(d) In spite of much larger release of AP from the 10% ethanol-treated cells (Figure 2 *b*), its $(TR)_E$ reduced nearly by 20% from that of the 5% ethanol-treated cells (Figure 2 *a*); this was perhaps because 10% v/v ethanol treatment caused approximately 20% cell killing (Table 1). Hence, during transformation, the more the membrane was disintegrated (without causing cell death by ethanol treatment), the more was the uptake of plasmid DNA. (e) After the heat-shock step, where no noticeable increase in the release of AP took place (Figure 2 *b*), $(TR)_E$ of both ethanol-pretreated and untreated cells was nearly doubled compared to the values obtained without applying the heat-pulse step (Figure 2 *a*). Thus it can be suggested that no further cell-wall disruption occurred by the heat-pulse step; on the other hand, this step helped DNA entry into the cell cytosol through the disintegrated membrane of competent cells. (f) This ethanol-mediated enhancement of $(TR)_E$ can be considered as an improved technique of artificial transformation of *E. coli* with plasmid DNA.

The whole study can be summarized as follows: during artificial transformation of *E. coli*, the DNA was first bound to the LPS molecules on the competent cell surface and uptake of this LPS-adsorbed DNA into the cell cytosol was associated with cell-wall disintegration.

1. Michod, R., Wojciechowski, M. and Hoelzer, M., *Genetics*, 1988, **118**, 31–39.
2. Redfield, R. J., *ibid*, 1988, **119**, 213–221.
3. Hanahan, D., *J. Mol. Biol.*, 1983, **166**, 557–580.
4. Cohen, S. N., Chang, A. C. Y. and Hsu, L., *Proc. Natl. Acad. Sci. USA*, 1972, **69**, 2110–2114.
5. Mandel, M. and Higa, A., *J. Mol. Biol.*, 1970, **53**, 159–162.
6. Micklos, D. A. and Freyer, G. A., *DNA Science: A First Course in Recombinant DNA Technology*, Cold Spring Harbor Laboratory Press, 1990, pp. 26–29.
7. Osborn, M. J. and Wu, H. C. P., *Annu. Rev. Microbiol.*, 1980, **34**, 369–422.
8. Rietschel, E. T. *et al.*, *FASEB J.*, 1994, **8**, 217–225.
9. Basu, T. and Poddar, R. K., *Colloids Surf. B*, 1994, 3, 85–89.
10. Sarkar, S., Choudhuri, S. and Basu, T., *Indian J. Biotechnol.*, 2002, **1**, 209–211.
11. Sambrook, J. and Rusell, D. W., *Molecular Cloning*, Cold Spring Harbor Laboratory Press, 2001, 3rd edn, vol. 1, p. 3, 12.
12. Sambrook, J. and Rusell, D. W., *ibid*, A3.3–3.5.
13. Sambrook, J. and Rusell, D. W., *ibid*, p. 1.116–1.118.
14. Basu, T. and Poddar, R. K., *Biochem. Mol. Biol. Int.*, 1997, **41**, 1093–1100.
15. Basu, T. and Poddar, R. K., *Folia Microbiol.*, 1994, **39**, 3–6.
16. Schlesinger, M. J. and Levinthal, C., *J. Mol. Biol.*, 1963, **7**, 1–12.
17. Pollard, E. C. and Davis, S. A., *Radiat. Res.*, 1970, **41**, 375–399.
18. Setlow, R. B. and Pollard, E. C., *Molecular Biophysics*, Addison-Wesley, 1962, p. 10–41.
19. Luderitz, O., Jann, K. and Wheat, R., *Compr. Biochem.*, 1968, **26A**, 105–228.
20. Van Die, I. M., Bergmans, H. E. N. and Hoekstra, W. P. M., *J. Gen. Microbiol.*, 1983, **129**, 663–670.

ACKNOWLEDGEMENT. We thank the Department of Science and Technology, and Council of Scientific and Industrial Research, Government of India for financial assistance.

Received 24 June 2002; revised accepted 20 September 2002

Carbon sequestration estimates for forestry options under different land-use scenarios in India

Suruchi Bhadwal* and Roma Singh

Tata Energy Research Institute, Darbari Seth Block, Habitat Place, Lodhi Road, New Delhi 110 003, India

Land resources have been under tremendous pressure since the very beginning of civilization for food and forest products. For better land-use management, these resources must be used sustainably and in accordance with the demands of the masses. To manage the land resources effectively and for future food security we need to find out the demands and potential of our land. In this study, a comparative estimate of land-use and carbon sequestration potential of different forestry options has been done for India. This has been done using the Land Use and Carbon Sequestration (LUCS) model. This model systematically incorporates Indian agricultural and forest statistics with geographical and demographic data. Besides this, various pressures exerted on land-use system due to the existing growth rates of population, fuelwood requirements, export of agricultural commodities and probable transfer of lands from one category to the other, are also considered here.

Three scenarios (LUCS-I, LUCS-II and LUCS-III) are generated with different land-use options following the demands and present land-use pattern prevailing in the country. The scenario LUCS-I puts maximum amount of land into the forestry sector and is an economically feasible scenario. The scenario LUCS-II is a 'business as usual' scenario, as it is projected according to the current five-year plan. The scenario LUCS-III puts maximum amount of land in the plantations category and is a potential scenario. These scenarios were generated for a time period of fifty years starting from the year 2000. The LUCS model estimates the amount of carbon sequestered by approximating land-use and relative biomass changes in the landscape over time. The amount of carbon sequestered in scenario LUCS-III is estimated to be 6.937 billion tonnes, which is the highest among those sequestered in all the three scenarios. According to this scenario, the carbon sequestered in aboveground vegetation of India will be more than double by the year 2050.

ANTHROPOGENIC activities have known to affect the biosphere through changes in land-use and forest management activities, thus altering the natural balance of greenhouse gases in the atmosphere. Over the last three centuries, forests have decreased by 1.2 billion hectares (bha), i.e. 19% and grasslands by 560 million hectares (mha)[1]. This has resulted due to an increase in croplands

*For correspondence. (e-mail: suruchib@teri.res.in)

and growth of urban areas. The rate of agricultural expansion during the period 1950–80 was greater than the entire span of 150 years between 1700 and 1850. During the decade 1981–90, land-use changes in the tropics accounted for CO_2 emissions of about 1.6 giga tonnes per year (Gt/yr). On the other hand, terrestrial vegetation assimilated approximately 1.8 Gt of carbon per year during the same period[2]. In sum, the carbon balance shows that in the 1980s the terrestrial vegetation in the tropics acted as a net sink of carbon.

According to estimates reported by the Intergovernmental Panel on Climate Change (IPCC)[3], emissions of CO_2 and other greenhouse gases have begun to affect the world's climate. Anthropogenic increases in greenhouse gases in the atmosphere are likely to bring about a global temperature rise of 1.4–5.8°C during the next century; with an associated rise in sea level of 0.09–0.88 m. Each 1°C rise in temperature will displace the limits of tolerance of land species some 125 km towards the poles, or 150 m vertically on mountains. Many species will not be able to redistribute themselves fast enough to keep up with the projected changes, and considerable alterations in ecosystem structure and function are likely. Hence the scientific community is now focusing on issues related to identification of carbon sinks.

The reductions in concentration of CO_2 in the atmosphere can be achieved either by reducing the demand for energy or by altering the way the energy is used, and by increasing the rates of removal of CO_2 from the atmosphere through growth of terrestrial biomass (e.g. forests). According to Winjum *et al.*[4], the most promising management practices for CO_2 mitigation are reforestation in the temperate latitudes, and agroforestry and natural reforestation in the tropics. The 1997 Kyoto Protocol to the climate convention recognizes that drawing CO_2 from the air into the biomass is the only practical way for mitigation of the gas from the atmosphere.

Human influence has affected forest cover in India over a long period. According to Flint and Richards[5], carbon storage in the vegetation in India from the year 1880 onwards shows a decreasing trend. Changes of land-use in the past were dominated by losses of fertile land and degradation of forests. Losses of fertile land in combination with the trend towards an increasing demand of agricultural products for a growing population have asserted the need to identify the long-term capacity of the country resources to feed its population. India is also more vulnerable to the impacts of climate change than its developed counterparts as it lacks the resources to adapt to the consequential changes. The vulnerability of human health and socio-economic systems in particular depends on economic circumstances and institutional infrastructure. The limited land resources of the country have to be managed efficiently to fulfil the demands of agriculture as well as the forestry sector. In the forestry sector also, we need to identify the best forestry option, which fulfils the demands of wood and its products along with increasing carbon sequestration.

In this study, an attempt has been made to identify the best forestry option through proper land-use management using the Land Use Carbon Sequestration (LUCS) model.

The LUCS model is embedded in a software package called LUCS VERSION 1.0 and was developed by World Resource Institute (WRI) in 1988. WRI researchers pioneered a way for the users to estimate carbon storage potential by feeding scenarios based on land-use data and future trends of land-use patterns into a land-use model.

LUCS is essentially a carbon-accounting device which allows the user to evaluate changes in the landscape and provides insight into different trends and interventions affecting land-use. These interventions can also be tested to assess their relative effectiveness in producing sustainable land-use patterns, in addition to their carbon sequestration potential. Key parameters and variables that derive land-use changes in this model are population, fuelwood demand, wood for permanent uses, forest harvesting and demand of agricultural commodities.

The LUCS model estimates the amount of carbon sequestered by approximating land-use and relative biomass changes in the landscape over time, allowing to estimate how much carbon a particular scenario can sequester. The model has the potential to represent a demographic transition from growth to stability. Rates of removal of biomass for firewood, permanent uses (e.g. lumber, fencing, poles, etc.) and land cleared for shifting agriculture in India have been accounted for in this model. Rate of degradation of land depends on the degree to which the agricultural system in a zone is dominated by shifting cultivation, the degree to which the population is directly or indirectly dependent on forest products for both timber uses and firewood purposes and the degree to which a region is a net exporter or importer of agricultural products. The LUCS model uses these interactions to compute carbon sequestration over a period of time and allows the user to analyse the outputs.

The carbon sequestration potential can be evaluated using site data and the LUCS model. This model has therefore been used to provide assistance in developing criteria for evaluating forestry and land-use projects that can mitigate CO_2 emissions over a period of time.

The data basically forms relationship between land-cover change and land degradation (due to agriculture purposes and firewood requirement). All land-use data values presented in the model are expressed in the units of hectares (ha). The human population is expressed in millions. The carbon content estimate for each year is expressed in billion tonnes (bt).

In order to evaluate the performance of the LUCS model in simulating changes in land-use patterns, a comparison of estimated vs model-simulated data of carbon sequestration for Indian forests has been done for the period 1980–2000 (Figure 1).

Specific information on carbon mitigation, though difficult to get, is critical to understand the trends in land-use and to run this model. Validation of the model is based on the rate of carbon sequestration during the period 1980–2000 for the forest cover of India, as data regarding the changes in total land area during this period were not available. The carbon content of Indian forests for the year 1980 has been taken from Flint and Richards[5]. Annual carbon increment for the years 1985, 1990 and 1995 has also been reported by Lal and Singh[6]. These values are used to calculate annual carbon uptake for the years from 1980 to 2000 by developing a regression equation:

$$Y = 27.66 + 0.6877X.$$

The total carbon content of Indian forests for the selected years is then calculated. The estimated and model-simulated values are then compared for validation. It is observed that the trend of year-to-year variations in carbon is well simulated by the model. Slight deviations in the model-simulated and estimated carbon storage values are perhaps due to some unaccounted factors such as natural calamities, etc.

This model therefore requires a thorough understanding of the past, present and future usage of land. It also requires an effort to understand the causes and consequences of land-use changes, complex interrelationships among population growth, food and fodder supply, urbanization and associated environmental problems.

From the very beginning, land has been under tremendous pressure due to changes in increasing rates of population and the consequent urbanization. The main objective of collecting land-use statistics has been to account for the present carbon storage of land and estimation of its future carbon sequestration potential under different land-use patterns.

The sensitivity of carbon sequestered to changes in land-use patterns varies regionally. Shifts in land-use have a major effect on terrestrial carbon storage, and the changes associated with over exploitation of land resources due to population are increasing worldwide. Therefore, specific information on population numbers is critical to understand the trends of land-use. India is a vast country with a diverse resource base. It has a land area of 328.73 mha, supporting a population of nearly 1 billion. Globally, it has an area of roughly 2%, supporting about 17% of the world's population. The population has grown in the previous decade at a rate of about 2% (ref. 7). Though the increase in population has been phenomenal in the last few decades, it has now acquired a decreasing trend. A decline in the same has been observed to 2% during the decade 1990–91 to 2000–01.

Carbon storage in the vegetation in India was 8.6 bt in the year 1880, 7.7 bt in 1920, 6.39 bt in 1950, 5.23 bt in 1970 and 4.39 bt in 1980 (ref. 5). Carbon storage in the vegetation in the country from 1880 onwards shows a decreasing trend (Figure 2). For the past hundred years or more, pressures on land were mostly due to the onset of the Industrial Revolution, increase in population and urbanization. During that period, maximum amount of land conversion was from the forestry sector to agricultural sector, i.e. from higher biomass category to lower biomass category. This unplanned land-use practice has led to consistent decrease in the green-belt area, resulting in environmental degradation in the past.

As the population grows, more land is required to supply food and to fulfil other needs. Besides this, future agricultural demand will strongly affect land-cover patterns and this in turn will affect the flux of CO_2 and other greenhouse gases from the terrestrial environment. While demand for food will increase, the ability of the land to meet the demand may increase or decrease consequently, depending on parameters such as changes in rates of productivity. If we look at the trends of increase in our land-use during the previous decades, there has been a gradual increase in the area under forest and net sown area, with gradual decline in the other categories. Almost half of

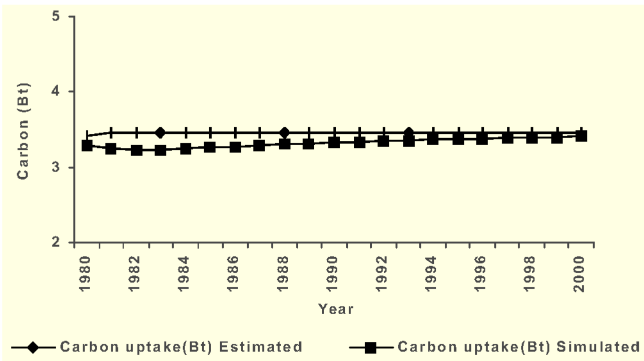

Figure 1. Estimated and model-simulated values of carbon from forestry sector in India for the period 1980–2000.

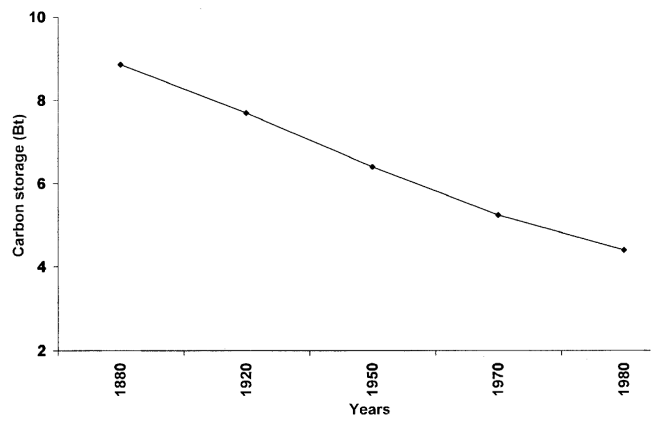

Figure 2. Carbon storage in various land classes.

India's land area is under cultivation without significant increases since 1970s. Taking a look at the past trends it is clear that the agricultural area was approximately 119.4 mha in 1950s, 140.3 mha in 1970s and increased up to 142.1 mha in 1994. Changes observed in the agricultural land category have been minimal since 1970, and have almost stabilized. Though there has been no marked increase in the land area under the agricultural sector, the yield per hectare for the total foodgrain in the country has increased from 0.872 t/ha during 1970–71 to 1.6 t/ha during 1996–97 (ref. 8). As a result, the foodgrain production in India has increased from 82 million tonnes (mt) during 1960–61 to an all-time high of nearly 209.8 mt during 1999–2000 (ref. 9). The total foodgrain requirement of India is expected to increase to about 269 mt by the year 2010. At present, increase in land area for foodgrain production is constrained by biophysical factors such as soil, climate and relief features. However, opportunities offered by commercialization of agriculture and higher economic potential of several non-agricultural activities, may fulfil the growing demands of the country with the limited-land resources[10]. Therefore, stress on land for agricultural purposes might not be severe in comparison to increasing rates of population.

Area under the forests in 1950s was approximately 40.48 mha; it marginally increased and reached up to 63.92 mha during 1970s, 64 mha during 1980s and is almost constant since then[11]. India has nearly 19.1% of its land area under forests. This value excludes land under tree plantations. About 43.11% of land area in India is devoted to croplands. The remaining 113.535 mha accounts for land in forest fallows, restored forest and degraded land. For our study, the geographical data of India have been classified into nine categories, i.e. permanent agriculture, shifting agriculture, agroforestry, open forests, dense forests, plantations, degraded land, forest fallow and restored forest. The total biomass in these categories differs according to the area under each land category, and hence any change in the area of these categories may change the total carbon content of vegetation (Table 1).

The source data needed were collected from different government reports, forestry department publications and forest-based literature. The input data required to run the LUCS model include: land conversion data from one category to the other; rate of population increase; time period for maturation of categories from primary to secondary growth stages and secondary to tertiary growth stages; time period required for conversion from one category to another. Other input data include: initial values for population, use of land, rate of agricultural productivity, rate of export of agricultural commodities and rate of requirement of wood for permanent uses and firewood.

The primary step includes the input of land-use data in the spreadsheets provided in the model. Then we input data for all relevant variables in the seven selected categories, say population and current growth rate of the population; land-use and biomass; forest management and uses; forest harvesting practices; agricultural production; fuelwood requirement and project management for the country. Compiling the changes in land-use data for each category together with the population density and fuelwood requirement information, carbon sequestered within the country for existing vegetation is estimated.

Historic and present land-use patterns in relation to biophysical and socio-economic determining factors are used to understand future land-use patterns. The relations between land-use distributions and determining factors are quantified. Selective adoption of a particular land-use then determines the actual change based upon relative advantage of the local situation and relative change in demand at the national level.

In this model carbon sequestration is calculated from standing biomass, wood products and fossil-fuel use; the equation is: carbon=carbon in standing biomass + carbon in wood products + carbon in fossil fuel. Carbon in standing biomass is determined by multiplying the area of each land-use category by its average biomass and then multiplying the sum by the carbon content of biomass, which is assumed to be 0.5. Carbon in fossil-fuel has a negative value. If there is an insufficient amount of fuelwood in the project region, the model automatically begins to burn fossil fuel, which results in increased carbon emissions. Carbon in wood products represents the amount of carbon stored in wood products. The amount of carbon going into wood products is determined by the fraction of closed forests and tree plantations cut for permanent uses. These variables are a fraction of the total biomass.

The LUCS model is able to simulate the spatial pattern of land-use change allocation, given the scenarios of land-use changes at the national level. Future demand for land-use is calculated by analysing the changes in consumption patterns and expected policy decisions (e.g. reforestation). For India, the 'business as usual' scenario used is based upon an analysis of recent land-use change trends.

To estimate how much carbon might be sequestered in the future, projections of land-use changes and the associated uptake of carbon were computed up to the year 2050. The purpose of these projections is to evaluate a range of possible exchanges of carbon between the atmosphere and land put into various categories.

Table 1. Total area in each land-use class and their total biomass for the year 2000

Land-use class	Area (mha)	Biomass (t/ha)
Closed forest	36.72	129.00
Degraded land	84.90	2.00
Forest fallow	7.21	16.00
Open forest	26.13	66.55
Permanent agriculture	141.73	16.00

Three scenarios (LUCS-I, LUCS-II and LUCS-III) are generated with different land-use options following the demands and present land-use pattern prevailing in the country. According to our assumptions, land that is degraded can be brought under conversion for afforestation purposes. The scenario LUCS-I puts maximum amount of land into forestry sector and is an economically *feasible scenario*. The scenario LUCS-II is a 'business as usual' scenario as it is projected according to the current five-year plan. The scenario LUCS-III puts maximum amount of land into plantation category and can be defined as a *potential scenario*. These scenarios were generated for a time period of fifty years starting from the year 2000. The LUCS model estimates the amount of carbon sequestered by approximating land-use and relative biomass changes in the landscape over time. These changes are driven by key variables such as population growth, subsequent food and fuel needs, agricultural productivity, technological change, wood use, land-use change and harvesting practices. Rates of removal of biomass for firewood, wood for permanent uses and land cleared for shifting agriculture in India have been accounted for in this model.

According to our assumptions, a maximum of 2 mha of degraded land can be brought under conversion for afforestation purposes, such as plantations for permanent uses (timber production, wood for fencing and poles, etc.); agroforestry for the fulfillment of fuelwood and fodder demands; afforestation of economically important species and non-timber forest products. The scenarios are presented in the context of land shifts from one category to another, so as to increase the carbon sequestration limits within each scenario generated. However, the model results can be used to analyse the amount of carbon sequestered per year for the projected fifty years (2000–50); we have used them only for a comparative analysis.

Here the geographical area of India has been divided into nine categories, viz. permanent agriculture, agroforestry, shifting agriculture, open forests, dense forests, plantations, degraded land, forest fallow and restored forest (Figure 3). Changes brought about in the land-use pattern after a period of fifty years for the three scenarios considered, are shown in Table 2 and Figures 4 *a–c*.

The fuelwood demand in all the scenarios is met by extraction of wood from agroforestry land, open forests and plantations. The fuelwood demand for the year 2000 is taken as 377 mt, according to estimates reported in the IX five-year plan[12]. In all the three scenarios, we have assumed biomass savings from stoves, which is taken as a constant for the three scenarios generated.

Three parameters – population growth rate, fuelwood requirement and biomass savings from stoves are kept constant to analyse the land-use changes comparatively (Figures 5 and 6). The amount of carbon sequestered by the year 2000 is assumed to be constant for the three scenarios generated, as the year 2000 is assumed by the model as zero-year for the project and changes in land-use begin after 2000. Therefore, the net carbon uptake recorded for a period of 50 years is the difference of uptake of carbon between the years 2000 and 2050 (Figure 7).

Out of the three scenarios, the net uptake in the forestry-based scenario, i.e. LUCS-I is 6.647 bt. The amount of carbon stored increased by 4.987 bt for the years 2000–25 and by 1.660 bt for the years 2025–50. Rate of uptake of carbon for LUCS-II is 5.227 bt, with net amount sequestered for the years 2000–25 being 3.916 bt and for 2025–50 1.311 bt. LUCS-III, which is a plantation-based scenario, sequestered maximum amount of carbon in comparison to the other scenarios. An amount of 6.937 bt of carbon is estimated to be sequestered during a time period of fifty years (Table 2). A comparison of the scenarios in Table 3 shows a marginal difference in the amount of carbon sequestered by them. The amount sequestered in the forestry-based scenario shows a net decrease of 290 mt of carbon in comparison to plantation-based scenario, and a net increase of 1.42 bt of carbon in comparison to the 'business as usual' scenario. Net increase in the amount of carbon sequestered in the potential scenario is 1.71 bt in comparison to the 'business as usual' scenario.

The scenarios project high value of carbon sequestration initially and it decreases consequently, such that after a period of fifty years sequestration amounts are

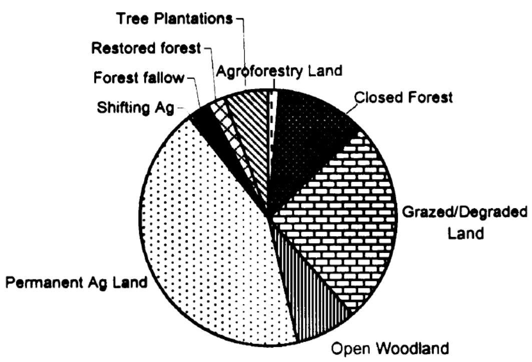

Figure 3. Land utilization in India (1998).

Table 2. Change in land-use categories and associated carbon uptake during the time period 2000–50

		Year 2050		
Land category (mha)	Year 2000	LUCS-I	LUCS-II	LUCS-III
Closed forest	36.72	92.63	93.88	91.64
Degraded land	84.9	0.10	0.38	1.10
Open forest	26.13	6.20	6.40	6.20
Permanent agriculture	141.73	130.18	129.88	130.18
Forest fallow	7.21	1.19	1.12	1.19
Net carbon uptake (bt)	5.27	11.92	10.50	12.21

least. This is due to the fact that initially the canopy species have the potential to achieve both great height and girth with high levels of biomass.

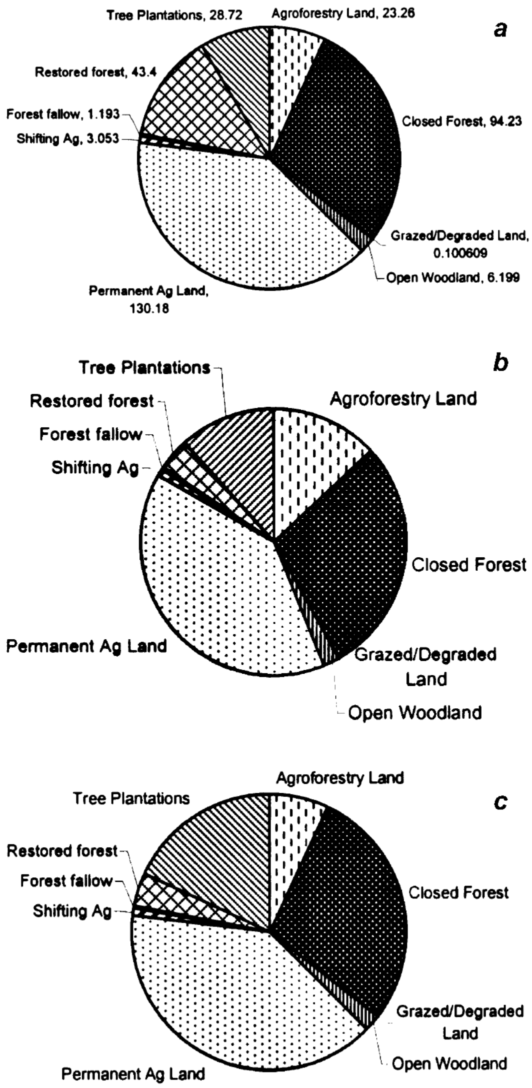

Figure 4. Projected changes in land area. ***a***, LUCS-I; ***b***, LUCS-II; and ***c***, LUCS-III.

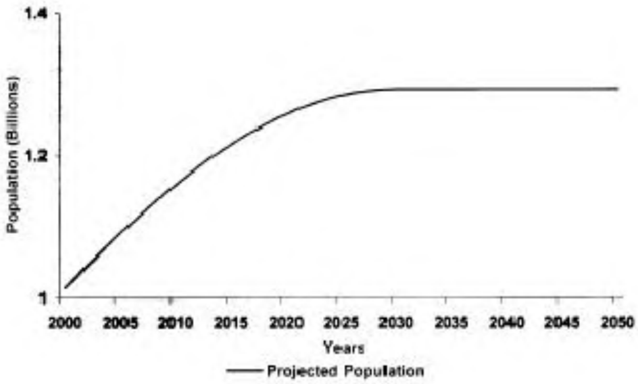

Figure 5. Projected population.

Land-use is constrained by biophysical factors such as soil, climate, relief and vegetation. Most land-cover modifications and conversions are anthropogenic rather than natural. Human activities make use of or change land attributes and are considered as the proximate sources of land-use/cover change. This disturbs the ecological balance and in turn reduces the potential productivity of land resources.

Our results reveal a dynamic picture of changes in land-use and carbon sequestration for India during the period 2000–50 for all the three scenarios. The carbon sequestered here through vegetation has more than doubled by the year 2050. This is due to the fact that the area under protected forests has been increasing with a step towards managing of forests in a sustainable manner. Policy initiatives are being taken by the Ministry of Environment and Forests to develop strategies to achieve 33% forest cover in the country. Stress on forests for fuelwood is also declining due to changes in existing resource use (fuelwood) by resource substitution (energy-efficient chulhas). Apart from conservation in the domestic sector, use of improved cooking stoves plays an important role in the reduction of emissions of greenhouse gases. In India, the share of total fuelwood consumption has declined from 30% in 1980 to 20% in 1994. Traditional energy consumption has also declined from 32 to 23% during the same period[13]. Initial degradation of land has also shifted towards restoration and conservation, resulting in increases in the amount of carbon stored in the vegetation.

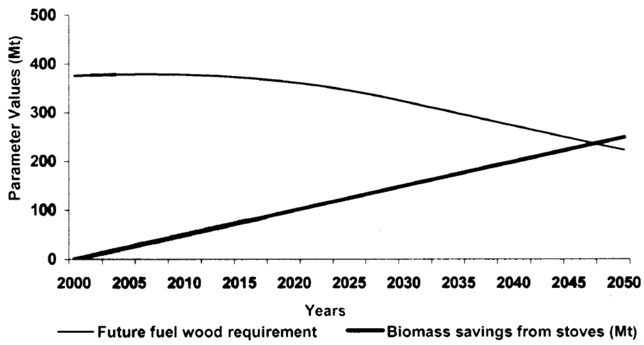

Figure 6. Future fuelwood requirement and biomass savings.

Table 3. Total carbon sequestered per year projected for the years 2000–50

	Total carbon sequestered (bt)		
Year	LUCS-I	LUCS-II	LUCS-III
2000	5.273	5.273	5.273
2010	7.403	7.037	7.229
2020	9.401	8.574	9.143
2030	10.800	9.545	10.640
2040	11.500	10.140	11.580
2050	11.920	10.500	12.210

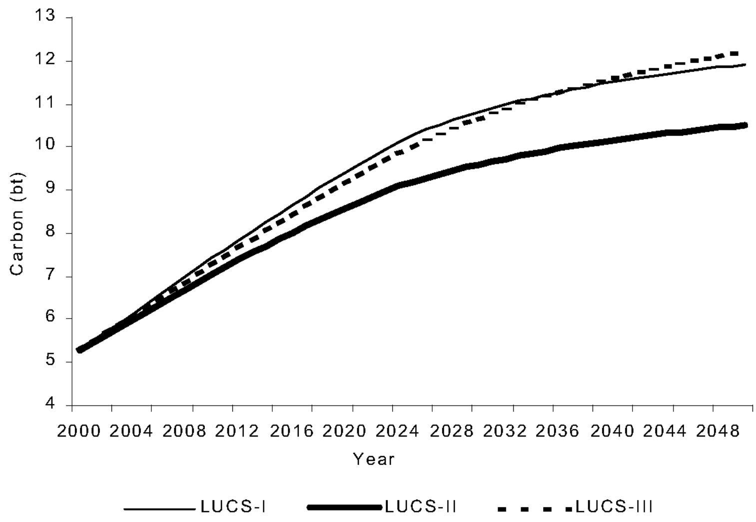

Figure 7. Projected carbon uptake for India (2000–50).

The LUCS model was basically developed to analyse the carbon sequestration potential on a regional basis. Here we have used it to estimate the carbon sequestration potential for India as a whole. As we have used the model for studies on a national basis, a comparative analysis approach for storage of carbon in various scenarios has been undertaken. We have tried to identify the best possible land-use pattern with which the future demands could be fulfilled in a sustainable manner. To account for the best possible conversion of land in the future, a comparative estimate of land-use and carbon sequestration potential of different forestry options has been done. Though the stress factors affecting the rates of biomass changes like rate of change in population, fuelwood demand and use of energy-efficient chulhas have been kept constant for the three scenarios, the amount of carbon sequestered for the plantation-based scenario is found to be the maximum. Thus, the plantation-based scenario is identified as the best land-use pattern which fulfils the demands in future in a sustainable manner on a long-term basis.

1. Watson, R. T., Zinyowera, M. C. and Moss, R. H. (eds), *Climate Change, Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, Contribution of Working Group II to the Second Assessment of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, 1995, p. 878.
2. Schimel, D., Enting, I. G., Heimann, M., Wigley, T. M. L., Raynaud, D., Alves, D. and Siegenthaler, U., in *Climate Change 1994 – Radiative Forcing of Climate Change and an Evaluation of the IPCC 1992 IS92 Emission Scenarios* (eds Houghton, J. T. *et al.*), Cambridge University Press, Cambridge, 1995, pp. 35–71.
3. Houghton, J. T., Ephramus, J. J. and G. J. (eds), *Climate Change, The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 2001.
4. Winjum, J. K., Dixon, R. K. and Schroeder, P. E., *Water, Air, Soil Pollut.*, 1992, **64**, 213–228.
5. Flint and Richards, Historic land use and carbon estimates for South and Southeast Asia, 1880–1980; 1994, App. 1994, C-3.
6. Lal, M. and Singh, R., *Environmental Monitoring Assessment, Carbon Sequestration Potential of Indian Forests*, 2000, 60, pp. 315–327.
7. Economic Survey, 2001–02, Ministry of Finance, Economic Division, Government of India, S-1.
8. *Agricultural Statistics at a Glance*, Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India, 1998.
9. See ref. 7, S-16.
10. Report of the Fact Finding Committee, Indian Council of Agricultural Research, New Delhi, May 1998, pp. 3–4.
11. *The State of the Forest Report*, Forest Survey of India, Ministry of Environment and Forests, Dehradun, India, 1999.
12. Report of the Working Group on Forestry for the Ninth Five-Year Plan, Ministry of Environment and Forests, New Delhi, 1998.
13. Wood Energy Today for Tomorrow, Regional Studies, The role of wood energy in Asia, Working Paper FOP, W/97/2, 1997, p. 107.

ACKNOWLEDGEMENTS. We are grateful to Mr Paul Faeth, World Resource Institute for providing us the LUCS model software. This study is funded by the Indian Council of Forestry, Research and Education, Dehradun under the World Bank FREE Project.

Received 30 January 2002; revised accepted 25 September 2002