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ORIGINAL ARTICLE

Impact of climate change on Indian forests: a dynamic vegetation modeling approach

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Abstract We make an assessment of the impact of projected climate change on forest ecosystems in India. This assessment is based on climate projections of the Regional Climate Model of the Hadley Centre (HadRM3) and the dynamic global vegetation model IBIS for A2 and B2 scenarios. According to the model projections, 39% of forest grids are likely to undergo vegetation type change under the A2 scenario and 34% under the B2 scenario by the end of this century. However, in many forest dominant states such as Chattisgarh, Karnataka and Andhra Pradesh up to 73%, 67% and 62% of forested grids are projected to undergo change. Net Primary Productivity (NPP) is projected to increase by 68.8% and 51.2% under the A2 and B2 scenarios, respectively, and soil organic carbon (SOC) by 37.5% for A2 and 30.2% for B2 scenario. Based on the dynamic global vegetation modeling, we present a forest vulnerability index for India which is based on the observed datasets of forest density, forest biodiversity as well as model predicted vegetation type shift estimates for forested grids. The vulnerability index suggests that upper Himalayas, northern and central parts of Western Ghats and parts of central India are most vulnerable to projected impacts of climate change, while Northeastern forests are more resilient. Thus our study points to the need for developing and implementing adaptation strategies to reduce vulnerability of forests to projected climate change.

Keywords Climate change · Forest · Forested grids · Forest vulnerability index · Impact of climate change · India · Model

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1 Introduction

Climate is one of the most important determinants of vegetation patterns globally and has significant influence on the distribution, structure and ecology of forests (Kirschbaum et al. 1996). Several climate–vegetation studies have shown that certain climatic regimes are associated with particular plant communities or functional types (Walter 1985). It is therefore logical to assume that changes in climate would alter the distribution of forest ecosystems. Based on a range of vegetation modeling studies, IPCC 2007 suggests potential forest dieback towards the end of this century and beyond, especially in tropics, boreal and mountain areas (Miles 2002; McClean et al. 2005). The most recent report from International Union of Forest Research Organization (Seppälä et al. 2009) paints a rather gloomy picture about the future of the world forests in a changed climate as it suggests that in a warmer world, the current carbon regulating services of forests (as carbon sinks) may be entirely lost, as land ecosystems could turn into a net source of carbon dioxide later in the century.

Assessments of potential climate change impacts on forests in India (Ravindranath and Sukumar 1996; Ravindranath and Sukumar 1998; Ravindranath et al. 2006) were based on BIOME model (versions 3 and 4)—which being an equilibrium model, does not capture the transient responses of vegetation to climate change. The recent study (Ravindranath et al. 2006) concludes that 77% and 68% of the forested grids in India are likely to experience shift in forest types for climate change under A2 and B2 scenarios, respectively. In addition there have been two regional studies, the first focusing on potential climate change impacts on forests in the northern state of Himachal Pradesh (Deshingkar 1997) and the second in the Western Ghats (Ravindranath et al. 1997). These studies indicated moderate to large-scale shifts in vegetation types with implications for forest dieback and biodiversity. The studies conducted for India so far have had several limitations, e.g., coarse resolution of the input data as well as the use of BIOME which is an equilibrium model with limited capability in categorizing plant functional types and dynamic representation of growth constraints.

Impacts of climate change on forests have severe implications for the people who depend on forest resources for their livelihoods. India is a mega-biodiversity country where forests account for more than one fifth of the geographical area. With nearly 173,000 villages classified as forest villages, there is a large dependence of communities on forest resources in India (Kishwan et al. 2009). India has a large afforestation programme of over 1.32 Mha per annum (Ravindranath et al. 2008), and more area is likely to be afforested under programmes such as ‘Green India mission’ and ‘Compensatory Afforestation Fund Management and Planning Authority’ (CAMPA). Thus it is necessary to assess the likely impacts of projected climate change on existing forests and afforested areas, and develop and implement adaptation strategies to enhance the resilience of forests to climate change.

The present study investigates the projected impacts of climate change on Indian forests using a dynamic global vegetation model (DGVM). It specifically assesses the boundary shifts in vegetation types, changes in NPP and soil carbon stocks, as well as the vulnerability of existing forests to future climate change.

2 Status of forests in India

According to the Forest Survey of India (FSI) “all lands, more than one hectare in area, with a tree canopy density of more than 10% is defined as Forest” (FSI 2009). The status of forests and forest management systems contribute to the vulnerability of forests to climate change.

2.1 Forest area

The Forest Survey of India has been periodically estimating the forest cover in India since 1987 using remote sensing techniques (FSI 1989). It can be observed from Fig. 1 that the forest cover in India has nearly stabilized and further it is increasing marginally over the years. In addition to forest cover, FSI has also included the tree cover in its 2001, 2003, 2005, and 2007 assessments.

2.2 Distribution of forest types

Indian forests are extremely diverse and heterogeneous. Classification of Indian forest types is available from two main sources—one by Forest Survey of India (FSI 2001) and another by Champion and Seth (1968). Due to forest heterogeneity, Forest Survey of India's classification scheme has a pan-Indian 'miscellaneous forest' category (with no dominant species), which accounts for 63% of forest area. This large miscellaneous category makes the FSI classification rather unattractive for further analysis. However, Champion and Seth (1968) classify Indian forests into 16 distinct forest types. Hence, we use the Champion and Seth classification for further analysis. The distribution of forest types in India according to Champion and Seth (1968) is shown in Fig. 2.

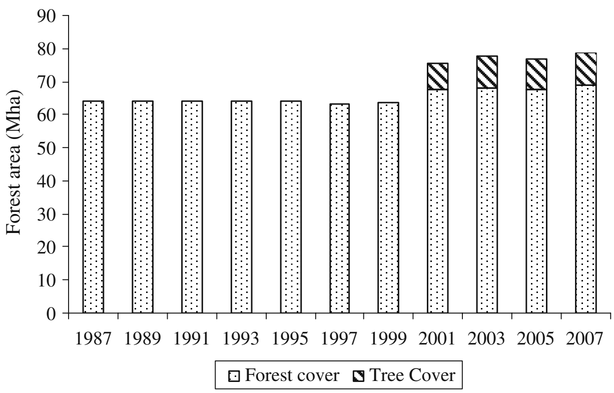
2.3 Carbon stocks in Indian forests

Estimates for forest carbon stocks, including biomass and soil carbon from literature are shown in Fig. 3. Forest carbon stocks including biomass and soil carbon for the year 1986 are estimated to be in the range of 8.5 to 9.5 GtC (the studies differ in the methods used). According to an FAO study, total forest carbon stock was estimated to be 10 GtC for 2005. Thus, carbon stocks in Indian forests may not have declined. Additionally, Kishwan et al. (2009) estimate that the carbon stock in biomass as well as soil has increased by 377 Mt C between 1995 and 2005. Forest soil carbon accounts for over 50% of the total forest carbon stock according to different estimates (Fig. 3).

2.4 Afforestation trend in India

India initiated large-scale afforestation under the social forestry programme starting in the early 1980s. Figure 4 presents the progress of afforestation in India for the period 1951–2005. It can

Fig. 1 Trends in area under forest and tree cover (FSI 1989–2009)



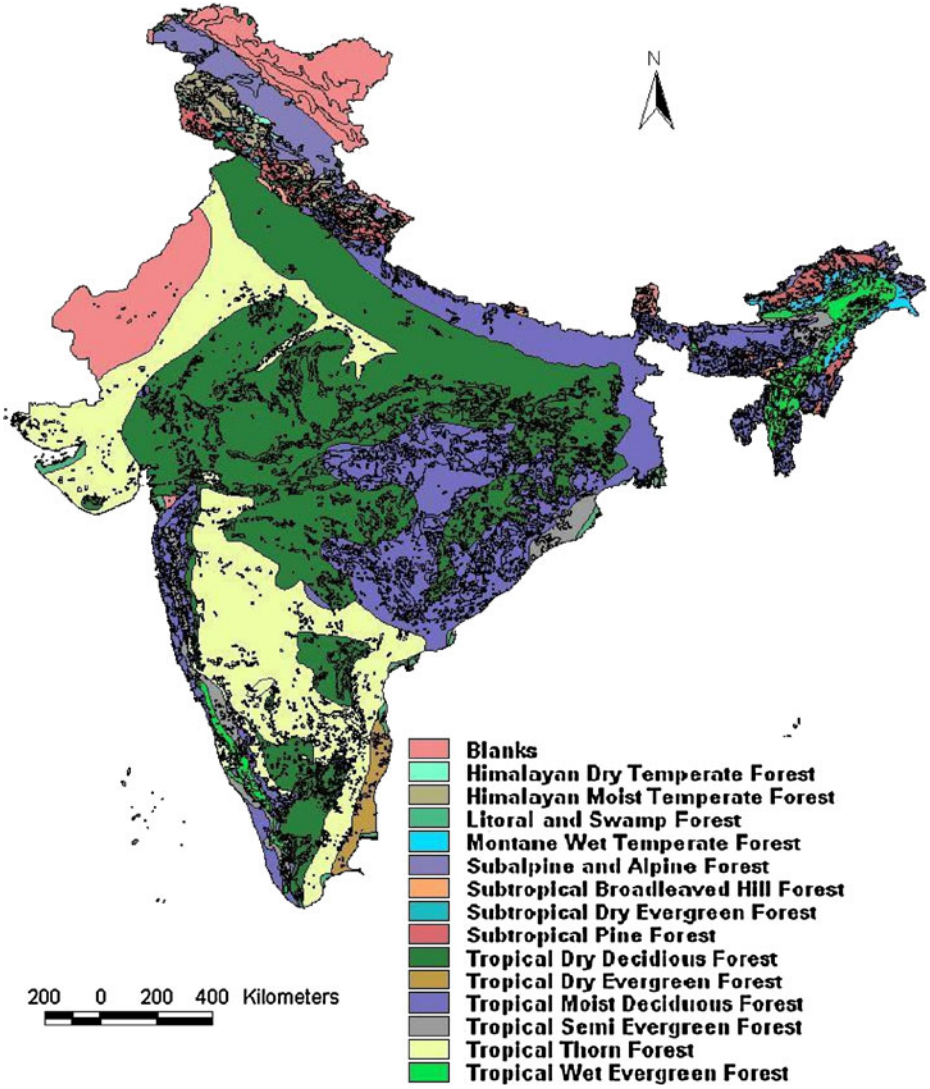


Fig. 2 Forest types of India (Champion and Seth, 1968). "Blanks" indicate that the region is not classified by Champion and Seth

be seen from Fig. 4 that the cumulative area afforested in India during the period 1980–2005 is about 34 Mha at an average annual rate of 1.32 Mha (Ravindranath et al. 2008).

3 Methods

The impacts of climate change on forests in India are assessed based on the changes in area under different forest types, shifts in boundary of forest types and NPP. This assessment was based on: (i) spatial distribution of current climatic variables, (ii) similar data for future climate projected by relatively high-resolution regional climate models for two different

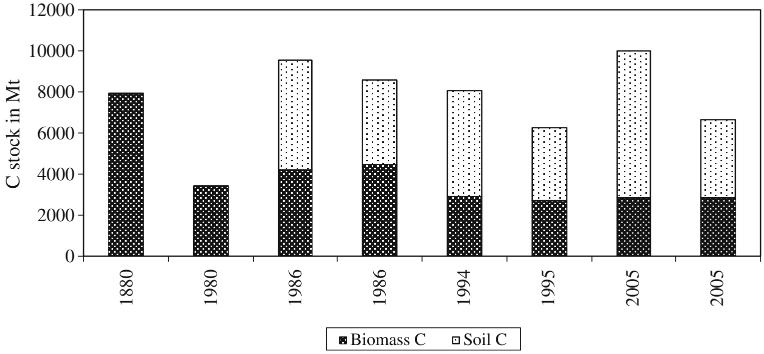


Fig. 3 Carbon stock estimates for Indian forests (Source: 1880—Richards and Flint 1994; 1980—Richards and Flint 1994; 1986—Ravindranath et al. 1997; 1986—Chhabra and Dadhwal 2004; 1994—Haripriya 2003; 1995—Kishwan et al. 2009, 2005—FAO 2005, 2005—Kishwan et al. 2009)

climate change scenarios, and (iii) vegetation types, NPP and carbon stocks as simulated by the dynamic model IBIS v.2 (Integrated Biosphere Simulator).

3.1 Vegetation model

The dynamic vegetation model IBIS is designed around a hierarchical, modular structure (Kucharik et al. 2000). The model is broken into four modules namely 1) the land surface module, 2) Vegetation phenology module, 3) Carbon balance module and 4) Vegetation dynamics module. These modules, though operating at different time steps, are integrated into a single physically consistent model that may be directly incorporated within AGCMs (Atmospheric General Circulation models). For example, IBIS is currently incorporated into two AGCMs namely GENESIS-IBIS (Foley et al. 2000) and CCM3-IBIS (Winter 2006). The state description of the model allows trees and grasses to experience different light and water regimes and competition for sunlight and soil moisture determines the geographic distribution of plant functional types and the relative dominance of trees and grasses, evergreen and deciduous phenologies, broadleaf and conifer leaf forms, and C3 and C4 photosynthetic pathways.

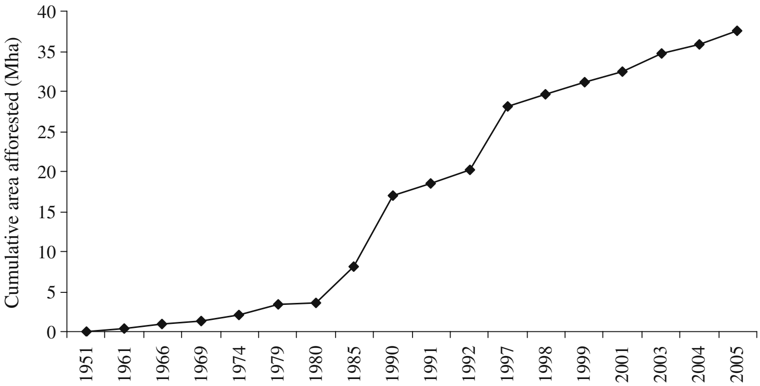


Fig. 4 Cumulative area afforested during 1951 to 2005

3.2 Input data

IBIS requires a range of input parameters including climatology as well as soil parameters. The main climatology parameters required by IBIS are: Monthly mean cloudiness (%), Monthly mean precipitation rate (mm/day), Monthly mean relative humidity (%), Monthly minimum, maximum and mean temperature (C) and wind speed (m/s). The main soil parameter required is the texture of soil (i.e percentage of sand, silt and clay). The model also requires topography information.

Observed climatology is obtained from CRU (New et al. 1999), while soil data was obtained from IGBP (IGBP 2000). For climate change projections, RCM outputs from Hadley centre model HadRM3 were used (Rupakumar et al. 2006). The climate variables for future scenarios were obtained using the method of anomalies. Briefly, this involved computing the difference between the projected values for a scenario and the control run of the HadRM3 model, and adding this difference to the value corresponding to the current climate as obtained from the CRU climatology. Climate Data Operators (CDO) software (Schulzweida and Kornblueh 2006) was used for the data editing and Climate Data Analysis Tool (CDAT) (Drach et al. 2007) for data processing and generation of various maps and plots.

3.3 Selection of forested grids

A digital forest map of India (FSI 2001) was used to determine the spatial location of all forested areas. This map was based on a high-resolution mapping (2.5′ by 2.5′), wherein the entire area of India was divided into over 165,000 grids. Out of these, 35,899 grids were marked as forested grids (along with the forest density and the forest type). Figure 5 shows the spatial location of these grids. Furthermore, these forest grids were classified into three categories as per forest density: 1) “Very dense forests” with crown density above 70%, 2) “Moderately dense forest” with crown density between 40% and 70%; 3) “Open forest” with crown density between 10% and 40%.

3.4 Scenarios of climate change

SRES scenario A2 (atmospheric CO_2 concentration reaches 740 ppm by 2085) is selected as one of the scenarios. However, since a more constrained emission pathway may emerge as a result of global mitigation actions, we also chose B2 scenario (575 ppm by 2085) in this study. We compare the results of these with the ‘baseline’ scenario, which represents the simulation using the 1961–91 observed climatology. ‘Baseline’ is also referred to as either ‘reference’ or ‘control’ case.

4 Model validation

We simulated the current vegetation pattern, NPP, biomass and soil carbon over India using the IBIS model driven by observed climatology from CRU (New et al. 1999). The validation of this baseline (or control) simulation is described below.

4.1 Vegetation distribution

Comparison of simulated vegetation cover with the observed vegetation map (Fig. 6) (Champion and Seth 1968) shows fair agreement. Many important observed vegetation

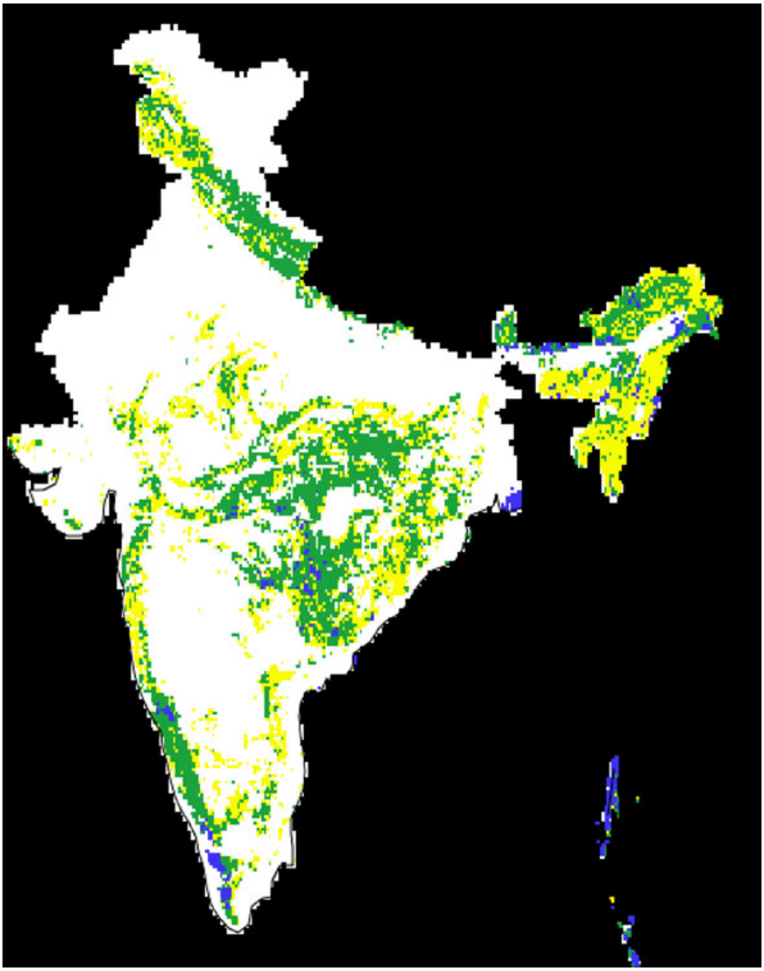
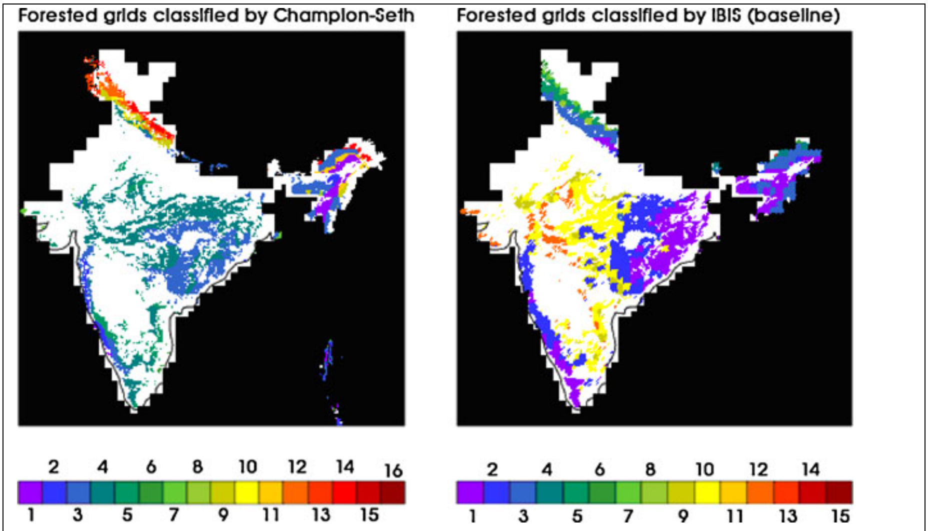


Fig. 5 The location of the 35,899 forest grid points (*coloured*) in India. Out of these, 4.3% of grid points (*blue*) were classified as “very dense forests”, 54.9% (*green*) as “moderately dense forest” and 40.7% (*yellow*) as “open forests”

distribution patterns are reproduced in the simulation, including (1) the tropical evergreen forest vegetation in Western Ghats and North-east; 2) desert and thorny vegetation types in Western and south central parts, 3) tropical deciduous forests in most of its present day locations except parts of western Madhya Pradesh where the model simulates savanna and shrublands; 4) temperate evergreen conifer forests in Himalayas and higher elevations of North east.

IBIS simulates forests at about 70% of the FSI forest grids (FSI 2001). However it simulates savanna and shrublands over most grids in western Madhya Pradesh, Gujarat and Rajasthan whereas Champion and Seth (1968) classify these regions as forests. This anomaly of IBIS under-representing forests in the tropics is documented in previous studies (Kucharik et al. 2000; Cramer et al. 2001; Bonan et al. 2003) which find that IBIS has higher (than observed) grass coverage in the great plains, southern South America, Africa and India.



1.Tropical wet evergreen forests, 2.Tropical semi evergreen forests, 3.Tropical moist deciduous forest, 4.Tropical dry decidious forest, 5.Tropical thorny/scrub forests, 6.Tropical dry evergreen forest, 7.Littoral and swampy forest, 8.Subtropical broad -leaved hill forests, 9.Subtropical pine forests, 10.Sub-tropical dry evergreen forests, 11.Montane wet temperate forests, 12.Himalayan wet/ moist temperate forests, 13.Himalayan dry temperate forests, 14.Sub-alpine forests, 15.Moist alpine, 16.Dry alpine	1: tropical evergreen forest / woodland, 2: tropical deciduous forest / woodland, 3. temperate evergreen broadleaf forest / woodland, 4: temperate evergreen conifer forest / woodland, 5: temperate deciduous forest / woodland, 6: boreal evergreen forest / woodland, 7: boreal deciduous forest / woodland, 8: mixed forest / woodland, 9: savanna, 10: grassland / steppe, 11: dense shrubland, 12: open shrubland, 13: tundra, 14: desert, 15. polar desert / rock / ice

Fig. 6 Model simulated current vegetation distribution (*right*) compared with observed vegetation distribution (*left*, Champion and Seth 1968)

4.2 NPP

The remotely-sensed mean NPP data from satellites for the period 1982–2006 was obtained from Nemani et al. (2003) (as well as personal correspondence). It was regridded to a 0.5º× 0.5º format and the geographical region outside India was masked out. The correlation between this distribution and the NPP simulated by IBIS control case is estimated to be about 0.65, indicating fair agreement (Fig. 7). IBIS simulations of NPP (Mean: 424.0, Min: 7.0, max: 1374.0 g/m^2/year) show a reasonable match with satellite observations (Mean: 431.0, min: 0.0, max: 1195.0 g/m^2/year) over India. . It should be noted that simulated NPP represents the NPP of natural potential vegetation but observations represent NPP of current vegetation (including croplands).

4.3 Soil organic carbon

We compared the soil organic carbon data from IGBP (IGBP-DIS 1998) with the IBIS simulated soil carbon estimates for the control case (Fig. 8). We find that the mean from both the sources is approximately 5 kg/m^2 over India (mean of IBIS=5.0 kg/m^2 and mean of IGBP=4.7 kg/m^2). However, we find that the IBIS simulated spatial distributions (spatial standard deviation=4.27; Max=20.83; Min=0.13) to be substantially different from IGBP estimates (Standard deviation=1.33; Max=11; Min=1.8).

For a more detailed investigation, we selected a grid point in the Western Ghats. We selected this grid point as it is nearer to the field research centre operated by the Indian

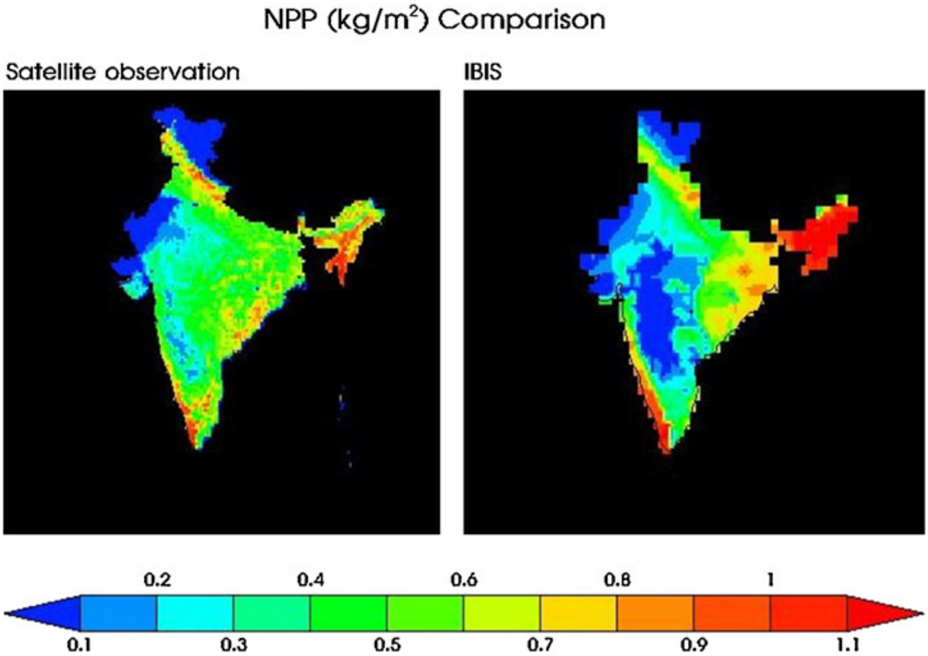


Fig. 7 Model simulated current NPP (kgC/m^2) compared with the remote-sensing-derived mean NPP data from 1982 to 2006

Institute of Science (IISc), Bangalore. Location of the grid can be seen in the map of India (inset of Fig. 9).

A total of 35 different locations were sampled in the Western Ghats out of which 15 sample locations were situated in forested areas and 20 were situated in non-forested areas. Sample sites are shown in Figs. 9 and 10. About 250 gms of soil samples were sampled

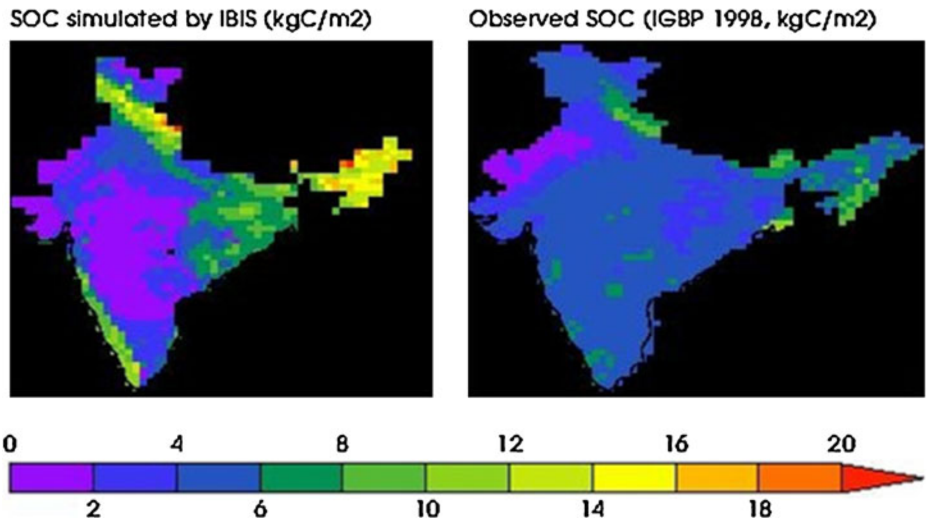


Fig. 8 Model simulated current SOC distribution compared with the observed SOC distribution

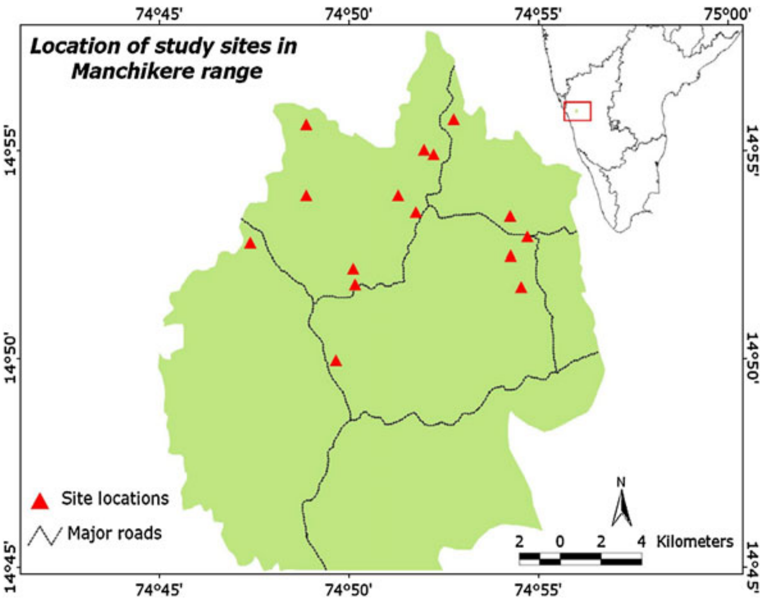


Fig. 9 Sample locations in forested sites

from two depth classes i.e. 0–15 cms and 15–30 cms. Soil organic carbon was analyzed using the Walkley and Black (1934) method.

Forested sites were found to have higher soil organic carbon with an average of 97 tonnes carbon per hectare (tC/ha) with a standard deviation (SD) of 19.8 tC/ha compared to non-forested areas with an average of 64 tC/ha (SD=27.2 tC/ha). The average soil organic carbon in the region is estimated to be 78.15 tC/ha (S.D=29.2 tC/ha) whereas IBIS simulates 89.13 tonnes C/ha for this particular grid. , Given the huge uncertainty involved with soil carbon estimation (Sudha et al. 2003), the model predictions appear to be reasonable.

Total carbon stocks For the control case (1975) IBIS simulated a total 3090 Mt of carbon in biomass over India while a review of published studies suggests a mean of 3386±989 Mt of carbon in biomass (Fig. 3). Further, IBIS simulations suggest a total of 4705 Mt of carbon in the form of SOC in the forested grids, while a review of published studies suggests a mean of 5,000±1464 Mt of SOC in Indian forests. SOC estimates are, in general, associated with larger uncertainty. In summary, IBIS simulates a total carbon stock (biomass plus SOC) of 7795 Mt of carbon for India while observational estimates suggest a mean of 8141±1705 Mt of carbon in Indian forests.

5 Impacts of climate change on forest types and extents

5.1 Changes in the distribution of forests

The vegetation distribution simulated by IBIS for baseline, A2 and B2 scenario in the forested grids are shown in Fig. 11. One can notice that there is an expansion of tropical

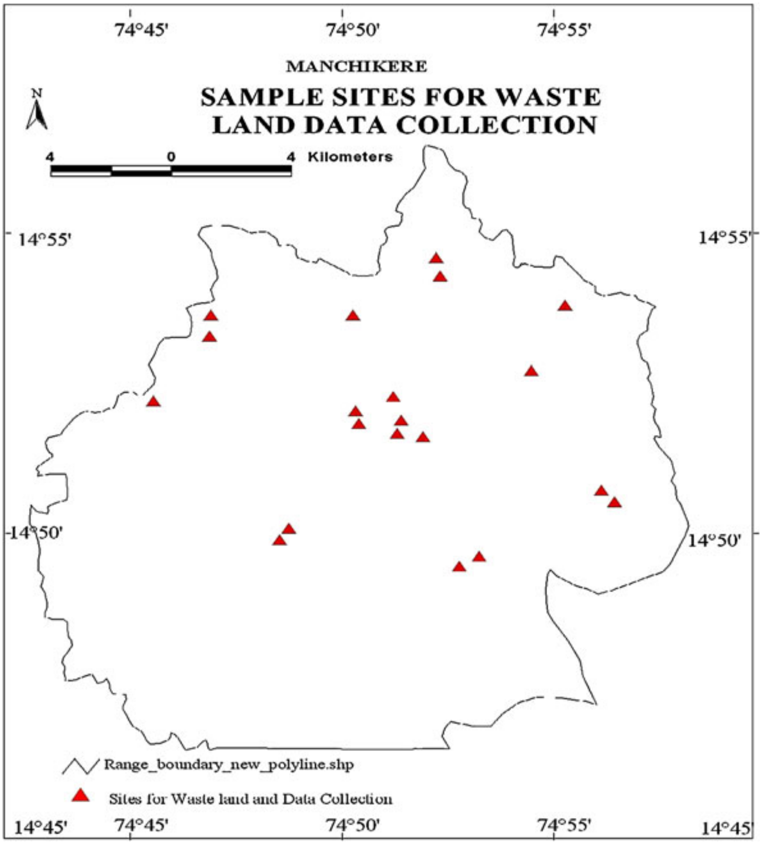


Fig. 10 Sample locations in Non-forest locations

evergreen forests (IBIS vegetation type 1) in eastern India plateau for both A2 and B2 scenarios. The same trend can be seen in the Western Ghats. It is interesting to note that there is almost no vegetation type change in the north-east. Further, there is a slight expansion of forests into the western part of central India. Overall, there is negligible difference between forest extents predicted for the future in the A2 and B2 scenarios except that forest expansion is higher into the western part of central India in the A2 scenario. This could be attributed to higher precipitation levels in A2 scenario relative to B2 in this region. One caveat to the expansion trend of forests (like tropical evergreen) is the assumption that forests are un-fragmented, and there is no dearth of seed-dispersing agents. In the real world, forests are fragmented, and, seed dispersal may not be efficient in the view of loss or reduction in number of dispersal agents due to human habitation pressures and climate change (Rosenzweig 1995). As the population of seed-dispersing agents may decline, predicted forest expansion is not guaranteed.

The vegetation change matrix corresponding to Fig. 11 (for both A2 and B2 scenario) is presented in Tables 1 and 2. One can notice from the table that the bulk of forest-type conversions are from tropical deciduous forests to tropical evergreen forests.

For further analysis, we consider the forested grid points obtained from Champion and Seth 1968 forest type classification (Fig. 2). Then, we identified grids where vegetation type

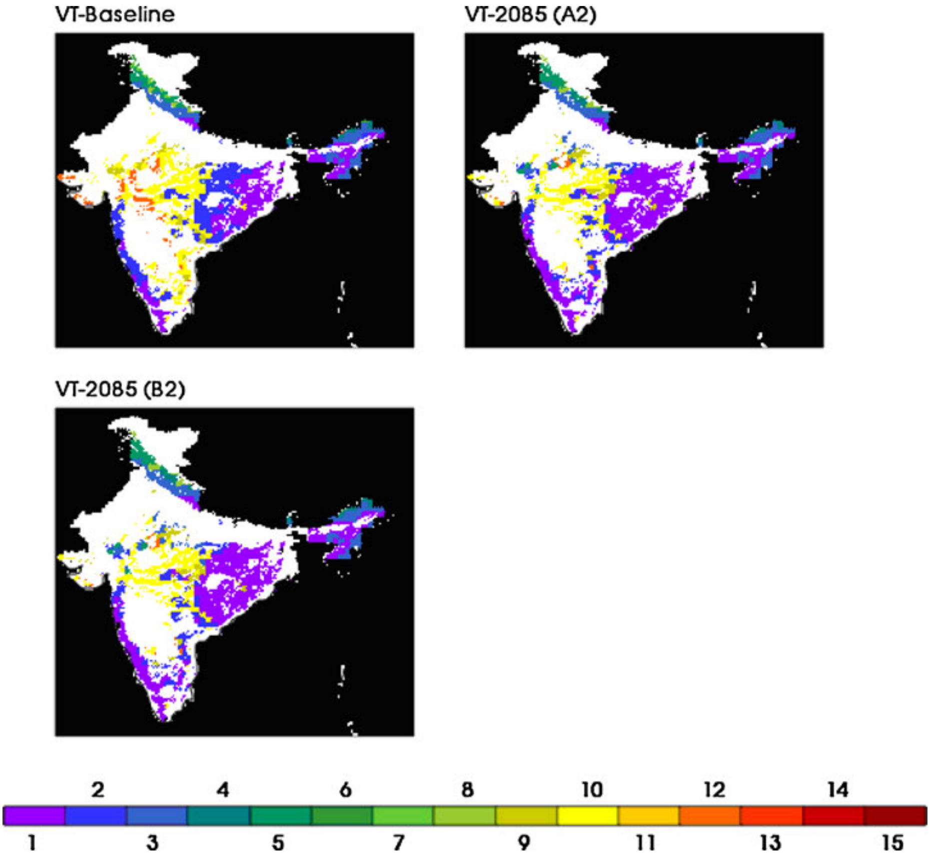


Fig. 11 Forest type distribution and extent simulated by IBIS for the baseline case and A2 and B2 scenarios. White areas represent non-forested grids. (VT—refers to Vegetation Types. The numbers refer to the following vegetation types 1: tropical evergreen forest / woodland, 2: tropical deciduous forest / woodland, 3. temperate evergreen broadleaf forest / woodland, 4: temperate evergreen conifer forest / woodland, 5: temperate deciduous forest / woodland, 6: boreal evergreen forest / woodland, 7: boreal deciduous forest / woodland, 8: mixed forest / woodland, 9: savanna, 10: grassland/ steppe, 11: dense shrubland, 12: open shrubland, 13: tundra, 14: desert, 15. polar desert / rock / ice)

(simulated by IBIS) is projected to change under A2 and B2 scenarios compared to baseline scenario (Fig. 12). Approximately 39 and 34% of forested grid are projected to experience vegetation type change under A2 and B2 climate scenarios, respectively. In agreement with earlier studies (Ravindranath et al. 2006), we too find a trend towards expansion of wetter forest types. Tropical dry deciduous forests currently constitute more than 40% of the Indian forested grids. Our analysis suggests that approximately 47 and 42% of these tropical dry deciduous grids undergo change under A2 and B2 climate change scenarios, respectively, as opposed to less than 16% grids for f tropical wet evergreen forests. Tropical moist forests, which constitute 20% of the grid points, appear to be relatively stable with only 38 and 34% of forested grids experiencing change under the two scenarios. However, tropical thorny scrub forest which constitutes 20% of the Indian forested area is projected to experience a larger change with majority of grids (more than 80%) undergoing change under A2 scenario and 50% grids experiencing change under the B2 scenario.

Table 1 Vegetation change matrix for A2 scenario. The table lists the number of grid points that changed from one IBIS vegetation type (in baseline) to another vegetation type (in 2085 for A2 scenario). For example, the number "6756" in 4th row and 3rd column denotes that 6756 forest grids changed from tropical deciduous forest (vegtype 2) to tropical evergreen forest (vegtype 1)

Changed from	Changed to														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	8143	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	6756	1675	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	4370	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	625	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	254	644	0	0	176	0	0	0	0	0	0	0
6	0	0	0	103	12	7	0	57	0	0	0	0	0	0	0
7	0	0	0	0	321	0	0	0	0	0	0	0	0	0	0
8	0	0	0	161	1	0	0	70	0	0	0	0	0	0	0
9	135	695	480	0	51	0	0	0	0	0	0	0	0	0	0
10	276	669	201	0	165	0	0	0	1075	3262	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	646	0	194	0	0	0
13	0	0	0	0	0	25	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Numbers 1–15 are IBIS vegetation types. These are: 1: tropical evergreen forest / woodland, 2: tropical deciduous forest / woodland, 3. temperate evergreen broadleaf forest / woodland, 4: temperate evergreen conifer forest / woodland, 5: temperate deciduous forest / woodland, 6: boreal evergreen forest / woodland, 7: boreal deciduous forest / woodland, 8: mixed forest / woodland, 9: savanna, 10: grassland / steppe, 11: dense shrubland, 12: open shrubland, 13: tundra, 14: desert, 15. polar desert / rock / ice

Table 2 Vegetation change matrix for B2 scenario. The table lists the number of grid points that changed from one IBIS vegetation type (in baseline) to another vegetation type (in 2085 for B2 scenario). For example, the number "6216" in 4th row and 3rd column denotes that 6216 forest grids changed from tropical deciduous forest (vegtype 2) to tropical evergreen forest (vegtype 1)

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	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	8041	102	0	0	0	0	0	0	0	0	0	0	0	0	0
2	6216	2215	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	4370	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	625	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	278	353	0	0	443	0	0	0	0	0	0	0
6	0	0	0	66	0	71	0	42	0	0	0	0	0	0	0
7	0	0	0	0	277	44	0	0	0	0	0	0	0	0	0
8	0	0	0	231	1	0	0	0	0	0	0	0	0	0	0
9	47	762	354	0	51	0	0	0	147	0	0	0	0	0	0
10	52	284	8	0	143	0	0	0	717	4398	0	46	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	581	0	259	0	0	0
13	0	0	0	0	0	25	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
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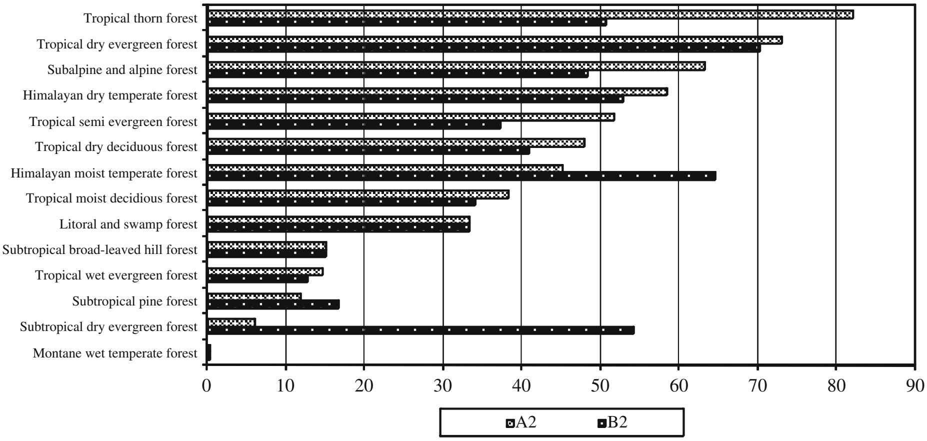

Fig. 12 Percentage of forest grids undergoing vegetation change by 2085 under A2 and B2 scenarios according to forest types

5.2 Impact on NPP

The NPP tends to increase over India (Fig. 13) for both A2 and B2 scenarios. It increases by an average of 66.5% by 2085 under A2 scenario and 49% by 2085 under the B2 scenario. Notably, increase is higher in the north-eastern part of India due to warmer and wetter climate predicated there.

Figure 14 shows the percent change in NPP under the A2 scenario compared to the baseline. While there is an increase in most places, the figure suggests that in central and western Indian forests NPP remains the same or increases only moderately and in some places even decreases by up to 12%. It must be noted that these areas already have a very low level of baseline NPP to start with (in most of cases, not exceeding more than 0.4 kg/m^2).

We analyzed the NPP change under A2 and B2 scenarios compared to the baseline scenario for forest grids classified according to Champion and Seth (Fig. 15). On an average, NPP increased by 67% and 49% under A2 and B2 scenarios, respectively, for these grids. Under A2 scenario, the Himalayan dry temperate forests and sub-alpine and alpine forests register maximum increase in NPP. Vegetation growth in these forests is limited by the lower temperatures, and hence increase in temperature (and precipitation) would favor NPP increase. The subtropical dry evergreen forests register lowest increase in NPP.

5.3 Impact on soil organic carbon (SOC)

A trend similar to NPP distribution can be observed for soil organic carbon (Fig. 16), which is to be expected as increased NPP is the primary driver of higher litter input to the soil. However, the quantum of increase compared to baseline in this case is lower: around 37% and 30%, for the A2 and B2 scenario respectively (averaged over whole of India). This increase is less due to the inertia of the SOC pool and increased soil respiration.

The SOC changes for A2 and B2 scenarios compared to baseline scenario for forested grids according to Champion and Seth 1968 forest type classification is presented in Fig. 17.

Tropical moist deciduous forests and sub-alpine and alpine forests are projected to have large (40–45%) increases in SOC. The increase in NPP results in augmented litter fall

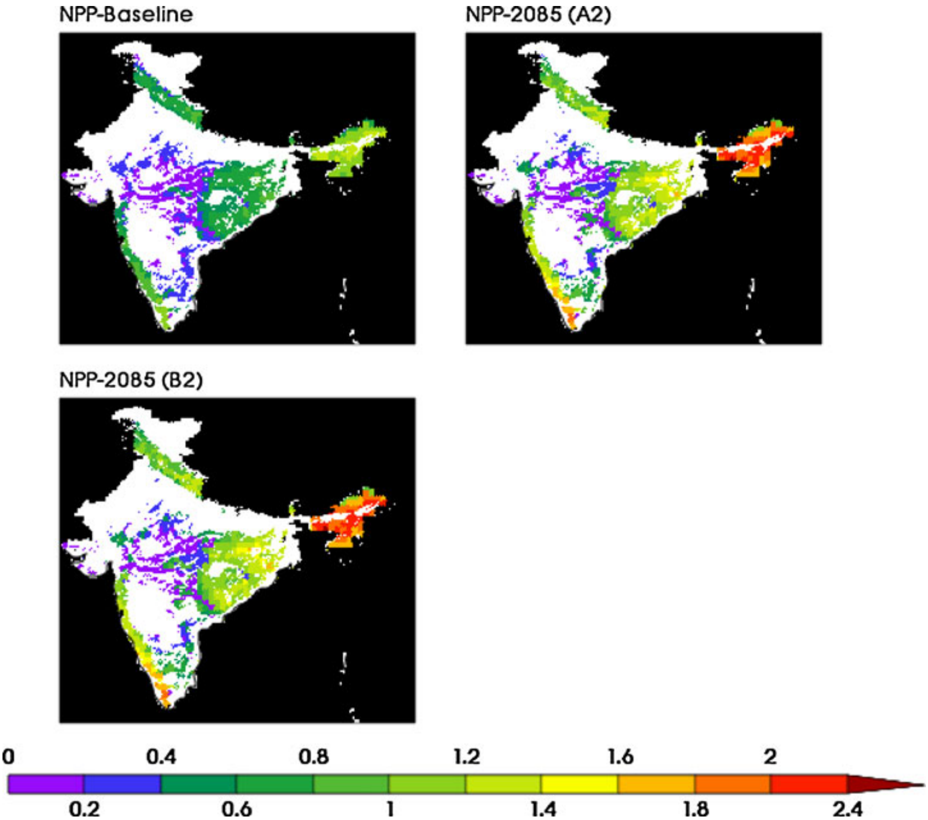

Fig. 13 NPP distribution (kgC/m^2) simulated by IBIS for the baseline case and A2 and B2 scenarios

which contributes to higher SOC. In contrast subtropical pine forests and Himalayan moist temperate forests have much smaller increases (20–30%) in SOC.

Our estimates for both NPP and SOC increase should be viewed with caution as IBIS, compared with other dynamic vegetation models, tends to simulate a fairly strong CO_2 fertilization effect (Cramer et al. 2001; McGuire et al. 2001). This can partly be explained by the fact that the nitrogen cycle and acclimation of soil microbiology to the higher temperatures are not explicitly taken into account in IBIS (Kirschbaum 2000; Tjoelker et al. 2001). It also does not simulate forest fires dynamically which are very common especially in dry deciduous forests of India (FAO 2001). IBIS does not simulate changed pest attack dynamics. Majority of forest species in India are susceptible to pest attack, and we have not included the impact of increased or decreased pest attack in a changed climate.

5.4 Implication at the state level

Statewise forest grid change estimates are provided in Table 3. Chattisgarh, Karnataka, Andhra Pradesh and Madhya Pradesh experience the largest percentage change in forested grids at 73 %, 67%, 62% and 49% respectively, under the A2 scenario while Northeastern states experience the least amount of changes in forested grids.

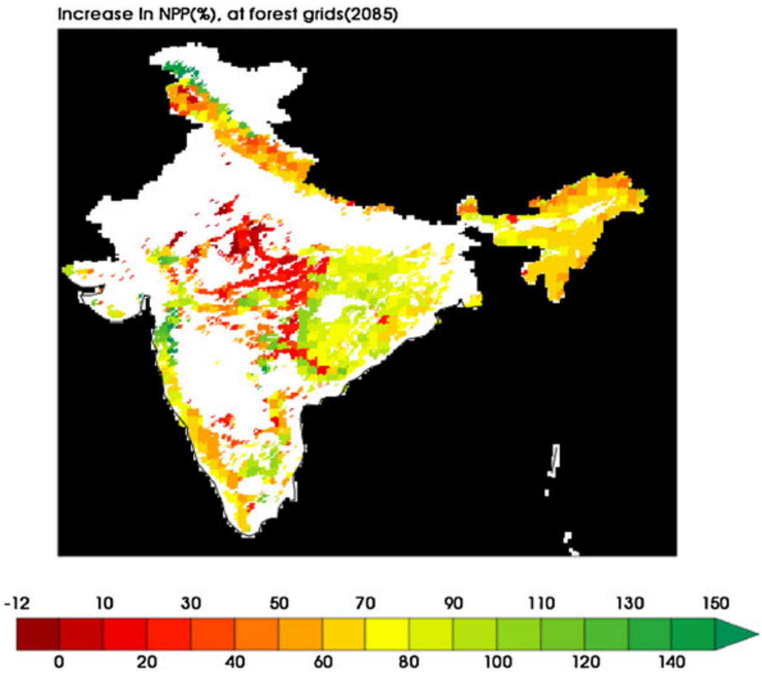

Fig. 14 The effect of climate change on the NPP of the forested grids by 2085 under A2 scenario. The values indicate percentage change in NPP compared to the baseline year

5.5 A vulnerability index for Indian forests

Forests in India are already subjected to multiple stresses including over extraction, insect outbreaks, live-stock grazing, forest fires and other anthropogenic pressures. Climate change will be an additional stress. Disturbed and fragmented forests and monoculture forests are likely to be more vulnerable to climate change (Rosenzweig 1995; Jandl et al.

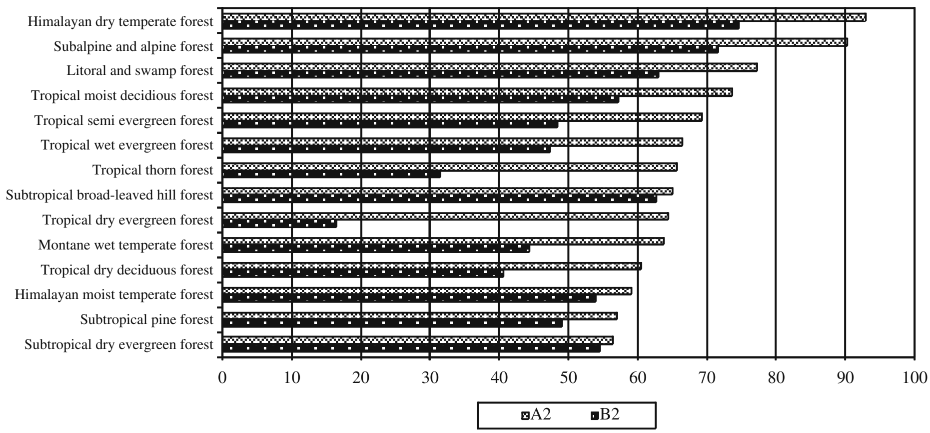

Fig. 15 Percentage change in NPP by 2085 for A2 and B2 scenarios compared to baseline (according to Champion and Seth 1968 classification)

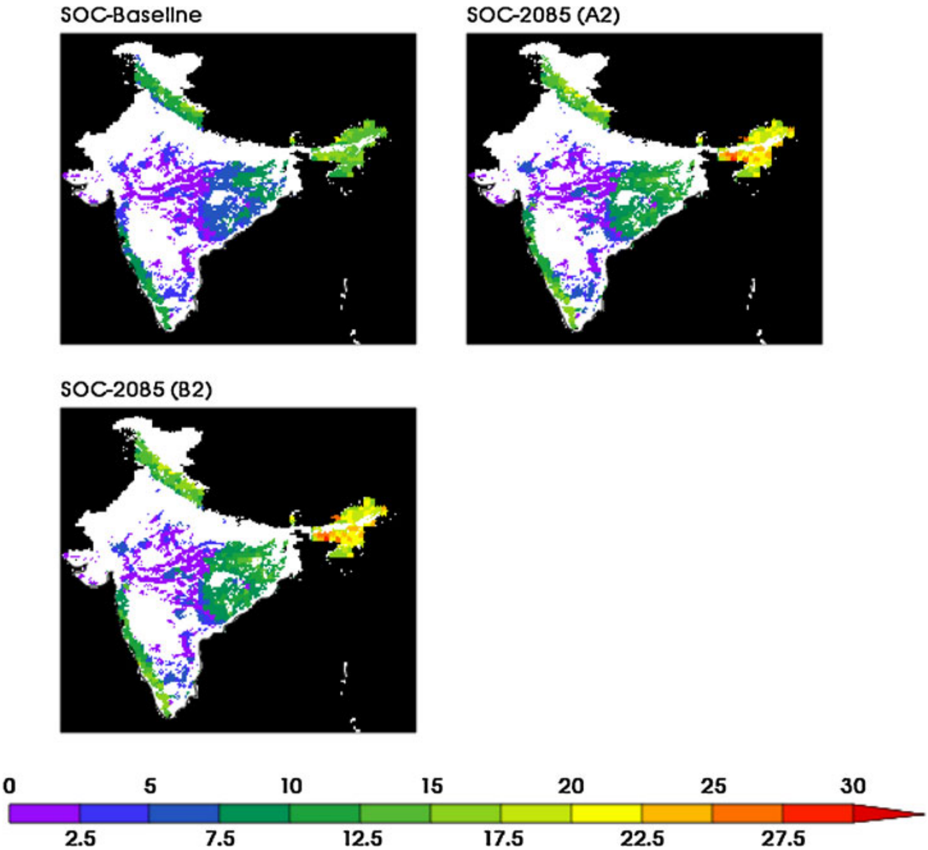

Fig. 16 Distribution of SOC (kgC/m^2) simulated by IBIS for the baseline case and A2 and B2 scenarios

2007). Therefore, we develop a vulnerability index and assess the vulnerability of different forest types and regions.

The various vulnerability index classes (Table 4) were defined by spatially combining information on forest diversity (monoculture versus natural forest), forest density (an indicator of degradation) and IBIS vegetation type change estimates for the forest grids under A2 scenario. For example, if a particular forest grid point had monoculture vegetation, a low forest density (or higher levels of degradation) and if there was a vegetation type shift in the future as predicted by IBIS, then this grid point is given the highest vulnerability Index of 7. The last row in Table 4 defines the "least vulnerability" scenario with no climate change. The distribution of this vulnerability index over the country is shown in Fig. 18.

From Table 4, one can notice that nearly 39% of forested grids are vulnerable to climate change in India.

– The forests in the central part of India, especially the north-western part of India are highly vulnerable. There are regions of vulnerability surrounded by non-vulnerable regions in that area.
– There are relatively few areas in the northeastern part of India that have a high vulnerability index. This low vulnerability index in this regions is because climate is

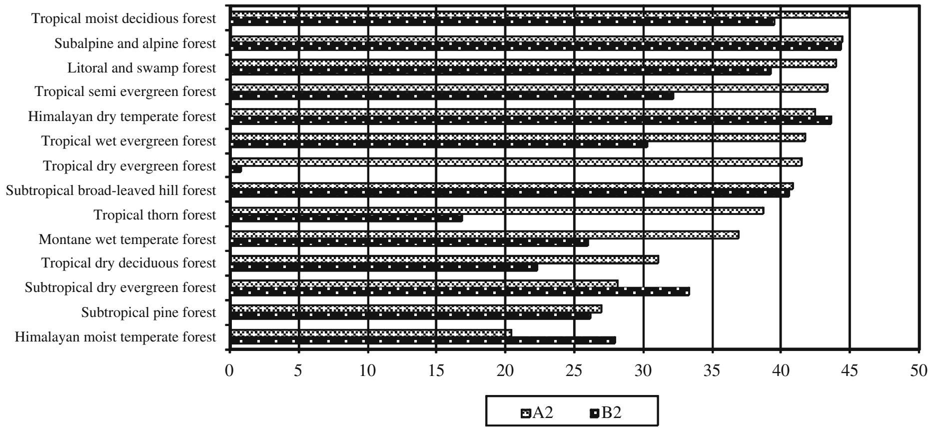

Fig. 17 Percentage change in SOC by 2085 for A2 and B2 scenarios compared to baseline

predicted to get hotter and wetter there, which is conducive to the existing vegetation types (such as tropical evergreen forests).

- A significant part of the Himalayan bio-diversity hotspot that stretches along the north-western part of India along the states of Punjab, Jammu and Kashmir and Himanchal Pradesh is projected to be highly vulnerable. This may be mostly attributed to the higher elevation of these regions. Our studies have shown that these regions will experience higher levels of warming.
- Northern and central parts of the Western Ghats seem to be vulnerable to climate change. Northern parts of the Western Ghats contain significant extent of open forests, which drive up the vulnerability score. High values of the index in the central part of

Table 3 Number of forested grid points projected to undergo change in different states

State name	Num. forest grids	Num. forest grids changed (A2)	% forest grids changed (A2)	Num. forest grids changed (B2)	% forest grids changed (B2)
Madhya Pradesh	4437	2183	49.20	1807	40.73
Arunachal Pradesh	3410	93	2.73	93	2.73
Chhattisgarh	3130	2292	73.23	2292	73.23
Andhra Pradesh	2588	1615	62.40	1191	46.02
Maharashtra	2338	1060	45.34	827	35.37
Orissa	2333	295	12.64	206	8.83
Karnataka	2004	1344	67.07	904	45.11
Jammu and Kashmir	1535	189	12.31	518	33.75
Assam	1247	12	0.96	12	0.96
Uttarakhand	1149	283	24.63	256	22.28
Others	10404	2573	24.73	2367	22.75

Table 4 Vulnerability Index for forested grid points in India

Forest diversity (monoculture vs. natural forest)	Forest crown density	Vegetation type change (IBIS projections)	Vulnerability Index	% of forest grids that fall into this vulnerability category (A2 scenario)
Yes	Low	Yes	7 (most vulnerable)	1.89
Yes	Medium	Yes	6	6.44
Yes	High	Yes	5	0.48
No	Low	Yes	4	11.61
No	Medium	Yes	3	18.16
No	High	Yes	2	0.68
Yes or No	Low or Medium or High	No	1 (least vulnerable)	60.75

the Ghats are likely caused by the negligible precipitation increase over there (with more than 3°C rise in temperature).Forests in the southern Western Ghats appear to be quite resilient as forests in this region are less fragmented, more diverse and they also support tropical wet evergreen forests which, according to IBIS simulations, are likely to remain stable.

6 Implications of climate impact assessment

We note that vulnerable forested grid points are spread across India. However, their concentration is higher in the upper Himalayan stretches, parts of central India, northern Western Ghats and Eastern Ghats. In contrast, northeastern forests, southern Western Ghats and the forested regions of eastern India are estimated to be least vulnerable.

6.1 Implications for afforestation and reforestation (A&R)

Currently, within the forested area of 69 Mha only 8.35 mha is categorized as very dense forest. More than 20 Mha of forest is monoculture and more than 28.8 mha of forests are fragmented (open forest) and have low tree density (FSI 2001; FSI 2009). Low tree density, low bio-diversity status as well as higher levels of fragmentation contribute to the vulnerability of these forests. It is very timely that Government of India under NAPCC (National Action Plan on Climate Change), has brought a proposal to afforest more than 6 Mha of degraded forested lands (Government of India 2008). We recommend that care should be taken to plant mixed species and planting should also be executed in such a way as to link the existing fragmented forests. Efforts should also be made to convert open forests to dense forests. Our analysis suggests that Western Ghats, though a bio-diversity hotspot, has fragmented forests in its northern parts. This makes these forests additionally vulnerable to climate change as well as to increased risk of fire and pest attack. Similarly, forests in parts of western as well as central India are fragmented and are having low bio-diversity. At the same time these are the regions which are likely to witness a high increase in temperature and either decline or marginal increase in rainfall.

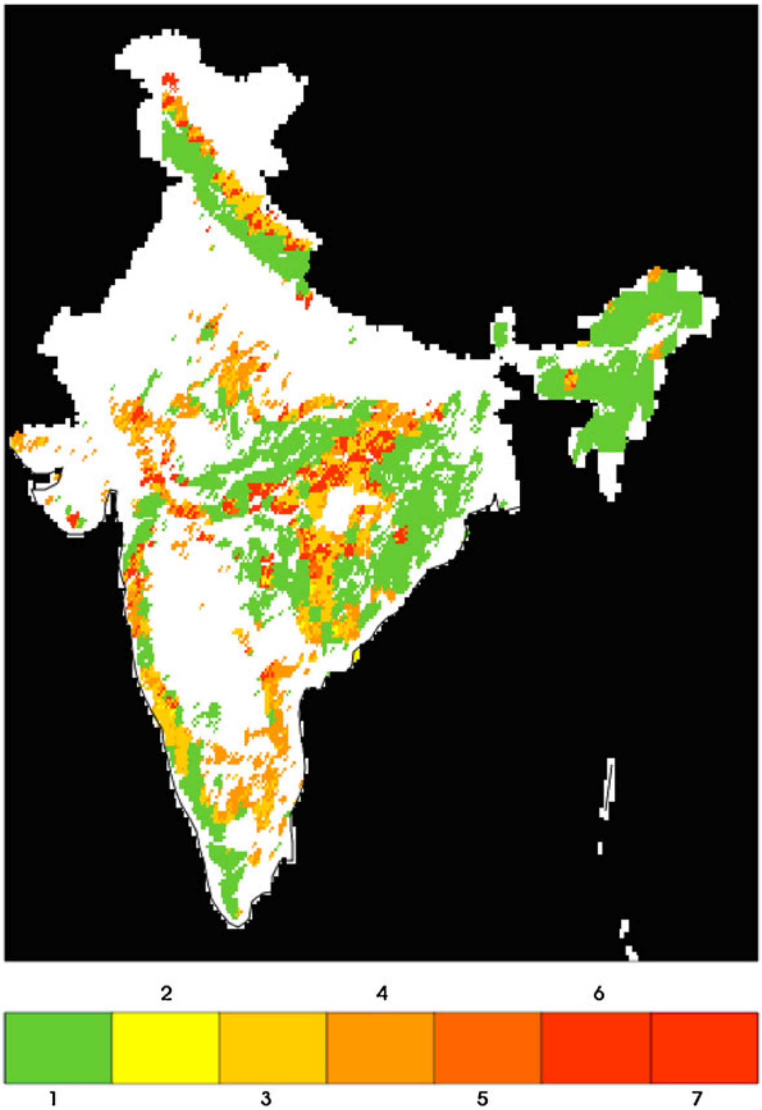

Fig. 18 Distribution of forest vulnerability index for A2 climate change scenario (for FSI forested grid points). Green colour indicates a vulnerability index of 1 (least vulnerable), while colours of yellow to red indicate increasing vulnerability with red indicating a vulnerability level of 7 (most vulnerable)

We notice that most of the mountainous forests (sub-alpine and alpine forest, the Himalayan dry temperate forest and the Himalayan moist temperate forests) are susceptible to the adverse effects of climate change (Fig. 12). This is because climate change is predicted to be larger for regions that have higher elevations. There is a need to explore win-win adaptation practices in such regions such as anticipatory plantations, sanitary harvest, and pest and fire management.

Forests are likely to benefit to a large extent (in terms of NPP) in the northern parts of Western Ghats and the eastern parts of India, while they are relatively adversely affected in western and central India (Fig. 14). This means that afforestation, reforestation and forest management in northern Western Ghats and eastern India may experience carbon sequestration benefits. Hence, in these regions, a species-mix that maximizes carbon sequestration should be planted. On the other hand, in the forests of western and central India, hardy species which are resilient to increased temperature and drought risk should be planted and care should be taken to further increase forest resilience. This may be achieved by planting mixed species, linking up forest fragmentations, devising effective pest and fire management strategies and carrying out anticipatory plantation activities.

6.2 Implication for forest conservation and REDD+

Northeastern forests, southern Western Ghats and Forests of eastern India are estimated to be least vulnerable. This is on account of their high biodiversity, low fragmentation, high tree density as well as low rates of vegetation change (as these regions experience lower levels of temperature increase and gain substantially in terms of precipitation). The resulting low vegetation vulnerability makes these regions especially suitable for reduced deforestation and forest conservation projects such as REDD+ (UNFCCC 2009). For example, northeastern India which has more than 80% of land area classified as forests is currently under severe pressure of deforestation. This region witnesses the highest rate of deforestation in India (65% of total deforestation in India over the period of 2005–2007), mainly due to encroachment and shifting cultivation (FSI 2009). Over the period 2005–2007, according to the latest FSI (2009), 201 km^2 in Nagaland, 119 km^2 in Arunachal Pradesh, 100 km^2 in Tripura and 66 km^2 in Assam were deforested. Given that the ecosystem in this region appears robust in the face of climate change, it is desirable to create REDD+ projects in this area to combat deforestation and resulting loss of flora.

7 Uncertainties, model and data limitations

There are a few notable limitations in this study. IBIS tends to simulate a fairly strong CO_2 fertilization effect (Cramer et al. 2001; McGuire et al. 2001) because IBIS does not have representation for nitrogen and other nutrient cycles (Cramer et al. 2001). It is known to over-predict grasslands (Bonan et al. 2003).

IBIS model, in its current form, does not include a dynamic fire module (Foley et al. 1996). It does not account for changes in pest attack in a changed climate. We believe that many of these limitations of the model have led to the overestimation of future NPP and SOC gains. Climate projections are currently not available in probabilistic terms, which currently limit us from presenting a probability based forest dynamics scenario for India.

There is uncertainty in climate projections, particularly in precipitation at down-scaled regional levels. Land-use change and other anthropogenic influences are not represented in the model projections. Effects of Afforestation and regeneration (e.g. on abandoned croplands or wastelands) on climate are also not taken into account.

Finally, due to lack of regional model predictions for short (2025) and medium term (2050), we could not provide policy relevant recommendations for short and medium periods. However, it is important to recognize the likely trends in the impacts, adopt win-win adaptation strategies and expand research programs to reduce uncertainties in climate projections and impacts of climate change in the forest sector.

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