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Carbon forestry economic mitigation potential in India, by land classification

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Abstract Carbon forestry mitigation potential estimates at the global-level are limited by the absence or simplicity of national-level estimates, and similarly national-level estimates are limited by absence of regional-level estimates. The present study aims to estimate the mitigation potential for a large diverse country such as India, based on the GTAP global land classification system of agro-ecological zones (AEZs), as well the Indian AEZ system. The study also estimates the implications of carbon price incentive (US$50 and $100) on mitigation potential in the short-, medium- and long-term, since afforestation and reforestation (A & R) is constrained by lack of investment and financial incentives. The mitigation potential for short and long rotation plantations and natural regeneration was estimated using the GCOMAP global forest model for two land area scenarios. One scenario included only wastelands (29 Mha), and the second enhanced area scenario, included wastelands plus long fallow and marginal croplands (54 Mha). Under the $100 carbon price case, significant additional area (3.6 Mha under the wasteland scenario and 6.4 Mha under the enhanced area scenario) and carbon mitigation is gained in the short-term (2025) compared to the baseline when using the GTAP land classification system. The area brought under A & R increases by 85–100% for the $100 carbon price compared to $50 carbon price in the short-term, indicating the effectiveness of higher carbon price incentives, especially in the short-term.

A comparison of estimates of mitigation potential using GTAP and Indian AEZ land classification systems showed that in the short-term, 35% additional C-stock gain is achieved in the $100 carbon price case in the enhanced area scenario of the

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Indian AEZ system. This difference highlights the role of the land classification system adopted in estimation of aggregate mitigation potential estimates, particularly in the short-term. Uncertainty involved in the estimates of national-level mitigation potential needs to be reduced, by generating reliable estimates of carbon stock gain and losses, and cost and benefit data, for land use sector mitigation options at a scale disaggregated enough to be relevant for national mitigation planning.

Keywords Mitigation potential · Carbon price · GTAP · AEZ · India · Forest mitigation

1 Introduction

The forest and land use sector has received significant attention globally in addressing the climate change problem. However, as evidenced by the Third Assessment Report (TAR) of IPCC, mitigation potential assessment in the land use change and forest (LUCF) sector has been limited by availability of information at the global-level, and by the lack of disggregation of mitigation potential at the national-level (IPCC 2001). This is particularly true for India since very few forest mitigation assessment studies have been published (Ravindranath et al. 2001; Ravindranath and Sathaye 2002), and no national forest-sector study prior to this one has used an economic model allowing dynamic interaction across land uses within the sector. Further, most mitigation potential assessments provide only technical potential estimates rather than economic or market or socio-economic potentials, which are likely to be a fraction of technical potential. The mitigation potential is assessed at the national-level often using only a few values for biomass or soil carbon sequestration rates, ignoring the regional variations in carbon sequestration rates due to diverse soil, rainfall and management practices. Studies such as Ravindranath and Somashekar (1995), Ravindranath et al. (2001), and Sathaye et al. (in press) have used single biomass growth or soil carbon accumulation rates for short- or long-rotation and other mitigation options, even though forestry options such as raising eucalyptus, a short-rotation species, occur in arid zones (<500 mm/annum rainfall) to humid zones (>2000 mm/annum rainfall).

Thus, more regional-level assessments of mitigation potential that can be aggregated to the national and ultimately to the global-level are required for policy makers and forest managers. In the emerging carbon market, carbon price is likely to be a critical determinant of LAND potentially available for additional afforestation and reforestation (A & R) for carbon sequestration. Few studies (outside the U.S.) have estimated the implications of carbon price on mitigation potential at the national-level. Studies by Sathaye et al. (in press) and Sohngen and Sedjo (in press), for example, have analyzed the sensitivity of global forest sector mitigation potential to carbon price variation, by mitigation activity and by region.

This study aims at estimating India's forestry mitigation potential at the regional-level, based on the agro-ecological zone concept, where the implications of carbon price changes on mitigation potential are assessed. The response of national governments, forest managers, private companies, and village communities is likely to be influenced by the price path of carbon prices over time. The study estimates the mitigation potential of A & R only, as two major forestry mitigation options in the literature (e.g., Brown et al. 2000) and being implemented in climate mitigation programs like the Clean Development Mechanism under the Kyoto Protocol. The study utilizes estimates of socio-economic potential land availability, since land projected as available according to official records or satellite assessments may not be actually available due to legal or tenurial problems, encroachment, or community requirements for degraded forest land for grazing, water storage, or settlement expansion.

The specific objectives addressed in the present study are to

- assess the current rate of A & R under the baseline scenario and the period required to exhaust the potential land available, since India has a large baseline rate of A & R
- estimate the mitigation or carbon sequestration potential under the baseline A & R scenario
- assess the implication of carbon price variation on land available for mitigation activities, rate of use of available land, carbon sequestration rates and mitigation potential at the regional-level aggregated to national-level using two land classification approaches:

GTAP (Global Trade Analysis Project) AEZ land classification system, and
Indian AEZ land classification system.

The land categories considered for assessing mitigation potential for A & R include wastelands as reported by NRSA (2005), and long fallow and marginal agricultural land as reported by the Ministry of Agriculture.

Wasteland is defined as ‘‘degraded land which can be brought under vegetative cover with reasonable effort, and which is currently under-utilized and deteriorating for lack of appropriate water and soil management or on account of natural causes. Wastelands can result from inherent/imposed disabilities such as location, environment, chemical and physical properties of the soil or financial or managerial constraints’’ (NRSA 2005). Fallow land includes both current fallow (cropped area kept fallow during the current year), and fallow land other than current fallow (temporarily out of cultivation for one-five years).

In the present study, two land availability scenarios are considered for estimating the mitigation potential under different carbon price cases. The selection of which lands are available for mitigation is a key driver of mitigation potential-levels. This analysis limits land availability to wastelands, long fallow, and marginal cropland (assumed to be 10% of cropland), and does not include lands categorized as forest land regardless of their current stocking-level, since felling in Reserve Forest lands is banned. Further, areas currently under forest are not likely to meet many additionality tests for eligibility for many GHG mitigation programs.

Wasteland (WL) scenario: Wasteland categories suitable for afforestation and reforestation are considered in the assessment. Of the total technical potential wasteland area available, only the socio-economic potential is considered for mitigation, based on the field studies as discussed in Sect. 3.3.

Wasteland + Long Fallow + Marginal Cropland (WL + LF + MC) scenario: Under this scenario, in addition to wasteland, long-term fallow and marginal cropland categories are also included for mitigation assessment. Current fallow land is excluded from the mitigation assessment, since this land would be cropped in the following year. Out of the total agriculture or cropped area, only 10% of the area is included in the mitigation assessment, considering marginal lands not ideally suitable for food production and can be profitably brought under tree crops or agroforestry. According to UNEP (1997), 110 Mha in India is degraded (about 57% of susceptible drylands), due to soil erosion, salinization and removal of nutrient-rich topsoil.

2 Approach, methods and GCOMAP model

The carbon price response of forest sector activities is assessed using a dynamic partial equilibrium model of the global forest sector, GCOMAP (Generalized Comprehensive Mitigation Assessment Process) (Sathaye et al. in press). Mitigation is assessed at the regional-level and aggregated to the national-level based on the GTAP AEZ global-level and the Indian AEZ national-level agro-ecological zoning approaches, as described in Box 1.

Box 1 Methodological steps in this analysis

Step 1: The spatial disggregation was obtained by overlaying GTAP global and Indian national AEZ zone maps on the district map of India. The districts were then allocated to each of the GTAP or Indian AEZs. Where a district appeared in more than one GTAP zone or AEZ, the geographic area of the district was allocated proportionately.

Step 2: *Wasteland scenario:* Area under different wasteland categories, based on the NRSA report (2005), was obtained at the district-level.

Step 3: *Wasteland + fallow land scenario:* Wasteland plus area under long fallow and 10% of net sown area (marginal agricultural land) was considered in this scenario. Data were obtained from the Ministry of Agriculture (Land Use Statistics at a Glance, 2001).

Step 4: Wasteland, long-term fallow, and marginal cropland suitable for A & R were identified and selected for three mitigation activities appropriate for their biophysical and social characteristics—short rotation (SR) forestation, long rotation (LR), and natural regeneration (NR). Land categories not suitable for A & R activities were excluded. For example, the NR option was included only for degraded forest lands under the control of state forest departments.

Step 5: The total technical potential area suitable for SR, LR and NR options under each GTAP zone was estimated using district-level wasteland, fallow, and cropland data:
Geographic area of India was spatially divided into 12 GTAP zones present in India
The district map of India was overlaid on the GTAP zones
Area under wastelands, fallow land and marginal cropland suitable for A & R was estimated for each of the GTAP zones using the district-level statistics.

Step 6: Socio-economic potential area for A & R activities was obtained based on estimates of previous studies applied nationally.

Step 7: Allocation of socio-economic potential area for SR and LR was made using the area planted under different species (both SR and LR) at the national-level. The area under NR was allocated only to the suitable wasteland categories in two of the dominant (maximum area) GTAP and Indian AEZs (refer to Sects. 3.4 and 3.5).

Step 8: Biomass and soil carbon stocks and growth rates were obtained from published literature and reports for different GTAP and Indian AEZs, for SR, LR and NR activities

Step 9: Cost and benefit data were obtained from reports of the Forest Department and Ministry of Environment and Forests as well as field studies, for different mitigation activities and GTAP zones.

Step 10: GCOMAP model was used to estimate the implications of various carbon price cases on carbon mitigation potential of SR, LR and NR activities.

Step 11: The carbon stock (C-stock) estimates for different periods for the baseline as well as different carbon price cases, and the net additional C-stock changes, were estimated using GCOMAP model outputs.

Step 12: The C-stock estimates of GTAP and Indian AEZ approaches were compared to study the suitability of adopting global zonal land classification approaches for national or sub-national assessments.

2.1 GTAP AEZ-based land classification

At the global-level, GTAP categorizes land into 18 zones, based on the FAO/IIASA convention of agro-ecological zoning (FAO/IIASA 1993, and Lee at al. 2005). Among the 18 GTAP zones (Table 1 and Fig. 1a), 6 boreal forest zones do not occur in India and are excluded. The dominant tropical GTAP AEZs are of critical importance to India. A critical factor distinguishing the GTAP AEZs is mean annual rainfall, dividing them into arid, semiarid, sub-humid, and humid.

2.2 Indian AEZ-based land classification for regional-level assessment

India is a large country with diverse temperature, rainfall, soil, vegetation type, tenurial and socio-economic conditions. India has adopted the principles of AEZ and developed its own methods to classify land. The AEZ categorization is based on the length of growing period (LGP) concept, derived from climate, soil, and topography data with a water balance model and knowledge of crop requirements (Sehgal et al. 1992, and FAO/IIASA 1993). LGP refers to the period during the year when both soil moisture and temperature are conducive to plant growth. The AEZ approach has been adopted globally for assessing the growth potential of crops, and can be extended to growth of forest or plantation biomass (e.g., Lee et al. 2005). India's geographic area is divided into 20 AEZs based on moisture and temperature regimes, soil type, land form, etc., described in Table 2 and Fig. 1b.

2.3 Overlay and comparison of Global GTAP and Indian AEZ land classification systems

When the GTAP and Indian AEZs for India are compared (Fig. 1c), only about 3% of the geographic area has an overlap of 75–100%, followed by 10% of area with an overlap of 50–75% and 27% with 25–50% overlap. The remaining 60% of the geographic area had less than 25% overlap. Thus, there is limited overlap between the two approaches of land classification, with fully 97% of the area having less than 75% overlap. The carbon mitigation potential is estimated separately for global GTAP and Indian AEZ classification of lands, since the mitigation potential may vary across AEZs and the land classification systems.

Table 1 Features of the 12 GTAP AEZs occurring in India

GTAP AEZ zones	Name of the zone	Features (Length of growing period (LGP))
1	Tropical arid	LGP < 59 days
2	Tropical dry semiarid	LGP 60–119 days
3	Tropical moist semiarid	LGP 120–179 days
4	Tropical sub-humid	LGP 180–239 days
5	Tropical humid	LGP 240–299 days
6	Tropical humid	LGP > 300 days
7	Temperate arid	LGP < 59 days
8	Temperate dry semiarid	LGP 60–119 days
9	Temperate moist semiarid	LGP 120–179 days
10	Temperate sub-humid	LGP 180–239 days
11	Temperate humid	LGP 240–299 days
12	Temperate humid	LGP > 300 days

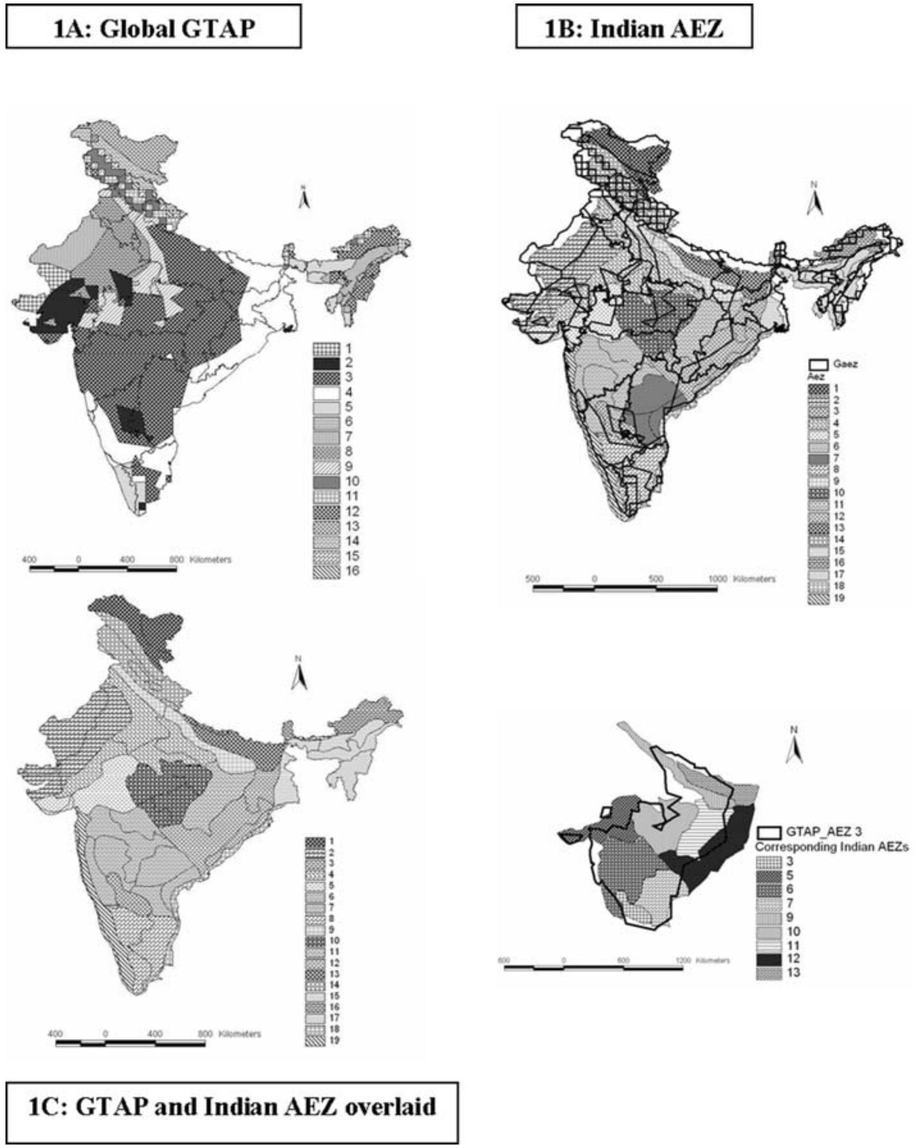

Fig. 1 GTAP AEZs (**a**), Indian AEZs (**b**) and overlay of the two land classification systems (**c**)

2.4 GCOMAP model

The model establishes a baseline scenario of land used for potential mitigation activities with no price for carbon for 2005–2100. The model then imposes a carbon price, and simulates the response of forest and wasteland users to these price incentives, and estimates additional land brought under the mitigation activity above the baseline-level. Next the model estimates the net changes in C-stocks, while meeting the annual demand for timber and non-timber products.

Table 2 Features of Indian AEZs

Zone No.	Indian AEZ zone	Features
1	Western Himalaya, cold arid eco-region	Cold arid climate, low AWC (60–90 days)
2	Western Plain Kutch and part of Kathiawar peninsula	Hot hyper arid climate, very low AWC (60–90 days)
3	Deccan Plateau, hot arid ecoregion	Hot arid climate, low to medium AWC (60–90 days)
4	Northern Plain and Central Highlands including Aravalis	Hot semi-arid climate, medium AWC (90–120 days)
5	Central Highlands (Malwa), Gujarat Plain and Kathiawar Peninsula	Hot moist semi-arid climate, medium to high AWC (120–150 days)
6	Deccan Plateau, hot semi-arid ecoregion	Hot moist semi-arid climate, medium to high AWC (150–180 days)
7	Deccan Plateau (Telangana) and Eastern Ghats	Hot moist semi-arid climate, medium AWC (150–180 days)
8	Eastern Ghats and Tamilnadu uplands and Deccan (Karnataka) Plateau	Hot moist semi-arid climate, low AWC (120–150 days)
9	Northern Plain, hot sub-humid (dry) ecoregion	Hot dry sub humid climate, medium to high AWC (150–180 days)
10	Central highlands (Malwa and Bundelkhand)	Hot arid climate, low to medium AWC (60–90 days)
11	Eastern Plateau (Chattisgarh)	Hot moist climate, medium AWC (150–180 days)
12	Eastern Plateau (Chota Nagpur)	Hot moist sub humid climate, low to medium AWC (180–210 days)
13	Eastern Plain, hot sub-humid	Hot dry to moist sub humid climate, low to medium AWC (180–120 days)
14	Western Himalaya	Warm moist to dry sub humid climate, medium AWC (150–210 days)
15	Assam and Bengal Plain	Hot moist to dry sub humid climate, medium to high AWC (210–240 days)
16	Eastern Himalaya	Warm to hot perhumid climate, low to medium AWC (>300 days)
17	Northeastern Hills (Purvanchal)	Warm to hot moist humid to perhumid climate, medium AWC (270–300+ days)
18	Eastern Coastal Plain	Hot moist semi-arid climate, high AWC (120–150 days)
19	Western Ghats and Coastal Plains	Hot moist sub-humid to humid transitional climate, low to medium AWC (210–270 days)
20	Island region	Excluded, since they are small islands separated by oceans

Note: AWC = Available Water Capacity

Source: Sehgal et al. (1992)

The GCOMAP model includes three modules (Sathaye et al. in press). First, the land use pattern in the baseline is described using input data on biophysical characteristics, including biomass yield, carbon content of biomass and soils, percent share of products, etc. The first module computes the annual changes in carbon stock over a 100-year period, and tracks both accumulation of carbon and its release due to the decay of vegetation and products separately on lands planted each year. The second module simultaneously computes the financial viability of the forestry option, using input data on fixed and variable costs, and product prices. The third module of the model then estimates the changes in land use under a carbon price scenario. The financial rate of return is maintained the same as in the baseline scenario, which decides the additional land area to be planted in the mitigation case each year. The first module is then rerun to compute the annual changes in carbon stock brought about by the change in mitigation land use. Finally, the model computes the difference in carbon stocks between the mitigation and baseline cases, and reports the carbon and land area gain for each decade.

2.5 Carbon prices for mitigation assessment

The baseline and two C-price cases are considered: US$50 per tC and $100 per tC. The baseline scenario represents the current rate of forestation in different zones, projected to continue, since in India the rate of afforestation has remained within a narrow range of 1–1.25 million hectares per year over the past 20 years. Relatively higher carbon price cases are considered, since the price may increase with the emergence of organized carbon markets in the years to come.

2.6 Carbon pools selected

Four of the five carbon pools identified by the UNFCCC Marrakech Accord are assessed using GCOMAP, including aboveground biomass (AGB), belowground biomass (BGB, through an expansion factor, litter, and soil organic carbon (SOC); dead wood (DW) is not included.

Data for mitigation assessment: Adoption of the GTAP/AEZ land classification-based assessment approach and the GCOMAP model required the following data at the zone-level:

- *Area data:* total available land, baseline annual land area planted (short rotation (SR), long rotation (LR) and natural regeneration (NR)) and land area available for mitigation activities;
- *Biomass and soil carbon data;* standing vegetation, mean annual increment of biomass, wood density, rotation period, initial soil C-stock and soil carbon accumulation rate, litter as percent of mean annual increment, decomposition period, percent of mean annual increment as timber, harvest categories and percent of timber, wood waste, fuelwood and harvest residue;
- *Financial inputs:* establishment, land, recurrent, harvest, transportation and monitoring costs, price of timber, fuelwood and non-timber products.

An attempt was made to obtain the data required for GCOMAP at the GTAP zone and Indian AEZ-level. Over 150 studies and reports were reviewed and biomass and soil carbon data was compiled separately for GTAP and Indian AEZ locations, but availability of data on area, biomass, soil carbon, and financial inputs is limited at the GTAP zone and Indian AEZ-level. The data were input into GCOMAP under both land classifications, and vary from zone to zone under both systems. As an illustration, the mean annual biomass increment data input into the model for analysis are given in Appendix 1.

3 Land available for mitigation

3.1 Land categories for mitigation assessment—wastelands

The important land use systems in India include cropland, fallow land, forestland, grassland and wasteland. The wastelands include degraded grasslands, forests and several other categories. Wastelands in India are classified into 28 categories by National Remote Sensing Agency (NRSA 2005), but 8 have been excluded (e.g., lands affected by salinity) as not suitable for forestry activities, and some of the remaining categories have been merged. The resulting nine land categories totaling 37.9 million ha were assessed, importantly including land with scrub (16.2 million ha), degraded forest-scrub dominated (12.2 million ha), and land without scrub (3.9 million ha).

In India, long-term fallow land has stabilized at around 8–10 Mha over the past 30 years (Annual Reports of Ministry of Agriculture), and these lands are considered for A & R mitigation activities. Current fallow land is not included, since it may be brought under crops during the following year. Further, 10% of the cropland area is also included for SR and LR mitigation assessment, using identical species and silvicultural practices as those adopted on wastelands.

3.2 GTAP and Indian AEZ land classification for mitigation analysis

The 18 GTAP zones are merged into seven broad GTAP zones for India. Six zones falling in the boreal category do not occur in India; zones 5 and 6 (tropical humid), zones 10–16, (temperate sub-humid to humid), and arid zones 1, 7, and 8 (tropical and temperate) are merged into single zones for this analysis. Zones with very small land area and identical AEZ features are merged, mainly due to lack of data. The large GTAP zones such as Tropical dry semiarid (Zone 2), Tropical moist semiarid (Zone 3), Tropical sub-humid (Zone 4) and Temperate moist semiarid (Zone 9) are retained (Table 3) as individual zones. The wasteland categories are also merged based on suitability of land for forestry mitigation and soil and rainfall features. Different wasteland categories and their area are allocated to GTAP zones by overlaying a district map of India and using NRSA statistics on wastelands at the district-level. The details of area under technical and socio-economic potential and allocation of land to different forestry mitigation activities in various GTAP zones are given in Table 3. The Tropical moist semiarid and sub-humid zones (3 and 4) dominate by accounting for 54% of the total potential area. Similarly the 20 Indian AEZs were merged to obtain 10 zones for analysis (Table 3).

3.3 Socio-economic potential land availability for mitigation

Many mitigation assessment studies at the national and global-level estimate the technical mitigation potential, assuming that all the potential land within a category is available for mitigation activities. These estimates are based on government records, national statistics, wasteland statistics, and satellite imagery data. However, in reality all such land may not be available due to a number of barriers, such as tenurial status, encroachment, and land required for grazing or other use. Currently, no national-level studies for India are available to show what percent of wastelands

Table 3 Socio-economic potential land for mitigation activities and allocation of land for SR, LR and NR according to GTAP and Indian AEZ land classifications

	Zone	Technical potential ('000 ha)	Socio-economic potential ('000 ha)	Allocation of socio-economic potential to different options ('000 ha)		
				Short rotation	Long rotation	Natural regeneration
GTAP	*WL scenario*[a]					
	1, 7, 8	9443	6610	4363	2247	
	2	2837	1986	1311	675	
	3	13,683	9578	3161	1628	4789
	4	5045	3532	1166	600	1766
	5, 6	1729	1210	79	412	
	9	3203	2242	1480	762	
	10–16	5683	3978	2625	1352	
	Total	41,623	29,136	14,905	7676	6555
	WL +LF + MC scenario[b]					
	1, 7, 8	41,703	11,839	7814	4025	
	2	15,276	3308	2183	1125	
	3	101,193	21,121	6970	3591	10,560
	4	30,834	7437	2454	1264	3718
	5, 6	13,981	2367	1563	805	
	9	10,361	3279	2164	1115	
	10–16	16,277	4366	2881	1484	
	Total	229,625	53,717	26,029	13,409	14,278
Indian AEZ	*WL scenario*[a]					
	1 & 14	6103	4282	2826	1456	
	2	2027	1419	468	241	709
	3, 6, 7	3723	2606	1341	691	574
	4, 9, 13	9953	6967	4598	2367	
	5	2345	1641	1083	558	
	8 & 19	5040	3528	1164	600	1764
	10	1989	1392	919	473	
	11 & 12	4807	3365	1110	572	1682
	15, 16, 17	5242	3660	1211	624	1826
	18	394	276	184	94	
	Total	41,623	29,136	14,905	7676	6555
	WL + LF + MC scenario[b]					
	1 & 14	21,326	5072	3348	1725	
	2	22,837	5359	1841	1050	2541
	3, 6, 7	32,821	7256	2588	1234	3489
	4, 9, 13	56,458	11,974	7903	4028	
	5	8468	2629	1735	894	
	8 & 19	28,142	6707	2213	1140	3215
	10	11,605	3225	2129	1096	
	11 & 12	22,253	5588	1844	950	2655
	15, 16, 17	21,147	5038	1662	997	2378
	18	4568	869	766	295	
	Total	229,625	53,717	26,029	13,409	14,278

[a] Technical potential includes all wastelands suitable for A & R

[b] Technical potential includes all wasteland area, all fallow land area (current as well as long-term fallow) and net cropped (sown) area

estimated by NRSA or land survey statistics are actually available. According to two studies conducted in Karnataka state in South India, nearly two-thirds of the technical potential land is available for mitigation activities (Sudha et al. 2006; Ravindranath et al. 2006). This socio-economic potential land availability was estimated through a group discussion with the sample village communities, to estimate the extent of land they would like to dedicate for A & R, considering competing needs for grazing, settlement expansion, water bodies, etc. We then applied the Karnataka district findings nationally (the only data available), and assume that about 70% of technical potential area is available for forestry mitigation activities, or 29.1 Mha out of 41.6 Mha (Table 3). The maximum potential of 41.6 Mha in principle could be available for A & R activities, if the carbon price incentives were high and policy and institutional barriers were overcome.

For the WL + LF + MC scenario, the socio-economic potential wastelands plus the area under LF as well as 10% of net sown area or MC is considered for analysis. Of the total technical potential area of 229 Mha, only about 54 Mha or 24% has been considered as available for assessment, to ensure adequate cropland is available to meet India's future food requirements.

3.4 Activities selected for mitigation assessment

The current assessment is limited to only wastelands under the control of state forest and land revenue departments and village communities, and a fraction of long-term fallow and marginal cropland under the control of individual farmers. Mitigation activities suitable for such land categories are given in Table 4.

3.5 Allocation of land for different mitigation activities

Allocation of land to different mitigation activities is based on species planted in A & R in the past (FSI 1999) and previous studies (Ravindranath et al. 2001). The

Table 4 Mitigation activities and their features

Activity	Dominant species	Rotation period (years)	End uses
Short rotation (SR)	*Eucalyptus* spp. *Casuarina* spp. *Acacia* spp. *Gmelina arborea*	7	Fuelwood, industrial wood, poles—with harvest
Long rotation (LR)	*Tectona grandis* *Shorea robusta* *Dalbergia sissoo* *Pinus* spp.	40	Timber for construction and furniture—with harvest
Natural regeneration (NR)	Promotion of native vegetation such as *Shorea robusta*, *Tectona grandis*, *Terminalia* spp, *Acacia nilotica* etc.	50	Non-timber wood products, biodiversity conservation, with harvest

share of SR in all the zones is assumed to be two-thirds, and of LR, one-third, even though the share are likely to vary across AEZs. However, due to lack of historical, current or proposed A & R planting pattern data in different AEZs, this study has assumed these identical proportions under SR and LR for all AEZs. In wasteland categories such as land with scrub and degraded forest dominated by scrub, the NR option is considered, and 50% of these lands is allocated to NR, and 50% apportioned to SR and LR at two-thirds and one-third, respectively (Table 5). Most of the fallow land and marginal cropland is allocated to SR and LR, largely for commercial purposes.

4 Baseline scenario: past and current A & R rates

The baseline scenario A & R rates are identical for WL as well as WL + LF + MC scenarios under the GTAP as well as Indian AEZ classifications (Table 5). This can be justified based on stable area under long fallow and net sown area. India has been implementing a large afforestation and reforestation program since 1980; annually between 1.00 and 1.25 Mha/year are brought under tree cover. The total area afforested in India since 1980 is over 30 Mha. Figure 2 shows that the mean annual rate of afforestation has been around 1.16 Mha/year based on the latest report of the Ministry of Environment and Forests (MoEF 2004), and has remained stable since 1980.

The allocation of total A & R area to different zones is based on the proportion of each GTAP or Indian AEZ category to the total wasteland area. Allocation of land area to SR, LR and NR is given in Table 5 (for explanation, see Sect. 3.5).

Table 5 Mean annual area (‘000 ha/year) brought under SR, LR and NR in the baseline scenario, according to GTAP and Indian AEZ systems

Zone	Short rotation	Long rotation	Natural regeneration	Total
GTAP				
1, 7, 8	86.8	44.7		131.5
2	260.9	13.4		39.5
3	125.8	64.8	290.0	480.6
4	46.4	23.9	290.0	360.3
5, 6	15.9	8.1		24.0
9	29.4	15.1		44.6
10–16	52.2	26.9		79.1
Total	382.8	197.2	580.0	1160.0
Indian AEZ				
1 & 14	56.2	29.0		85.2
2	18.6	9.6	290.0	318.2
3, 6, 7	34.2	17.6		51.9
4, 9, 13	91.5	47.1		138.6
5	21.6	11.1		32.7
8 & 19	46.3	23.9		70.2
10	18.3	9.4		27.7
11 & 12	44.2	22.8	290.0	357.0
15, 16, 17	48.2	24.8		73.0
18	3.6	1.9		5.5
Total	382.8	197.2	580.0	1160.0

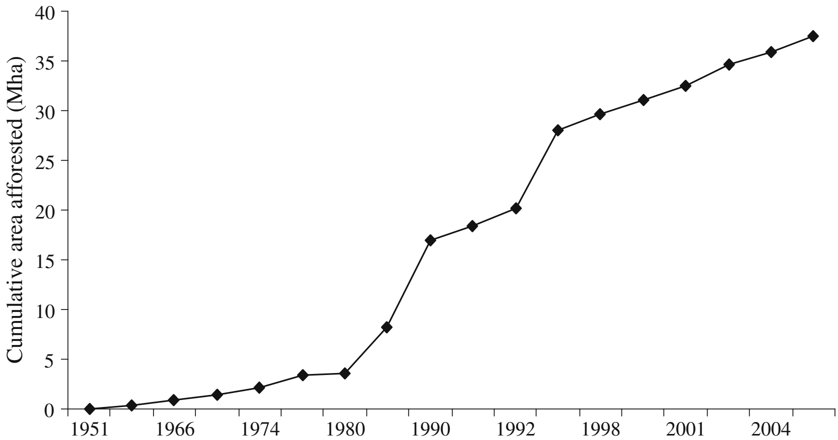

Fig. 2 Cumulative area afforested in India for the period 1951 to 2005

5 Projection of rate of coverage under A & R baseline scenario

5.1 Wasteland area scenario (Wl)

Since India has a large A & R program, it is necessary to project the rate of A & R area into the future under the baseline scenario, to determine land available for additional A & R mitigation activities. Land area projected to be brought under SR, LR and NR under the baseline for the WL scenario, is estimated and aggregated to the national-level (Fig. 3), identical for the GTAP and Indian AEZ systems. Under the baseline, all potential wasteland categories in this analysis available will be exhausted by around 2050.

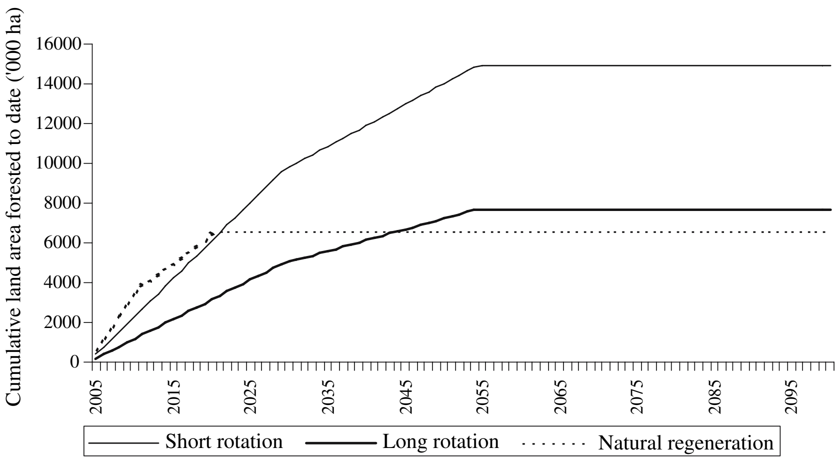

Fig. 3 Rate of A & R (SR, LR and NR) under baseline in WL land area scenario

5.2 Enhanced land area scenario (WL + LF + MC)

Under the baseline, when long fallow and marginal cropland is considered in addition to wasteland (WL + LF + MC scenario), land will still be available for A & R under SR even after 100 years (Fig. 4). Under LR, all area available for A & R is exhausted by 2097. All land dedicated for NR will be afforested by 2041. Figure 4 is identical for GTAP as well as Indian AEZ land classification systems.

Two main implications emerge from Figs. 3 and 4. One option to exploit the additional mitigation potential of A & R under both WL and WL + LF + MC scenarios is to significantly enhance the rate of A & R under the mitigation scenarios, to derive carbon benefits early for mitigation of climate change. Another implication is that different land categories have very different baseline rates of land use, due to driver variables and trends already in effect. GHG mitigation programs and the market thus need to identify which land categories can be brought more quickly or in greater area into which mitigation options and concentrate their efforts to reduce barriers and increase incentives there. This approach may help maximize mitigation potential in the near- and mid-term.

6 Rate of A & R for different carbon price cases under GTAP and Indian AEZ systems

The rate of land brought under A & R in India in the baseline scenario and the period when all potential land is exhausted is largely determined by two key barriers—government land use and economic policies, and investment capital availability (Ravindranath and Somashekar 1995; Ravindranath et al. 2001). Further, some A & R options have a low Internal Rate of Return (Ravindranath et al. 2001). In India, A & R programs are promoted more for their social (such as meeting

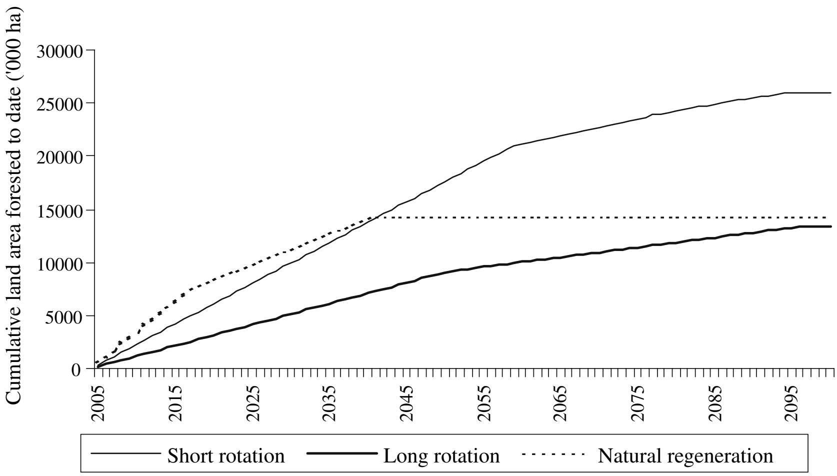

Fig. 4 Rate of A & R (SR, LR and NR) under baseline in WL + LF + MC land area scenario

fuelwood requirement) and environmental (forest conservation) benefits. Enhancement of the rate of A & R would require financial incentives, which carbon prices may offer.

6.1 Incremental area brought under A & R in the US$50 and $100 carbon price cases in the short-term

6.1.1 GTAP land classification

Table 6 illustrates that when only wastelands are considered (WL scenario), the annual additional area brought under $50 and $100 carbon price cases in the short-term year 2025 (after 20 years) is 98,210 ha/year and 183,120 ha/year, respectively, over the baseline rate of A & R. But when fallow lands and marginal croplands are considered along with wastelands (WL + LF + MC scenario), 161,194 ha/year and 322,755 ha/year of additional area will be brought under A & R annually in the $50 and $100 carbon price cases, respectively, during the short-term—a significant increase.

6.1.2 Indian AEZ land classification

A similar trend is observed under the Indian AEZ land classification systems. The cumulative area is higher than the baseline by 11 and 19% for the WL scenario for the $50 and $100 carbon price cases, respectively, and the values are 18 and 27% higher than the baseline for WL + LF + MC scenario.

Thus in the short-term, carbon price incentive of US$50 or $100 brings large additional area under A & R compared to the baseline. The higher carbon price of $100 brings 52–100% additional area under A & R over the lower carbon price of $50 in the short-term under the two land use systems and area scenarios.

6.2 Comparison of A & R rates under WL and WL+LF+MC land area scenarios for US$50 and $100 carbon price

6.2.1 GTAP land classification

Figure 5 demonstrates that under the $100 carbon price case, the area under SR will be exhausted 2 years ahead and will peak by 2051. Similarly, there is only a 3-year difference between $50 and $100 carbon price cases for LR and there is a 4-year difference

Table 6 Cumulative additional area ('000 ha) brought under A & R during 2005–2025, in the baseline scenario, under two carbon price cases for GTAP and Indian AEZ land classifications

Land classification	Scenario	Cumulative additional area brought under A & R, 2005–25 ('000 ha)	
		US$50 Carbon price	US$100 Carbon price
GTAP	WL scenario	1964	3662
	WL + LF + MC scenario	3224	6455
Indian AEZ	WL scenario	2048	3475
	WL + LF + MC scenario	4354	6626

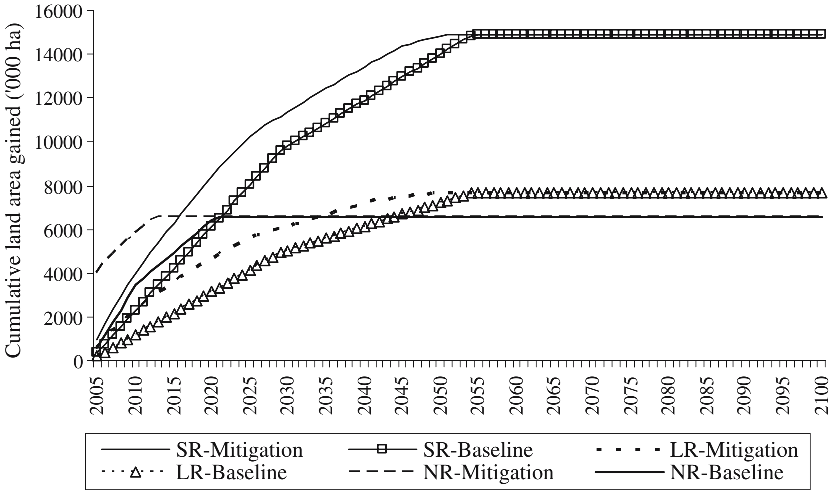

Fig. 5 Cumulative land area brought under A & R under $100 carbon price case in WL scenario under GTAP land classification

for NR between the two carbon price cases. Under the WL+LF+MC land area scenario (Fig. 6), the area under both SR and LR will peak near the end of the analysis around 2091, with only 2–3 years difference between the two carbon price cases.

However, when the short-term date of 2025 (20 years out) is considered, additional area brought under SR and LR is around 2.2 and 1.3 Mha, respectively under WL as well as WL + LF + MC land area scenarios with a carbon price of $100; for $50, the values are 1.2 Mha and 0.7 Mha. This indicates that on an average, an

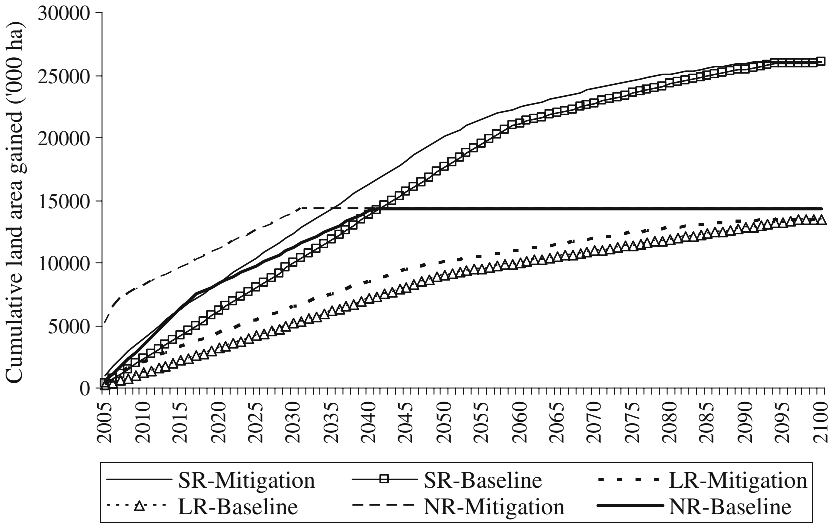

Fig. 6 Cumulative land area brought under A & R under $100 carbon price case in WL + LF + MC land area scenario under GTAP land classification

annual additional area of about 185,000 ha for a carbon price of $100 will be brought under A & R over the baseline scenario rates.

6.2.2 *Indian AEZ land classification*

Area brought under SR under the WL area scenario increases annually and peaks during the period 2050–2053 under the two carbon price cases (Fig. 7). With a higher carbon price of $100, the area under SR will be exhausted by 2050, just 5 years ahead of $50 carbon price. For the LR option, all land is exhausted about 7 years earlier in the higher carbon price case. However, in WL + LF + MC land area scenario, with significant additional area available, the area afforested under SR and LR increases annually, and all land will be exhausted by around 2090 under the higher carbon price case (Fig. 8). Under the $50 carbon price case, SR land still remains after 2100, while LR land is exhausted by 2092.

The main observation is that significant additional area will be brought under A & R over the baseline rates when a $50 carbon price incentive is considered. However, the difference between $50 and $100 is marginal. This indicates that increasing the carbon price incentive from $50 to $100 enhances the rate of A & R only marginally over the long term, but brings significant additional area in the initial 20 years.

7 Mitigation potential assessment under GTAP and Indian AEZ land classifications

7.1 Mitigation potential per hectare by AEZ

When mitigation potential to 2025 is considered for the GTAP AEZs, SR carbon stocks vary from 67 tC/ha in tropical moist semiarid (zone 3) to 100 tC/ha for the

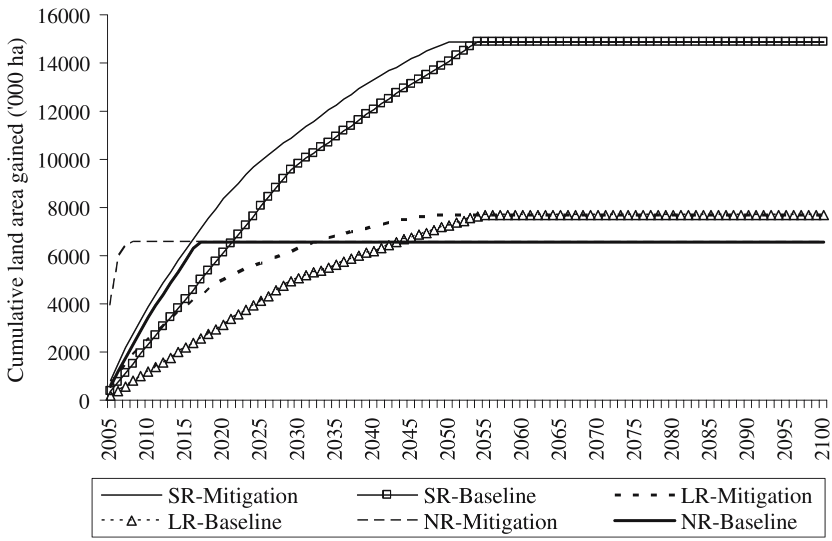

Fig. 7 Cumulative land area brought under A & R under $100 carbon price case in WL scenario under Indian AEZ land classification

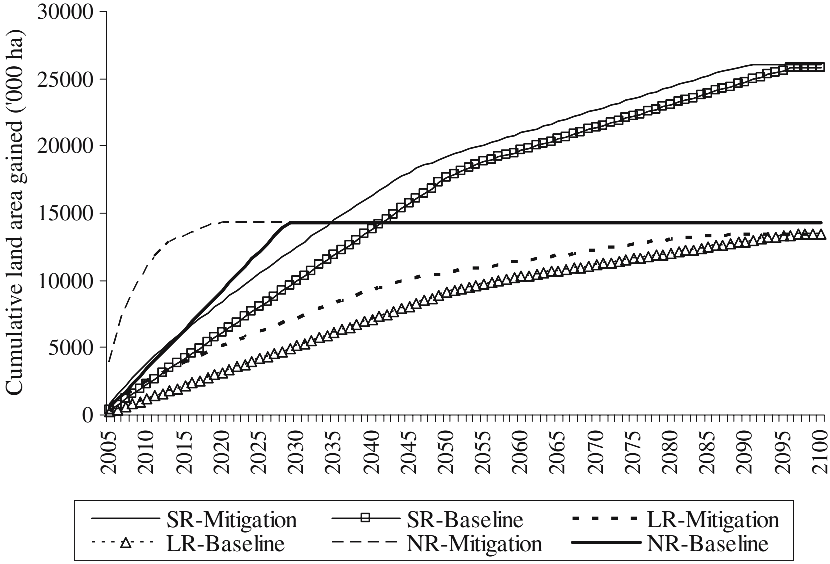

Fig. 8 Cumulative land area brought under A & R under $100 carbon price case in WL + LF + MC land area scenario under Indian AEZ land classification

combined temperate sub-humid to humid zones (zones 10–16). This indicates significant difference in mitigation potential across GTAP AEZs (Table 7). Similarly when LR is considered, the variation in the mitigation potential is 72–116 tC/ha across the GTAP AEZs, and a parallel trend occurs for Indian AEZs (Table 7). This variability indicates the need for disaggregated analysis for mitigation potential assessment, using an approach such as the AEZ.

Table 7 Cumulative carbon stocks per ha by GTAP and Indian AEZs, for $100 carbon price case, WL scenario, to 2025, in tC/ha

Zone	Short rotation	Long rotation	Natural regeneration
GTAP AEZs			
1, 7, 8	98	103	
2	84	86	
3	67	72	85
4	68	85	93
5 & 6	80	95	
9	85	88	
10–16	100	116	
Indian AEZs			
1 & 14	94	116	
2	63	86	89
3, 6, 7	74	79	88
4, 9, 13	101	118	
5	85	88	
8 & 19	67	58	71
10	80	86	
11 & 12	57	84	89
15, 16, 17	80	84	89
18	67	76	

7.2 Implications of carbon price on mitigation potential

Carbon stock gain under $50 and $100 carbon prices, aggregated for all the three mitigation options for the WL and WL + LF + MC land area scenarios, in the short-term (2005–2025), is given in Table 8. The mitigation potential under the GTAP land classification WL scenario increased by about 84% as the carbon price doubled from $50 to $100. This trend holds for the Indian AEZ WL and enhanced area scenarios. Thus a higher carbon price will bring significant additional area (Table 8) as well as increase the mitigation potential (68–90%) in the short-term.

It is interesting to note that in the enhanced area scenario at $100 carbon price, even though the area increased marginally by around 3% in the Indian AEZs compared to the GTAP AEZs (Table 6), the carbon stock increased by 35% during the same period. This could be due to higher-levels of disaggregation in the Indian AEZ system with differential biomass and soil carbon increment rates (discussed in detail in Sect. 8).

7.3 Carbon stock gain under WL and WL+LF+MC Land area scenarios

The total socio-economic potential area available for A & R is 29 Mha under WL scenario and 54 Mha (85% higher) under the WL + LF + MC scenario.

7.3.1 GTAP

When the two land area scenarios are considered, the aggregate additional carbon stock gained in the baseline by adopting the WL + LF + MC enhanced area scenario is 960 MtC for the short term to 2025, and 2930 MtC in the long term to 2100, in the WL scenario. Under the $100 carbon price case, the values are 1045 MtC and 1492 MtC, respectively, for the same time periods (Table 9). For an 85% increase in area under the WL + LF + MC land area scenario, the additional carbon stock gained in the short term is 54% higher compared to the WL scenario, and 81% higher in the long term.

7.3.2 Indian AEZ

The additional carbon stock gained in the enhanced land area scenario, using the Indian AEZ system, cumulative to 2025, is 1181 MtC. By 2100, it reaches 3218 MtC under the $100 carbon price mitigation scenario (Table 9).

Table 8 Incremental mitigation potential under $50 and $100 carbon price cases in the short-term period to 2025, under two land classification systems

Land classification system	Scenario	Incremental mitigation potential for the period 2005–2025 (MtC)	
		US$50 Carbon price	US$100 Carbon price
GTAP	WL scenario	129	238
	WL + LF + MC scenario	170	323
Indian AEZ	WL scenario	139	234
	WL + LF + MC scenario	244	435

Table 9 Comparison of cumulative carbon stocks (MtC) gained between WL and WL + LF + MC land area scenarios under the baseline and $100 carbon price mitigation case for GTAP and Indian AEZ systems

	2005	2025	2045	2065	2085	2100
GTAP—WL scenario						
Baseline	1134	1686	2531	3170	3663	3881
Mitigation	1112	1924	2813	3301	3777	3950
Increment	–21	238	282	131	114	69
GTAP—WL + LF + MC scenario						
Baseline	2022	2645	3837	5063	6129	6811
Mitigation	2035	2969	4305	5469	6519	7137
Increment	13	323	469	406	391	326
Indian AEZ—WL scenario						
Baseline	1122	1652	2474	3097	3570	3763
Mitigation	1110	1886	2757	3230	3685	3821
Increment	–12	234	283	133	116	58
Indian AEZ—WL + LF + MC scenario						
Baseline	2064	2631	3832	4972	6045	6696
Mitigation	2058	3067	4413	5464	6530	7039
Increment	–6	435	582	492	485	343

Thus, India could gain significant additional mitigation potential of 257 MtC (under GTAP) to 285 MtC (under Indian AEZ), if fallow land and marginal cropland are brought under A & R in addition to wastelands under a $100 carbon price scenario.

7.4 Comparison of national aggregate mitigation potential with disaggregated AEZ estimates

There are very few studies conducted at the national-level in India estimating the mitigation potential. Further, the area, growth rates of biomass and soil carbon considered differ among the studies. However, a preliminary comparison between this study and Ravindranath et al. 2001, with comparable area and for a period of 30 years, shows the mitigation potential under the disaggregated GTAP AEZ is only about half of the estimate of Ravindranath et al. 2001 (Table 10). National mitigation potential estimates, therefore, could vary significantly depending on the-level of aggregation, area eligible, and growth rates considered.

8 Comparison of mitigation potential under GTAP and Indian AEZ land classification systems

One of the objectives of this analysis is to compare the mitigation potential obtained using the global GTAP and Indian AEZ land classification systems. The total land area under the two systems is identical, and the allocation pattern of land to the different mitigation options is similar. However, the spatial overlap between the GTAP zones and the Indian AEZs is low (Sect. 2). Further, the aboveground

Table 10 Comparison of estimates of Indian forestry mitigation potential across aggregate national and disaggregated AEZ-based estimates, using different methods (cumulative MtC by year given)

Mitigation options	This study: $100/tC, 30-year period, for two land classification systems, WL scenario 2005–2035		This study: $100/tC, 30-year period, for two land classification systems, WL + LF + - MC scenario 2005–2035		Sathya et al. (in press): $100, 2000–2030, GCOMAP National model	Ravindranath et al. (2001): 30-year period	Sohngen and Sedjo, in press): $100/tC, 30-year period, GTM model
	GTAP AEZ	Indian AEZ	GTAP AEZ	Indian AEZ			
Short rotation	51	34	75	67	348	25	NA
Long rotation	129	150	95	179	505	75	NA
Natural regeneration	80	75	254	273	NA	215*	NA
Total	260	258	424	520	853	315	210

Note: *Includes forest protection and natural regeneration options

NA = not available or not included in analysis

biomass growth rates and soil carbon uptake rates input into the individual zones of the two systems are different (Appendix 1).

Wasteland (WL) scenario: The carbon stocks under the baseline and the $100 carbon price case for the 100-year period are given in Table 9. Baseline carbon stocks under the GTAP and Indian AEZ systems follow an increasing trend from 2005 to 2100, with stocks slightly higher in the GTAP system. Total carbon stocks under the GTAP baseline scenario over the 100-year period are marginally higher than in the Indian AEZ baseline.

WL + LF + MC land area scenario: Carbon stocks for the GTAP and Indian AEZ systems for the enhanced area scenario (85% higher than WL scenario) follow a reverse trend compared to the WL scenario, with Indian AEZ stocks higher than GTAP stocks (Table 9) during most periods. For example, the carbon stock under the Indian AEZ system is 35% higher than under the GTAP land classification for 2025 in the $100 carbon price case.

This difference between the carbon stock gain estimates under the two land classification systems can be explained by

- The GTAP system (Table 1) is characterized by higher-levels of aggregation, e.g., GTAP Zone 3 (tropical moist semiarid) accounts for nearly 33% of the geographic area of India;
- GTAP Zone 3 is comprised of parts of 14 Indian AEZs, (Table 2) ranging from hot arid to moist sub-humid zones;
- The mean annual biomass increment value for GTAP Zone 3 is 4.4 t/ha/year for long rotation option, whereas this value varies for the Indian AEZs falling in GTAP Zone 3, e.g., it is 7.37 t/ha/year for Zone 14 (Western Himalayas), 6.6 t/ha/year for Zone 4 (northern plains and central highlands) and 5.07 t/ha/year for Zone 10 (central highlands). Similarly, the values for other Indian AEZs vary, and the trend is similar for SR and NR options;

- Thus, the mitigation potential estimate for the Indian AEZ land classification system is higher, compared to GTAP.

9 Conclusions

India has been implementing one of the world's largest A & R programs to meet its biomass requirement (fuelwood, timber and non-timber products) and for forest conservation purposes. India has also set a goal of covering about one-third of the geographic area under forests, compared to less than 20% area currently under forests. The investment capital barrier mainly limits the A & R program in India. The present study has explored the potential of carbon price incentive for carbon stocks gained in A & R programs as a strategy to overcome the investment capital barrier. This study also has attempted to overcome the limitations of existing studies estimating mitigation potential using aggregate area and growth rates of soil and biomass carbon, by conducting a disaggregated analysis using the agro-ecological zone approach for spatially disaggregating or classifying the area available for mitigation.

The study has adopted GTAP's global land classification system, as well as the indigenous Indian AEZ system. Results indicate that a financial incentive of a constant carbon price of US$100/tC over the short-term period of 20 years to 2025 generates 3.76 and 6.4 Mha of additional area brought under A & R under the wasteland and enhanced area scenarios, respectively, over the baseline under the GTAP land system. This $100 price also brought significant additional area under A & R compared to $50 price scenario, illustrating that a higher incentive can drive A & R rates, particularly in the short term. A comparison of estimates of mitigation potential using the GTAP and Indian AEZ systems shows that in the short term, for the enhanced land area scenario, 35% additional C-stock gain is achieved under the $100 price case. However in the long term, the difference between the global GTAP and Indian AEZ systems is marginal.

These results highlight that mitigation potential estimates can be significantly different depending on the land classification system adopted, particularly when larger areas are considered, due to differences in growth rates at the disaggregated AEZ-level. The Indian AEZ l system has a larger number of zones compared to the more aggregate GTAP. Thus, nationally derived land classification systems with a greater-level of disaggregation need to be considered when estimating aggregate land use mitigation potential.

Additionally, decisions regarding what lands are to be considered available for mitigation have a major impact on mitigation potential estimates. In this analysis, the enhanced area scenario showed significantly higher mitigation potential. This analysis included only 10% of agricultural land in India, i.e., those considered marginal. An analysis with land-use competition across forest, crop, pasture, biofuel and carbon sequestration land uses, which ensures that demand for food is met in the future, may yield a higher potential.

These estimates of mitigation potential at the disaggregated AEZ-level using either land classification are limited by availability of data on growth and stock of carbon in different pools, particularly aboveground biomass and soil carbon, by mitigation option. Some AEZs, even though spread over a large number of districts, had only one or two observations, for e.g., for biomass growth rate, resulting in the merging of zones and loss of disaggregation. A larger number of estimates would minimize this error. Each AEZ, particularly the larger ones, could be subdivided to homogeneous sub-zones in the GTAP land classification. The 20 AEZs of the Indian land classification system, for instance, are subdivided into 64 sub-zones.

The uncertainty in the estimates of mitigation potential could be reduced by generating reliable, disaggregated estimates of the carbon stock gain and losses by mitigation option. Disaggregated data are also needed on land use establishment, maintenance, harvest, and replanting costs and benefits for major mitigation options. More detailed data on the Internal Rate of Return (IRR) of competing land uses that drive this analysis would help improve the calculation of economic carbon benefits. However, this study offers a significant advance over previous studies for India, by utilizing a dynamic economic model of the forest sector. It also provides a roadmap for future work in support of forestry mitigation analysis and implementation.

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Appendix 1

Input data – Mean annual biomass increment data for Global GTAP and Indian AEZs

Zones	Mean annual increment (t biomass/ha/year)	
	Short rotation	Long rotation
Global GTAP AEZ		
1, 7, 8	3.9	3.94
2	3.9	3.94
3	6.5	4.4
4	5.94	5.05
5 + 6	7.13	7.7
9	4.9	3.96
10–16	7.9	7.7
Indian AEZ		
1 & 14	3.63	7.37
2	4.56	4.82
3, 6, 7	3.35	4.07
4, 9, 13	5.41	6.63
5	3.38	4.93
8 & 19	3.38	2.01
10	4.01	5.07
11 & 12	3.67	5.02
15, 16, 17	8.74	5.09
18	4.66	5.09

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