	53.87	55.13	24.78	25.36	65.21	65.03
Picea smithiana (Spruce)	0.04	0.05	12.40	13.68	4.97	5.48	2.29	2.52	57.25	50.40
Fir – Spruce	0.12	0.12	32.42	32.05	12.43	12.30	5.72	5.66	47.67	47.17
Cedrus deodara	0.13	0.14	26.84	30.36	12.53	14.18	5.76	6.52	44.31	46.57
Pinus wallichiana	0.40	0.41	72.70	73.68	25.11	25.45	11.55	11.71	28.88	28.56
Mixed conifers	1.53	1.63	359.88	398.38	149.77	165.79	68.89	76.27	45.03	46.79
Total	2.6	2.74	652.90	700.19	258.68	278.33	118.99	128.04	48.06[a]	47.42[a]
Tropical forests										
Hardwood & conifers	0.48	0.50	39.30	43.55	20.72	22.68	9.53	10.43	19.85	20.86
Pinus roxburghii	1.35	1.30	96.20	95.60	44.43	44.09	20.44	20.28	15.14	15.60
Up–lands hardwoods	1.44	1.44	141.72	145.43	66.17	67.80	30.44	31.19	21.14	21.66
Total	3.27	3.24	277.22	284.58	131.32	134.57	60.41	61.90	18.71[a]	19.37[a]

(*Continued on next page*)

TABLE II
(*Continued*)

Forest strata/Forest type	Forest area (Mha)		Growing Stock (Mm^3)		Biomass (Mt)		Carbon (Mt)		Carbon ($t\ C\ ha^{-1}$)	
	1984	1994	1984	1994	1984	1994	1984	1994	1984	1994
Other forests										
Acacia catecheu	0.21	0.20	2.54	2.65	1.92	2.04	0.87	0.92	4.14	4.60
Bamboo	1.03	1.02	32.47	31.76	21.63	21.19	9.30	9.11	9.03	8.93
Boswellia serrata	0.22	0.22	3.75	3.81	1.87	1.90	0.86	0.87	3.91	3.95
Deciduous	0.24	0.24	5.44	5.45	3.22	3.23	1.45	1.45	6.04	6.04
Dipterocarp forests	0.01	0.01	1.05	0.91	0.62	0.54	0.28	0.24	28.00	24.00
Evergreen forests	0.65	0.66	37.48	36.77	24.62	24.21	11.08	10.89	16.38	15.92
Mangrove forests	0.42	0.46	37.41	39.44	26.35	28.02	11.86	12.61	28.24	27.41
Pinus khasiana	0.15	0.15	6.10	6.32	2.63	2.72	1.21	1.25	8.07	8.33
Shorea robusta	7.58	7.54	550.29	514.12	396.57	371.48	182.42	170.88	24.07	22.66
Tectona grandis	6.21	6.13	294.69	286.13	161.40	156.79	71.02	68.99	11.44	11.25
Total	16.72	16.63	971.22	927.36	640.83	612.12	290.35	277.21	13.93[a]	13.31[a]
Miscellaneous forest	41.27	40.73	2426.65	2427.42	1367.36	1370.10	615.31	616.54	14.91	15.14
Total	63.86	63.34	4327.99	4339.55	2398.19	2395.12	1085.06	1083.69	24.94[a]	24.54[a]

[a] Average.

TABLE III
Negative change in forest area, growing stock, biomass and carbon of various states and UTs of India during 10 years (1984–1994) and last 4 years (1991–1994)

States/union territories	Area (Mha)		Growing stock (Mm^3)		Biomass (Mt)		Carbon (Mt)		Carbon loss ($Mtyr^{-1}$)	
	10 yrs	4 yrs	10 yrs	4 yrs	10 yrs	4 yrs	10 yrs	4yrs	10 yrs	4 yrs
A & N Islands*	0.003	0.001	0.058	0.020	0.033	0.011	0.015	0.005	0.0015	0.0013
Andhra Pradesh	0.569	0.562	27.651	27.287	20.813	20.539	9.359	9.236	0.9359	2.3090
Arunachal Pradesh	0.059	0.024	5.130	3.456	1.811	1.220	0.815	0.549	0.0815	0.1373
Assam	0.145	0.102	12.555	8.787	7.266	5.086	3.270	2.289	0.3270	0.5721
Bihar	0.048	0.040	2.180	1.815	1.467	1.221	0.660	0.550	0.0660	0.1374
Goa, Daman & Due	0.001	–[a]	0.009	–	0.005	–	0.002	–	0.0002	–
Gujrat	0.014	0.009	0.572	0.498	0.381	0.011	0.172	0.140	0.0172	0.0349
Himachal Pradesh	0.001	0.001	0.017	0.004	0.009	20.539	0.004	0.001	0.0004	0.0003
Jammu & Kashmir	0.007	0.002	1.076	0.920	0.408	1.220	0.184	0.157	0.0184	0.0393
Karnataka	0.006	0.004	0.502	0.277	0.309	5.086	0.139	0.077	0.0139	0.0192
Madhya Pradesh	0.608	0.573	16.312	16.758	10.259	1.221	4.617	4.742	0.4617	1.1855
Maharashtra	0.161	0.143	2.081	0.675	1.224	0.011	0.551	0.178	0.0551	0.0445
Manipur	0.073	0.067	2.030	2.030	1.124	20.539	0.506	0.506	0.0506	0.1265
Meghalaya	0.087	0.030	4.567	1.542	2.978	1.220	1.340	0.452	0.1340	0.1131
Mizoram	0.134	0.108	3.581	2.897	1.930	5.086	0.869	0.703	0.0869	0.1757
Nagaland	0.083	0.063	4.786	3.638	2.594	1.221	1.167	0.887	0.1167	0.2218
Orissa	0.089	0.077	2.557	2.205	1.775	0.011	0.799	0.689	0.0799	0.1723
Punjab	0.002	0.002	0.146	0.130	0.099	20.539	0.045	0.040	0.0045	0.0099
Rajasthan	0.010	0.003	0.086	0.000	0.053	1.220	0.024	0.033	0.0024	0.0082
Tamilnadu	0.022	0.011	0.459	0.459	0.292	5.086	0.131	0.131	0.0131	0.0329
Tripura	0.004	0.0003	0.147	0.008	0.079	1.221	0.036	0.002	0.0036	0.0005
Uttar Pradesh	0.019	0.003	0.361	0.084	0.197	0.011	0.089	0.021	0.0089	0.0052
West Bengal	0.003	0.0028	0.096	0.084	0.049	20.539	0.022	0.019	0.0022	0.0048

*Union territory.
[a]Data not available.

contributing approximately 58.85% (1.53 Mha) and 59.49% (1.63 Mha) followed by *P. wallichiana,* 15.38% (0.40 Mha) and 14.96% (0.41 Mha), and *A. pindrow,* 14.61% (0.38 Mha) and 14.23% (0.39 Mha) in 1984 and 1994 respectively (Table III).

3.2. GROWING STOCK (GS) AND BIOMASS

Total GS and biomass were 4327.99 Mm^3 and 2398.19 Mt in 1984 and 4339.55 Mm^3 and 2395.12 Mt in 1994 respectively. Madhya Pradesh, with highest forest area (Table I), reported maximum growing stock (708.49 and 696.44 Mm^3 in 1984 and 1994 respectively), and miscellaneous (56.07 and 55.93%), *Shorea robusta* (12.71 and 11.85%) and *Tectona grandis* forests (6.81 and 6.59%) were the main contributors to the total GS respectively for 1984 and 1994. Arunachal Pradesh, J & K, Assam, U.P. and A.P. were the other main contributors to the total GS of the country (Table II).

In the case of biomass, Madhya Pradesh again was the main contributor (18.66 and 18.36%) and A.P. (9.13 and 11.17%), Arunachal Pradesh (7.67 and 7.54%), J & K (7.49 and 7.55%), Orissa (7.32 and 7.15%), U.P. (7.05 and 7.17%), Assam (7.02 and 6.92%) and Karnataka (6.13 and 6.17%) were the other significant contributors to the total biomass of the country for the year 1984 and 1994 respectively.

Miscellaneous forests, with 2426.65 and 2427.42 Mm^3 GS and 1367.36 and 1370.10 Mt biomass, were the most dominant forest strata (Table III). *S. robusta* and *T. grandis* forests were the other main contributors to the total GS and biomass. Tropical forests accumulated 277.22 and 284.58 Mm^3 GS and 131.32 and 134.57 Mt biomass in 1984 and 1994 respectively. The temperate forests accumulated 652.90 (1984) and 700.19 Mm^3 (1994) GS, and 258.68 (1984) and 278.33 Mt (1994) biomass, with mixed conifer forests contributing more than half of the GS in both 1984 (359.88 Mm^3) and 1994 (398.38 Mm^3). Mangrove forests covered 0.42 and 0.46 Mha forest area, 37.41 and 39.44 Mm^3 GS, and 26.35 and 28.02 Mt biomass for 1984 and 1994 respectively.

3.3. CARBON STOCK

The total carbon stock for the country was 1085.06 and 1083.69 Mt in 1984 and 1994 respectively. Carbon content for various states shows that maximum carbon was stored in the forests of M.P., 202.06 and 198.43 Mt for 1984 and 1994 respectively. Other states also followed the same trend, as shown in the case of the biomass, because carbon is directly related to biomass i.e. higher the biomass greater will be the carbon (Table II).

The order of contribution of carbon stocked for the major forests was Miscellaneous forest > *S. robusta* forest > *T. grandis* forest > Temperate forest > Tropical forest > Bamboo forest etc. (Table II). The average carbon stock for the country was 29.94 t C ha^{-1} in 1984 and 24.54 t C ha^{-1} in 1994. Temperate forest stocked 48.06 and 47.42 t C ha^{-1} with *Abies pindrow* forests having maximum, 65.21 and 65.03 t C ha^{-1}, and *Pinus wallichiana* forests minimum, 28.88 and 28.56 t C ha^{-1}, carbon stock in 1984 and 1994 respectively. Mangrove forests and Dipterocarp forests stocked 28.24 and 28.00 t C ha^{-1} in 1984 and 27.41 and 24.00 t C ha^{-1} in 1994 followed by *Shorea robusta* forests 24.07 t C ha^{-1} (1984) and 22.66 t C ha^{-1} (1994). Miscellaneous forests stocked 14.91 and 15.14 t C ha^{-1} and *Boswellia serrata* forests stocked only 3.91 and 3.95 t C ha^{-1} in 1984 and 1994 respectively. The trend of rate of carbon stock (t C ha^{-1}), on the basis of average carbon stock, can be summarized as follows:

Temperate forests > tropical forests > miscellaneous forests > other forests

3.4. NEGATIVE CHANGE

To assess the rate of carbon loss (Mt yr^{-1}) by the negative changes (decrease in forest area) the negative change occurred during 1984–1994 (10 yrs) and 1991–1994

TABLE IV
Negative change in forest area, growing stock (GS), biomass and carbon of various forest strata during 1984–1994 (10 yrs) and 1991–1994 (4 yrs)

	Area (Mha)		GS (Mm^3)		Biomass (Mt)		Carbon (Mt)	
Strata	10 yrs	4 yrs	10 yrs	4 yrs	10 yrs	4 yrs	10 yrs	4 yrs
Abies pindrow	0.002	0.001	0.50	0.49	0.09	0.08	0.04	0.04
Acacia nilotica	0.002	0.002	0.03	0.03	0.02	0.02	0.01	0.01
Bamboo	0.011	0.009	0.22	0.21	0.15	0.14	0.07	0.06
Boswellia serrata	0.002	–[a]	0.02	–	0.01	–	0.01	–
Evergreen forests	0.031	0.031	0.10	0.02	0.06	0.01	0.03	0.01
Mixed conifers	0.003	0.001	0.34	0.29	0.05	0.04	0.02	0.02
Pinus roxburghii	0.001	–	0.03	–	0.01	–	0.01	–
Pinus wallichiana	0.002	–	0.19	–	0.02	–	0.01	–
Shorea robusta	0.124	0.111	8.24	7.02	5.85	4.98	2.69	2.29
Tectona grandis	0.186	0.167	5.12	4.38	2.82	2.41	1.24	1.06
Up–lands hardwoods	0.025	0.013	1.93	1.41	0.88	0.66	0.40	0.30
Miscellaneous forest	1.762	1.493	70.24	59.76	44.97	39.06	20.24	17.58
Total	2.151	1.828	86.96	73.61	54.93	47.40	24.75	21.35

[a]Data not available.

(4yrs) were calculated (Tables III and IV). Table III reveals that 2.15 Mha forest area decreased during 1984–1994, M.P. (0.608 Mha) and A.P. (0.573 Mha) experienced maximum decrease of forest area. The annual decrease in forest area was 0.21 Mha yr^{-1} and 85.71% (0.18 Mha) of the total forest area lost was miscellaneous forests. Total 55.16 Mt of biomass and 24.81 Mt of carbon was removed from the forest ecosystem with annual loss of 5.52 Mt yr^{-1} & 2.48 Mt yr^{-1} respectively.

The forest area lost during 1991–1994 (4yrs) was 85.12% (1.83 Mha) of the total forest area (2.15 Mha) reduced between 1984 and 1994 (10yrs) with A.P. and M. P. as the major contributors (Table III). 47.40 Mt of biomass and 21.35 Mt of carbon were removed from these forest ecosystems during this period. The annual loss of biomass (11.89 Mt yr^{-1}) and carbon (5.35 Mt yr^{-1}) was approximately double (Figures 1 and 2) the rate than between 1984 and 1994 (10 yrs). The reduction of forest area and subsequently the biomass and carbon was mainly in Miscellaneous, *T. grandis* and *S. robusta* forest strata (Table IV).

3.5. SHIFTING CULTIVATION

Shifting cultivation is a method of cyclical cultivation in vogue where cultivators cut the tree crop burn it and raise agricultural crop for one or more years before moving on to another site and repeating the process (FSI, 1997). Shifting cultivation

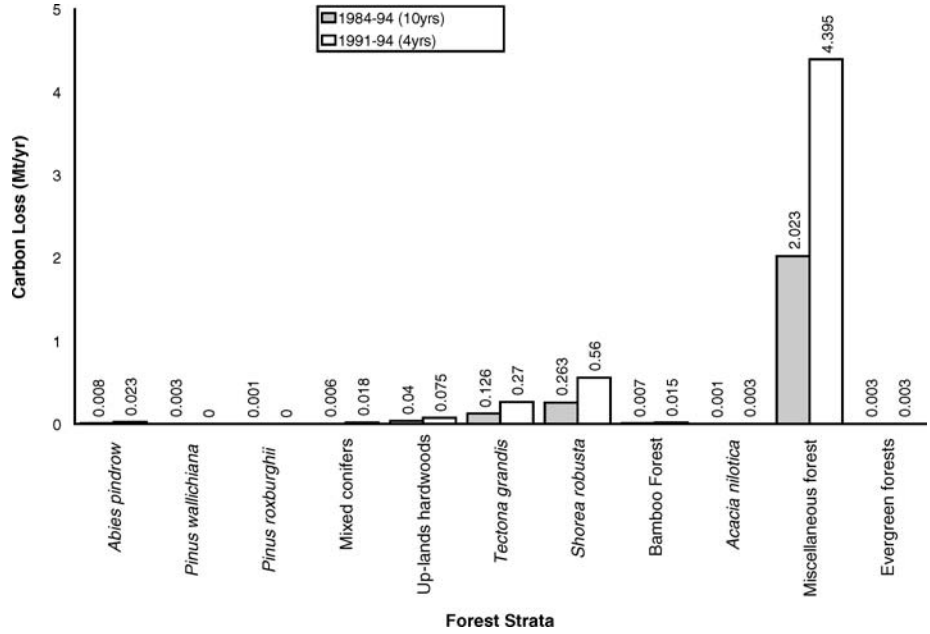

Figure 1. Carbon loss (Mt yr^{-1}) in different forest strata during 1984 to 1994 (10 yrs) and 1991 to 1994 (4 yrs).

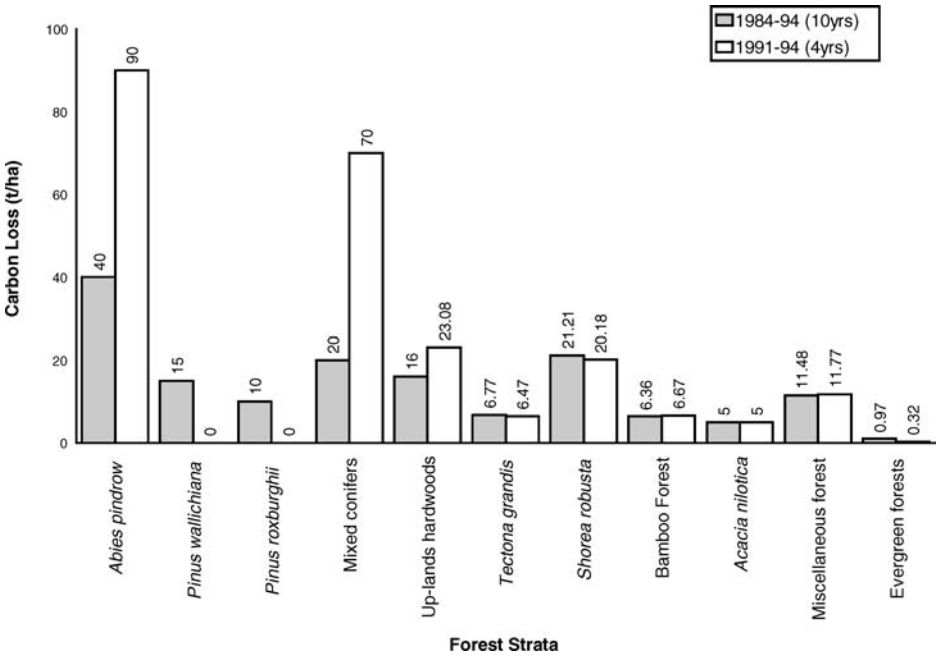

Figure 2. Carbon loss (t ha^{-1}) in different forest strata during 1984 to 1994 (10yrs) and 1991 to 1994 (4 yrs).

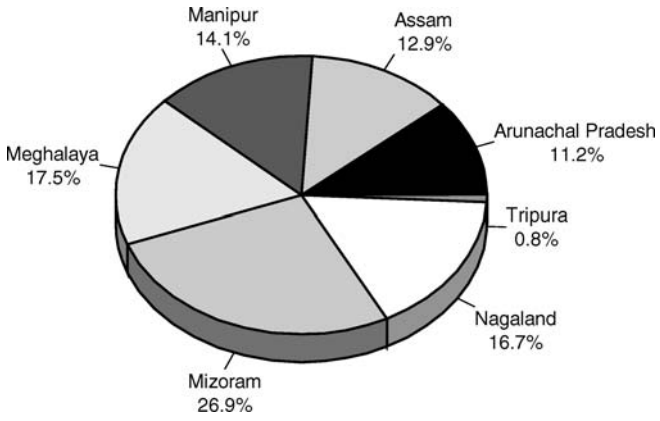

Figure 3. Forest Area (Mt) cleared in northeastern states due to shifting cultivation during 1984–1994.

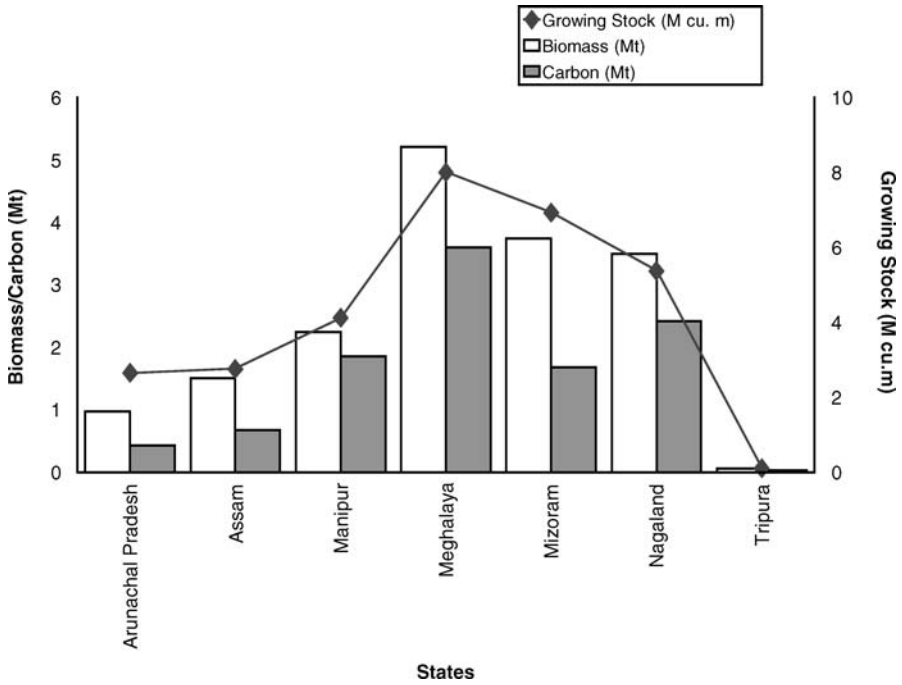

Figure 4. Growing stock (M m^3), Biomass (Mt) and Carbon stock (Mt) lost in northeastern states due to shifting cultivation during 1984–1994.

cleared 0.05 Mha of forest area every year in northeastern states of India and total 17.22 Mt wood biomass and 10.69 Mt C was removed at the rate of 1.72 Mt and 1.07 Mt C yr^{-1} respectively (Figures 3 and 4). Maximum damage was evidenced in Mizoram with a loss of 0.13 Mha area, 6.94 Mm^3 growing stock, 3.74 Mt biomass and 2.42 Mt C.

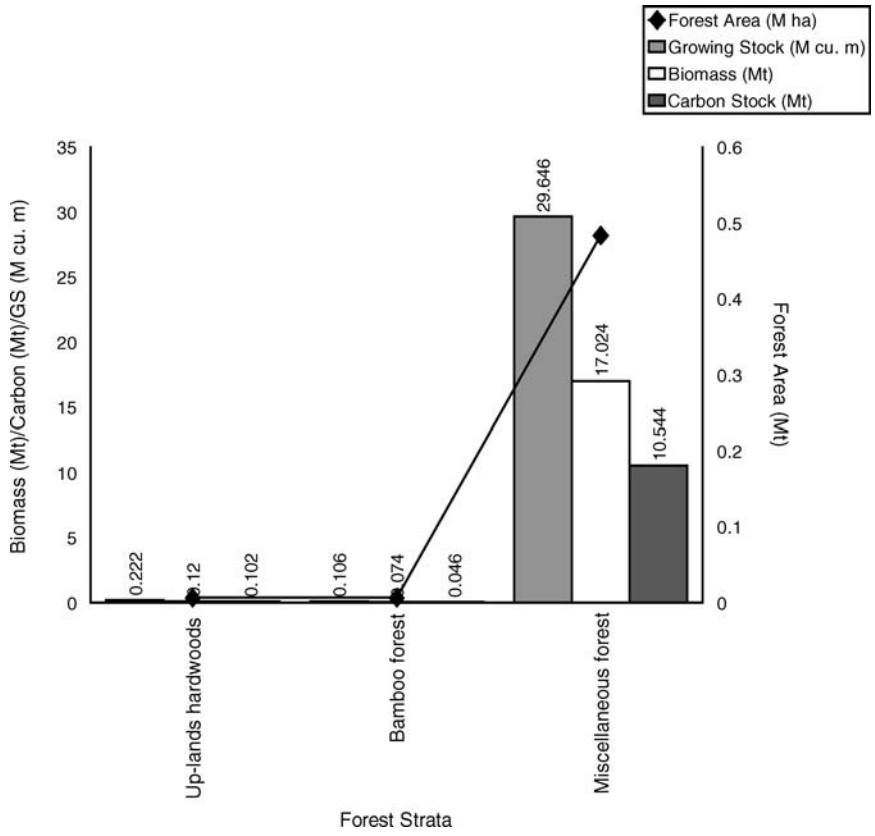

Figure 5. Growing stock (M m^3), Biomass (Mt) and Carbon stock (Mt) lost in various forest strata due to shifting cultivation during 1984–1994.

Only three forest strata, viz. miscellaneous, up-land hardwood and bamboo forests, experiences significant forest reduction (Figure 5). About 90% of the total forest area (0.50 Mha) cleared was from miscellaneous forest strata whereas both up-land hardwood and bamboo forests contributed 5% each (0.007 Mha).

4. Discussion

4.1. FOREST AREA

India, in spite of having 2.5% of the world's geographical area and 1.8% of the world's forests, sustains 16% of the planet's human population and 18% of its livestock population. The total forest area of India is estimated to be 63.88 Mha and 63.34 Mha, nearly 19.52 and 19.27% of country's total geographic area in 1984 and 1994 (FSI, 1989 and 1997), which is well below the National Forest

Policy 1988 under which the total forest area for the country should be 33% of its total geographical area. But, in context of the forest area of various continents and countries of the world, it is still reasonable. According to the State of Worlds Forest 1999 published by FAO for the period of 1990 – 1995, forest cover of India is higher than the total percentage of forest cover for Asia (16.4%) and some of its neighboring countries like China (14.3%), Bangladesh (7.8%) and Pakistan (2.3%) but less than World's (26.6%), Europe's (41.3%), Nepal's (33.7%) and Sri Lanka's (27.8%) total forest area.

M.P. is the largest state of India, with geographical area of 44.44 Mha and forest area 13.12 Mha (29.5%). The forests of M.P. are different from rest of the country as they are the largest reservoir of *Shorea robusta* in the world and other than this they also contain large number of ethno-botanical species. The state has a rural population of 44,282,528, which is approximately 73% of the total population. Also, there are a high percentage of villages in the state that are located within or close to the forests. The people living in and around the forests depend heavily on the resources for food, fodder, fiber and livelihood needs (Bahuguna, 2000).

In northeastern region, except Assam (30.4%) and Tripura (52.9%), all the states have more than 66% forest areas, as recommended for hilly states in National Forest Policy 1988. In Assam and Tripura low percentage of forest area may be due to floods in the Brahmaputra basin in Assam, which engulfs large forest land every year; high population density and high population of uneducated and poor immigrants from Bangladesh. These immigrants depend only on these forests for their livelihood. High percentage of forest area in other states is assured due to high percentage of educated people, less number of immigrants and low population density.

In Himalayan states of J & K, H.P. and U.P., the forest area is 9.2, 22.5 and 11.5% of the total geographical area respectively. Low percentage of forest area in J & K and H.P. is due to large mass of land covered by snow in these states. In U.P. the low percentage of forest area may be due to high population density, large agricultural fields, sodic soils (wastelands) and urbanization along the holy rivers, the Ganges and Yamuna, which embanks numerous spiritual and industrial cities right from their origin in the Himalayas to Bay of Bengal.

The results of forest area of the various forest strata (Table II) show that miscellaneous forests are the most dominating forests. In India, most of the forests use to be dominated by climax species. These species (like *S. robusta*) generally have pure patches but, with the increase in population and expansion of agricultural fields, these forests were subjected to disturbances, which resulted in the invasion of various secondary successional species thereby converting them to miscellaneous forests. The other possible reasons for the high percentage of miscellaneous forests may be the mass scale afforestation and plantations in degraded and open forests, and large-scale mortality in *S. robusta* forests due to various biotic and abiotic reasons (Negi et al., 2002).

TABLE V
Forest area, biomass, carbon (Mt) and carbon (t ha^{-1}) of India

Year	Forest area (Mha)	Components	Biomass (Mt)	Carbon[a] (Mt)	Carbon (t ha^{-1})	Reference
1985	64.2	AG + BG	4432.0	1994.40	31.07	Dadhwal and Nayak (1993)
1986	64.0	AG + BG	8358.0	3761.10	58.77	Ravindranath et al. (1997)
1988	63.9	AG + BG	7742.4	3484.08	54.52	Chhabra et al. (2002)
1993	64.0	AG + BG	8683.7	3907.67	61.06	Chhabra et al. (2002)
1995	63.9	AG + BG	4503.8	2026.71	31.72	Lal and Singh (2000)
1984	63.9	Wood	2398.50	1085.16[b]	16.98	Present study
1994	63.3	Wood	2395.40	1083.81[b]	17.12	Present study

AG = aboveground and BG = belowground.
[a]Carbon proportion taken was 0.45 (Carvalho et al., 1998; Lal and Singh, 2000).
[b]Actual carbon proportions for various forest species (Negi et al., 2003) was taken.

4.2. GROWING STOCK (GS) AND BIOMASS

The biomass estimation of Indian forests has been done by various workers either following the ecological based density approach or growing stock volume based inventory estimates (Table V). Chhabra et al. (2002) reported that ecological based procedure overestimates biomass more than four times in comparison to GS based estimates because GS estimates are based on large field surveys whereas ecological studies are confined to smaller number of plots of observations on typical forests without accounting for forest degradation (Brown and Lugo, 1984).

Interestingly, it was observed that despite a marginal decrease in the forest cover between 1984 and 1994 the growing stock has registered a slight increase during this period. This may be attributed to the conversion of open to dense forest and very dense forests, or improvement in density, without increase in area.

In the present study data of GS from 1, 70, 000 grids of $2.5' \times 2.5'$ (lat. $\times$ long.), spread all over the country, was used for the estimation of biomass. The total wood biomass ranged between 2398.19 and 2395.12 Mt for 1984 and 1994 respectively. If the total biomass (aboveground + belowground) is calculated from the wood biomass following Malhi et al. (1999), the biomass will be 5995.48 and 5987.80 Mt respectively for 1984 and 1994. These estimates are higher than Dadhwal and Nayak (1993) and Lal and Singh (2000), both used GS data and conversion factors related to biomass and less than the estimates of Ravindranath et al. (1997) and Chhabra et al. (2002), as they used phytomass densities and biomass expansion factors (BEF) respectively in their studies.

4.3. CARBON STOCK

Total carbon stored in Indian forests (wood only) was 1085.06 Mt (or 1.09 Pg) and 1083.69 Mt (or 1.08 Pg) at a density of 24.94 and 24.54 t C ha^{-1} for 1984 and

1994 respectively. Singh et al. (1985) in their study on Central Himalayan forests reported that the carbon stocked in poor forests is 35.0 to 75.2 t C ha^{-1}; in medium forests is 75.2 to 131.5 t C ha^{-1} and in good forests is 131.5 to 225.6 t C ha^{-1}. These estimates are higher than the present study, firstly because they took a very small area for sampling as compared to ours, and secondly, the Himalayan forests are one of the most fertile and preserved forests in the country with high tree density. Studies carried out in some other parts of the earth shows that United States forests 12.1 Pg (Turner et al., 1995), European forests accumulated 7.5 Pg of carbon (Kaupii et al., 1992), Chinese forests 4.63 Pg (Fang et al., 2001), and Japanese forests accumulated 1.39 Pg carbon (Alexandrov et al., 1999). Alexeyev et al. (1995), Isaev et al. (1995) and Krankina et al. (1996) showed that Russian forests accumulated a large amount of carbon i.e. 28.04, 35.07 and 42.1 Pg respectively. The carbon stock per unit area for Asian forests is 135, 90 and 40 t C ha^{-1} (average, 88 t C ha^{-1}) for moist, seasonal and open forests respectively (Brown and Lugo, 1984; Houghton et al., 1985), derived from wood volumes, and 250, 150 and 60 t C ha^{-1} (average, 153 t C ha^{-1}) for moist, seasonal and open forests respectively (Atjay et al., 1979; Brown and Lugo, 1982), based on direct measurements. These estimates are higher than ours; this may be because of taking of wood biomass only in this study or due to high percentage of degraded and fragmented forests in India.

4.4. NEGATIVE CHANGE

Madhya Pradesh (28.4%) and Andhra Pradesh (26.5%) were the two main states where maximum reduction in forest area was estimated during 1984–1994 (10 yrs) and 1991–1994 (4 yrs). M.P. is the largest reservoir of *Shorea robusta* in the world and other than this, the forests of M.P. also contain large number of ethno-botanical species like *Diospyros melanoxylon* (Tendu patta), which is used in the preparation of *'Biri'* (a cheap substitute of cigarette, leaves of *D. melanoxylon* are used to wrap the tobacco); *Madhuca indica* and *Borassus flabellifer* used in the preparation of local beverages; and *Terminalia alata, Pterocarpus marsupium, Emblica officinalis*. These economical species on one hand gives livelihood to a large population of ethnic people and on the other hand is the major cause of disturbances in these forests. Studies in M.P., Orissa, Himachal Pradesh and Bihar have indicated that over 80% of forest dwellers depend entirely on NWFPs. In Madhya Pradesh as high as 67% of tribal income is derived from forests (Bahuguna, 2000). In Andhra Pradesh, '*Podu'* cultivation or encroachment into forestland for cultivation is a major problem and reason for deforestation. Whereas a degraded forest can be regenerated through tending of rootstock or through plantation, once the land is occupied for cultivation it is very difficult to regain the forest. In AP approximately 0.33 Mha of forestland is under *Podu* cultivation and the rate of conversion has been approximately 0.01 Mha per year since 1980.

Reduction in forest area in India is mainly due to the population pressure coupled with land use changes. These forests are also shrinking as a result of developmental

activities like inundations for irrigation and hydroelectric power projects, and construction of new urban areas, industrial plants, roads, power lines, and schools.

The major land use changes are deforestation, clearance of forests for agriculture and pastures and degradation and fragmentation of forests. Annual forest reduction rate for Indian forests is 0.27 Mha yr^{-1} and deforestation is the main cause of this decline in forest area. The overall rate of deforestation in tropics was 1.0–3.0 Mha yr^{-1} between 1880 and 1930, but since then accelerated to about 12 Mha yr^{-1} in 1990 (Houghton, 1996). Posey (1993) reported that for the year 1990 the deforestation rate of tropical countries was 0.56 Mha (Brazil), 0.11 Mha (Indonesia and Zaire), 0.07 Mha (Peru), 0.05 (Columbia, Mexico and Bolivia), 0.04 (Sudan) etc., which shows that only Brazil had higher deforestation rate than India. In India, fuelwood collection is the major contributor to the total deforestation as annually 2.7 Mt of fuelwood is removed from the forests through clear-cutting (FSI, 1988). Other reasons for the deforestation may be the illicit felling of trees for construction, furniture and other household and industrial requirements.

Clearance of forests for agriculture and pastures is the second major force affecting the forests. Nearly half of the India's geographical area is under crops and agriculture is the mainstay of the Indian economy. Ravindranath et al. (1997) reported that from 1951 to 1980 about 4.3 Mha of forests were officially converted to non-forest area mainly for agriculture fields (63%) and pastures (20%). Houghton (1996) calculated the global area of land under cultivation for the period 1850 to 1990 and reported a net increase of 2228 Mha of cultivable land since 1850, with tropical forest clearance contributing 508 Mha.

Degradation can result from grazing, fire, death due to diseases and pests, illegal removal of timbers and fuelwood (Brown and Lugo, 1991; Houghton, 1991; Flint and Richards, 1991; Ravindranath et al., 1997) extraction of non-wood food products (NWFP's) etc., whereas, fragmentation is a common side effect of logging and clearance (Skole and Tucker, 1993). Both degradation and fragmentation can cause immense losses as there is frequently low level of forest wood in areas of forests that are close to cleared areas, perhaps driven by changes in microclimate (Laurance et al., 1997 and Laurance et al., 1998), which can reduce forest density and subsequently biomass and carbon. In India grazing and forest fires are significant and one of the increasing contributory factors 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. Out of 445 million cattle in the country, nearly 270 million graze in forest areas. Forest Survey of India, FSI, (1996) estimated that the current requirement of green and dry fodder is 593 and 482 Mt respectively, which will increase to 699 and 552 Mt in 2001 and 817 and 615 Mt respectively in 2006. It is generally agreed that nearly 30% of the fodder requirement of the country comes from the forest areas. Therefore, there is removal to the extent of 145 Mt of dry fodder and 178 Mt of green fodder annually from the forest areas of the country. In certain cases lopping of trees during crunch period is a common practice and this has been causing considerable depletion of the forest resources.

Forest fires in India are generally ground fires. About 90% of the forest fires are caused by human agencies to promote new flush of grasses, collection of fruits and honey or to prepare land for shifting cultivation. During 1980–1985, 17, 852 cases of fires affecting an area of 5.7 Mha with an annual average of 1.14 Mha (Sangal, 1989), whereas Forest Survey of India reported that the forest area affected by annual fires might be as high as 37 Mha (FSI, 1988).

The calculated carbon loss for Indian forests (wood only), in the present study, was 24.81 Mt C at a rate of 2.8 Mt C yr^{-1} and 11.5 t C ha^{-1} for the period of 1984 to 1994. Ravindranath et al. (1997) reported that a total of 27.6 Mt C is emitted from the Indian forests annually as a result of deforestation and 12.87 Mt C from degraded forests. Houghton et al. (1987) reported that forests hold more carbon per unit area in vegetation and soils than any other ecosystem that replaces them therefore conversion of forests into another land use also accompanies loss of biomass and carbon. Conversion of tropical forests to permanent agriculture and grazing lands has reduced the carbon density by 40%, whereas conversion to pasture has reduced the carbon content by 20% (Detwiler and Hall, 1988). Houghton et al. (1987) have reported that for 1980, approximately 80% of the net carbon flux from biota (2.0–2.5 Gt C yr^{-1}) is associated with change in land use in the tropics. Achard et al. (2002), in his study of humid tropical biomes of the world, estimated that due to land-use changes 0.96 Gt C yr^{-1} is emitted. Another study by Defries et al. (2002) on carbon emission from tropical deforestation and regrowth, based on satellite observation for the 1980s and 1990s, noted that for the 1990s total carbon flux from tropical deforestation and regrowth is 0.95 Gt C yr^{-1}.

4.5. SHIFTING CULTIVATION

Shifting agriculture is a mainstay of traditional farming systems in the hilly terrains of the tropics. In humid climate of northeastern hilly states of India, where shifting agriculture (locally called as *jhum*) is a predominant land use system, has caused large-scale degradation of forests. This degradation has occurred mainly due to the shortening of the *jhum* cycle from a more favourable 20–30 years to 4–5 years. The shorter cycles have resulted in the depletion of soil fertility (Ramakrishnan and Tokey, 1981) and loss of woody germplasm (Ramakrishnan et al., 1981). Shifting cultivation extends over 360 Mha or 30% of the exploitable soils of the world (Spencer, 1966; Grandstaff, 1980; Ruthenberg, 1980) and more than 6% area under tropical forests was converted to shifting cultivation between 1980 and 1990 across all tropical countries. About 10% of forestland was converted to shifting cultivation in Asia during the above period (Singh and Marzoli, 1995). On the basis of data given in FAO and other sources, it is estimated that each year approximately 1.9–3.6 Mha land of primary close forests, 3.4–40 Mha land of secondary close forests, and 6.9–21.9 Mha land of secondary open forests are being lost due to shifting cultivation (Detwiler and Hall, 1988).

Shifting cultivation is prevalent mostly in tropical countries. In India, the people of the eastern and northeastern region practice shifting cultivation on hill slopes, and 85% of the total cultivation in the northeast region is by shifting cultivation (Singh and Singh, 1992). We estimated that between 1984 and 1994 about 17.22 Mt wood biomass and 10.69 Mt C was removed at the rate of 1.72 Mt yr^{-1} and 1.07 Mt C yr^{-1} respectively from the northeastern states. The rate of forest loss due to *jhum* declined in states such as Arunachal Pradesh and Meghalaya, increased in Nagaland and Manipur and fluctuated in other states. In Mizoram, net change in forest cover varied from a loss of 0.16 Mha between 1989 and 1991 to a gain of 0.20 Mha between 1993 and 1999, the latter occurring mainly because of regeneration of successional fallows to dense forest (FSI, 1993, 1995 and 1997). Ranjan and Upadhyay (2002) reported that shifting cultivation has already affected 2.7 Mha of land, and each year 0.45 ha of land is cleared under shifting cultivation. According to FSI (1988) about 1.99 Mha of area is subjected to shifting cultivation annually in India and 1.56 Mt C is emitted from the cutting of secondary forests in fallow area, uptake in the fallow and degradation or burning of new areas.

Annexure I

Code	Forest type/Forest strata	Description	Carbon[1] (%)
1	*Abies pindrow* (Fir)	When Fir constitute more than 50%	46
2	*Picea smithiana* (Spruce)	Where Spruce constitute more than 50%	46
3	Fir-Spruce	Where Fir & Spruce together constitute more than 50%	46
4	*Pinus excelsa* (Blue –pine)	Where Blue-pine constitute more than 50%	46
5	*Cedrus deodara*	Where *C. deodara* constitute more than 50%	46
6	*Pinus roxburghii* (Chir-pine)	Where Chir-pine constitute more than 50%	46
7	Mixed conifers	Where all conifers taken together constitute more than 50%	46
8	Hardwood mixed with conifers	Where the conifers & broad leaved species occur in more or less in same proportion	45
9	Up-land hardwoods	Broad leaved species constitute more than 50% in the upper/Chir zone above 1500 m altitude	45
10	*Toona ciliata* (Teak)	Where Teak constitute more than 20%	44
11	*Shorea robusta* (Sal)	Where Sal constitute more than 20%	46
12	Bamboo forest	Where the crop is of almost pure bamboo	43
13	Mangrove forests	Mangrove forest	45
14	Dipterocarp Forests	Where *Dipterocarpus* spp. constitute more than 50% in top canopy.	45
16	*Pinus khasia*	Where *P. khasia* constitute more than 50%	46
17	*Acacia nilotica*	Where *A. nilotica* trees constitute more than 50%	45
18	*Boswellia serrata*	Where *B. serrata* constitute more than 50%	45
20	Miscellaneous forest	Forest which could not be classified in any of the above class	45
21	Evergreen forests	Forest having more than 50% evergreen species	45
22	Deciduous forest	Deciduous species were dominant	45

Source. Forest Survey of India.
[1]*Source*. Negi et al. (2003).

Annexure II: Specific gravity (SG) of various forest strata (Rajput et al., 1993)

	Forest strata																			
State/UTs	1	2	3	4	5	6	7	8	9	10	11	12*	13	14	16	17	18	20**	21	22
A & N Island[a]	–	–	–	–	–	–	–	–	–	–	–	–	0.69	–	–	–	–	0.58	0.58	0.58
Andhra Pradesh	–	–	–	–	–	–	–	–	–	0.58	–	0.75	0.56	–	–	–	–	0.76	–	–
Arunanchal	–	–	–	–	–	0.43	0.44	–	0.44	–	–	0.31	–	–	–	–	–	0.31	–	–
Assam	–	–	–	–	–	–	–	–	–	–	0.70	0.70	–	–	–	–	–	0.54	–	–
Bihar	–	–	–	–	–	–	–	–	–	–	0.72	0.60	–	–	–	0.60	0.50	0.58	–	–
D & N Havel[a]	–	–	–	–	–	–	–	–	–	0.52	–	–	–	–	–	0.88	–	0.54	–	–
Goa, D&D	–	–	–	–	–	–	–	–	–	–	–	–	0.68	–	–	–	–	0.52	0.78	–
Gujrat	–	–	–	–	–	–	–	–	–	0.54	–	–	0.71	–	–	–	–	0.71	–	–
Haryana	–	–	–	–	–	–	–	–	–	–	0.70	–	–	–	–	–	–	0.67	–	–
HP	0.39	0.40	0.40	0.34	0.47	0.49	0.42	0.44	0.44	–	–	0.70	–	–	–	0.70	–	0.53	–	–
J & K	0.36	0.41	0.39	0.34	0.47	0.49	0.41	0.41	0.41	–	–	–	–	–	–	0.72	–	0.55	–	–
Karnataka	–	–	–	–	–	–	–	–	–	0.56	–	0.56	–	–	–	–	–	0.62	–	0.62
Kerala	–	–	–	–	–	–	–	–	–	0.59	–	0.64	–	–	–	–	–	0.53	–	–
Madhya Pradesh	–	–	–	–	–	–	–	–	–	0.54	0.68	0.66		–	–	0.66	0.50	0.64	–	–
Maharashtra	–	–	–	–	–	–	–	–	–	0.55	0.68	0.66	0.68	–	–	–	0.50	0.66	0.65	–
Manipur	–	–	–	–	–	0.43	–			0.54	0.70	0.70	–	0.60	0.43	–	–	0.54	–	–
Meghalaya	–	–	–	–	–	–	–			0.59	0.70	0.70	–	–	0.43	–	–	0.65	–	–
Mizoram	–	–	–	–	–	–	–	–	–	–	–	0.70	–	–	–	–	–	0.54	–	–
Nagaland	–	–	–	–	–	–	–	–	–	–	0.70	0.70	–	–	–	–	–	0.54	–	–
Orissa	–	–	–	–	–	–	–	–	–	0.58	0.77	0.77	0.50	–	–	–	0.50	0.62	–	–

(*Continued on next page*)

(*Continued*)

State/UTs	Forest strata																			
	1	2	3	4	5	6	7	8	9	10	11	12*	13	14	16	17	18	20**	21	22
Punjab	–	–	–	–	–	0.49	–	–	–	–	–	0.49	–	–	–	0.88	–	0.68	–	–
Rajasthan	–	–	–	–	–	–	–	–	–	0.55	–	–	–	–	–	0.88	0.50	0.64	–	–
Sikkim	–	–	–	–	–	–	0.37	–	–	–	0.75	–	–	–	–	–	–	0.51	–	–
Tamilnadu	–	–	–	–	–	–	–	–	–	0.64	–	–	–	–	–	–	–	0.64	–	–
Tripura	–	–	–	–	–	–	–	–	–	0.54	0.70	0.70	–	–	–	–	–	0.54	–	–
Uttar Pradesh	0.45	0.39	–		0.44	0.46	0.44	0.57	0.57	0.57	0.72	0.72		–	–	0.88	–	0.55	–	–
West Bengal	0.37	–	0.40	–	–	–	0.38		0.58	0.57	0.75	–	0.75	–	–	0.83	–	0.51	–	–

In case the SG of any forest strata in a state was not available, the SG of strata, from another state, falling in the same latitude was taken.
Forest strata are decoded in Annexure-I.
**Source.* Wealth of India.
**Specific gravity of 20th forest strata was calculated by averaging the values of SG of all the species present in that state.
[a]Union Territory.

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