Carbon flux and land use/cover change in a Himalayan watershed

The land use change from forest to other usages has been quite conspicuous in the last few decades, causing depletion of natural resources in the Himalaya[1,2]. The quest for fast economic development and expanding agricultural activities has increased the exploitative pressure on the forests in the Himalaya[3]. It is clear that changes in land use have caused a significant release of CO_2 to the atmosphere[4,5]. In tropical Asia, the emissions of carbon from land use change in the 1980s accounted for approximately 75% of the region's total carbon emissions[6]. The concentration of atmospheric CO_2 has increased by 15–20% over the past 100 years[7]. An estimate of the release of carbon from terrestrial ecosystems as a result of land use/cover change in low-latitude forests is estimated at 1.65 ± 0.4 Pg C yr^{-1}, due to the modification of high biomass forest ecosystems to systems of lower biomass such as secondary and degraded forests, cultivated land and pastures[8,9]. Although links between land use/cover changes and flux of carbon to the atmosphere are commonly acknowledged, uncertainties exist concerning the magnitude of such fluxes[10]. Because of these uncertainties, estimates of the global CO_2 release from biomass reductions and land clearing vary between 8 and 44% of total anthropogenic CO_2 emissions[11,12]. More accurate estimates of global or continental CO_2 emission from land use/cover change can only be obtained from extrapolation of reliable local estimates[13]. Therefore, comprehensive information on the spatial and temporal distribution of land use and land-cover change is a prerequisite for understanding the carbon flux.

The present study was carried out in Mamlay watershed, which is located in the southern part of Sikkim, eastern Himalayan biogeographic zone (27°10°8″ to 27°14′6″N, 88°19′53″ to 88°24′43″E) of India. The present data are the result of two consecutive years of study of three sites of each land use/cover. The watershed lies entirely in the mountainous zone. The area is typified by folded structure and varied lithology with older rocks occupying the upper structural levels. It bears the evidence of two persistent thrusts, viz. the Sikkim and the Tendong[14]. The average rainfall varied from 1200 mm at 800 m to 3000 mm at 1900 m during 1999–2000, most of which occurred in the rainy season during June to September. The average temperature varied between 11 and 30°C. The soils are either sandy loam, silty loam or clay loam varying at different land use/cover types. Most soils are acidic (pH ranged from 5.02 to 6.43), and average soil moisture levels ranged from 17 to 34%. Total nitrogen ranges from 1.50 ± 0.33 to 2.84 ± 0.70 mg g^{-1}, total phosphorus from 0.46 ± 0.09 to 0.83 ± 0.16 mg g^{-1} and organic C from 12 ± 0.4 to 32 ± 4.3 mg g^{-1} in different land use classes. As expected, all nutrients were higher in temperate natural forest dense and lower in wastelands.

To develop better insight into the spatial and temporal characteristics of land use/cover change dynamics, satellite imageries, IRS 1A, LISS-II, 1988 and IRS 1C, LISS-III, 2001, FCC bands 2, 3, and 4 in the scale of 1 : 50,000 were used in combination with the India topographical map. The impact of these changes on carbon emissions to the atmosphere was studied by field-collected carbon density and flux data to each land use/cover class. Carbon density data for the major land use/cover classes and for the main C pools in each class were collected in 27 field plots of 20 m × 30 m each. The number of plots in each land use/cover class was three. Average C storage was calculated per unit area (Mg C ha^{-1}) for the various pools of each land use/cover class. Woody-plant biomass was measured using allometric equations[15–17]. All saplings, herbaceous plants and litter were sampled in 1 m^2 subplots, dried and weighted in the laboratory, and the C content was determined. Soil samples were collected in three 1-m deep pits and separated into seven (0–15, 15–30, 30–45, 45–60, 60–75, 75–90 and 90–100 cm) deep strata. Carbon content of various plant parts, viz. bole, branch, foliage, litter, humus, roots and herbaceous shoots and soils was determined using a Heraceus CHN-0 Rapid Analyser. The CO_2 flux was measured in each plot of all the land use/cover classes through CO_2 Infrared Gas Analyser on monthly basis and flux was translated in terms of C flux on annual basis. Statistical analyses were conducted[18] using SYSTAT version 6.0.

The land-use pattern in the watershed as a whole showed about 14 and 31% area under agricultural practices in 1988 and 2001 respectively. The agroforestry practices in the watershed are traditional and about 4% area came under these practices during both the years. The total forest land in the watershed accounted for 69 and 49% of the total area and wasteland covered about 11 and 15% in 1988 and 2001 respectively. During the 13-year period, the most dramatic changes are the increase in open-cropped area and decrease in forest cover area. The open-cropped area increased by more than 100% for the 13-year period, while wasteland increased by about 149%. The total forest cover (temperate natural forest dense, temperate natural forest open and subtropical natural forest open) decreased by 28% during 1988–2001. Ground-truth information supports the finding that depletion of closed forest or its conversion into other categories is the result of maximum anthropogenic pressure on the limited forest resources and farm family fragmentation.

The total mean C densities varied more than fifteenfold between the land use/cover classes, from a low of around 46 Mg ha^{-1} in open-cropped area temperate to a high of 669 Mg ha^{-1} in temperate natural forest dense. The C in aboveground and belowground plant biomass varied significantly with land use/cover classes ($P < 0.0001$). Mean difference of aboveground biomass C showed significant difference between temperate natural forest dense with other forests and agroforestry stands ($P < 0.05$). Mean differences were not significant between open-cropped area of subtropical and temperate belts and mandarin-based agroforestry system ($P > 0.05$), but these were significantly different with temperate natural forest open and subtropical natural forest ($P < 0.05$). The mean C densities for aboveground biomass C ranged between 4 and 182 t C ha^{-1}. More than 80% C was recorded in aboveground biomass in all the stands except cardamom-based agroforestry system. Mean difference in belowground biomass C showed significant difference between cardamom-based agroforestry systems and other stands ($P < 0.05$). Belowground biomass C in agroforestry stands contributed more (30%) to total C storage compared to different types of forest stands (4%).

Floor litter and humus C varied significantly with land use ($P < 0.0001$).

Table 1. Area-weighted total stand carbon in the Mamlay watershed. Values are in ($\times 10^3$ Mg C)

Land use/cover	Vegetation	Litter	Humus	Soil	Total stand
Temperate natural forest dense	30.60	0.73	0.22	75.52	107.07
Temperate natural forest open	84.60	2.89	0.86	215.11	303.46
Subtropical natural forest open	32.70	1.10	0.23	45.60	79.63
Cardamom-based agroforestry system	4.91	0.60	0.13	29.30	34.94
Mandarin-based agroforestry system	0.01	0.007	–	2.61	2.63
Open-cropped area temperate	3.84	–	–	15.30	19.14
Open-cropped area subtropical	4.15	–	–	24.30	28.45
Wasteland area temperate	–	–	–	40.00	40.00
Wasteland area subtropical	–	–	–	8.52	8.52
Total watershed	160.81	5.33	1.44	456.26	623.84

Table 2. Carbon flux estimates resulting from land use/cover change between the 1988s and 2001s in the Mamlay watershed of Sikkim Himalaya

From	To	Changed area (ha)	Release of vegetation C ($\times 10^3$ Mg)	Release of litter C ($\times 10^3$ Mg)	Release of humus C ($\times 10^3$ Mg)	Release of soil C ($\times 10^3$ Mg)	Total release ($\times 10^3$ Mg)
Temperate natural forest dense	Temperate natural forest open	446.810	54.761	0.728	0.237	113.043	168.769
Temperate natural forest open	Open-cropped area temperate	169.730	16.481	0.499	0.148	30.891	48.019
Temperate natural forest open	Wasteland area temperate	109.930	11.140	0.323	0.096	14.291	25.850
Subtropical natural forest open	Open-cropped area subtropical	316.37	36.151	0.959	0.196	24.677	61.983
Subtropical natural forest open	Wasteland area subtropical	2.920	0.334	0.009	0.002	0.006	0.351
Total		1045.76	118.867	2.518	0.679	182.908	304.972

Total carbon content in floor litter ranged from 1.50 to 5.20 Mg ha^{-1}. Cardamom-based agroforestry system had significantly higher floor litter C concentration than other stands ($P < 0.05$). Total C mass in humus ranged from 0.63 to 1.41 Mg ha^{-1} and showed significant variation between temperate natural forest dense with other forests and agroforestry systems ($P < 0.05$). Soil total carbon content up to 1-m depth in different land use/covers ranged from 37 Mg ha^{-1} in open-cropped area temperate to 472 Mg ha^{-1} in temperate natural forest dense.

Area-weighted standing crop values for vegetation, litter, humus and soil are calculated on each land use/cover class in the entire watershed (Table 1). Total vegetation C in forested land use ranged between 30.6 and 84.6 $\times 10^3$ Mg. In agroforestry, this value ranged from 0.01 to 4.91 $\times 10^3$ Mg. The overall range of soil C was 45.6 to 215 $\times 10^3$ Mg in forested land area, and between 2.61 and 29 $\times 10^3$ Mg in agroforestry systems. Total stand carbon in the studied watershed area (3014 ha) was 624 $\times 10^3$ Mg, total C stored in the soil to a depth of 1-m was 456 $\times 10^3$ Mg. Total vegetation C was 161 $\times 10^3$ Mg, litter C 5.33 $\times 10^3$ Mg and humus C 1.44 $\times 10^3$ Mg in the whole watershed. Differences in carbon mass in different land use/covers support the hypothesis that land use transformation from forest to agriculture and wastelands causes tremendous losses of terrestrial carbon that reduce the land sustenance potentials. Agriculture land occupied about 31% of the total watershed area, and the stand total C was only 48 $\times 10^3$ Mg of which 39 $\times 10^3$ Mg was contributed by the soil. Other studies have indicated 20–40% loss in soil carbon due to conversion of forest to permanent agriculture and pasture[19,20]. The greatest changes in carbon storage result from the conversion of forests to cultivated land typically leading to loss of soil C sequestration potential.

Land use change detection study involving a total area of 3014 ha indicated changes in 1046 ha. This involved changes in vegetation stock (as dense forest converted into open forest to open-cropped area and wastelands) and consequently in the standing crop of carbon. The total release of carbon to the atmosphere from the watershed was 305 $\times 10^3$ Mg over a 13-year period (1988–2001). Reductions in the biomass of the forest as a result of conversion were responsible for a net loss of 119 $\times 10^3$ Mg vegetation C and 183 $\times 10^3$ Mg soil C (Table 2). This translates into release of 7.78 Mg C ha^{-1} yr^{-1} due to land use/cover change. Based on the results obtained for Mamlay watershed and assuming the same conditions, the total release of carbon from the entire Sikkim and Indian Himalayan region can be assessed. Sikkim occupies 284,779 ha forest land (about 40% of the total geographical area of Sikkim); land use change (harvest and forest clearings) releases 22.16 $\times 10^5$ Mg annually. If the same result is applied to the entire Indian Himalayan forests area (6.692 million ha), the total release of carbon would be 520 $\times 10^5$ Mg C annually. It is clear that because of overexploitation and continuous land conversion, the land use/cover changes have become a net source of C to the atmosphere. Obviously, further land use/cover changes in the region must be prevented, the existing open forests should be allowed to attain dense condition and open-cropped area should be strengthened with more agroforestry components, and wastelands should be afforested. In conclusion, efforts should be made to allow carbon sequestration under the Kyoto protocol irrespective of scale and geographic location.

1. Singh, J. S. and Singh, S. P., *Forests of the Himalaya*, Gyanodaya Prakashan, Nainital, 1992.
2. Rai, S. C., Sharma, E. and Sundriyal, R. C., *Environ. Conserv.*, 1994, **21**, 30–34.
3. Singh, J. S., Pandey, U. and Tiwari, A. K., *Ambio*, 1984, **13**, 80–87.
4. Singh, J. S., Tiwari, A. K. and Saxena, A. K., *Environ. Conserv.*, 1985, **12**, 67–69.
5. Singh, J. S., Singh, L. and Pandey, C. B., *Curr. Sci.*, 1991, **61**, 477–479.
6. Houghton, R. A. and Hackler, J. L., *Global Change Biol.*, 1999, **5**, 481–492.
7. Houghton, R. A., Hobbie, J. E., Melillo, J. M., Moore, B., Peterson, B. J., Shaver, G. R. and Woodwell, G. M., *Ecol. Monogr.*, 1983, **53**, 235–262.
8. Lugo, A. E., Sanchez, M. J. and Brown, S., *Plant Soil*, 1986, **96**, 185–196.
9. Dixon, R. K., Brown, S., Houghton, R. A., Soloman, A. M., Trexler, M. C. and Wisniewski, J., *Science*, 1994, **263**, 185–190.
10. De Jong, B. H. J. *et al.*, *Environ. Manage.*, 1999, **23**, 373–385.
11. Cook, A. G., Janetos, A. C. and Hinds, W. T., *Environ. Conserv.*, 1990, **17**, 201–212.
12. Schimel, D. S., *Global Change Biol.*, 1995, **1**, 77–91.
13. Cairns, M., Barker, J., Shea, R. and Haggerty, P., *Interciencia*, 1996, **21**, 216–223.
14. Sharma, E., Sundriyal, R. C., Rai, S. C., Bhatt, Y. K., Rai, L. K., Sharma, R. and Rai, Y. K., *Integrated Watershed Management*, Gyanodaya Prakashan, Nainital, 1992, p. 120.
15. Sundriyal, R. C., Sharma, E., Rai, L. K. and Rai, S. C., *Vegetatio*, 1994, **113**, 53–63.
16. Sharma, R., PhD thesis, HNB Garhwal University, Srinagar, 1995.
17. Sundrial, R. C. and Sharma, E., *For. Ecol. Manage.*, 1996, **81**, 113–134.
18. SYSTAT, Statistic, SYSTAT 6.0 for Windows, SPSS, Chicago, 1996.
19. Detwiler, R. P. and Hall, C. A. S., *Science*, 1988, **239**, 42–47.
20. Srivastava, S. C. and Singh, J. S., *Biol. Fertil. Soils*, 1989, **8**, 342–348.

ACKNOWLEDGEMENTS. We thank the Director, G.B. Pant Institute of Himalayan Environment and Development for providing necessary facilities and staff of the Sikkim unit for help in the laboratory and field. We acknowledge financial support from Council of Scientific and Industrial Research, New Delhi.

Received 22 September 2003; revised accepted 13 February 2004

S. C. Rai*
Purnima Sharma

G.B. Pant Institute of Himalayan Environment and Development,
North-East Unit,
Vivek Vihar,
Itanagar 791 113, India
**For correspondence.*
e-mail: raisc1958@rediffmail.com

Palynological assemblage from the Anjar intertrappeans, Kutch district, Gujarat: Age implications

In the recent past, the Anjar intertrappean beds have been considered important Deccan-volcano-sedimentaries to document Cretaceous–Tertiary boundary events[1–4]. After the discovery of Ir anomalies in this intertrappean section, a greater thrust was laid on documenting palynological evidences in support of Cretaceous–Tertiary boundary events. In view of this, extensive survey was undertaken to explore palynological data from the Anjar intertrappeans of Kutch district, Gujarat. This is a record of the palynological assemblage from this intertrappean section.

The pollen- and spore-yielding Anjar intertrappean beds are exposed near Viri village about 3.5 km south of Anjar town, Kutch district. These intertrappeans lie between III and IV basalt flows in the study area and are lithologically made up of carbonaceous shales, marl, limestones and a thin bed of gypsum. The limestones are mostly cherty in nature (Figure 1).

The Deccan traps cover substantial areas in Madhya Pradesh, Maharashtra, Karnataka, Gujarat, Andhra Pradesh and parts of Uttar Pradesh and Rajasthan. Palaeobiological investigations of the intertrappeans in the above areas have been extensively carried out by a number of workers[1,3,5,6]. The palynological microbiota has already been recorded from infra- and intertrappean beds of Jabalpur region, Madhya Pradesh[7–10] and Lalitpur, Uttar Pradesh[6]. However, many animal fossils[1,3,11–14], and anomalously high concentration of iridium[2,15] have been documented from the Anjar intertrappeans. The palynological assemblage recovered in the present study, though quantitatively poor, is a detailed documentation of palynoflora from the Anjar intertrappeans. The present miofloral assemblage is made up of *Gabonisporis bacaricumulus*, *G. vigourouxii*, *Gabonisporis* sp., *Proxapertites granulatus*, *Proxapertites* sp., *Palmidites* sp., *Racemonocolpites maximus*, *Triorites* sp., *Proteacidites reticulatus, Proteacidites* sp. cf. *P. miniporatus*, *Aquilapollenites indicus* and some Early Cretaceous reworked palynomorphs, viz. *Crybelosporites striatus*, *Aequitriaradiates ornatus* and fungal spores. Besides the above palynobiota, a rich assemblage of freshwater fauna comprising gastropods and ostracods has also been recovered during the present investigation.

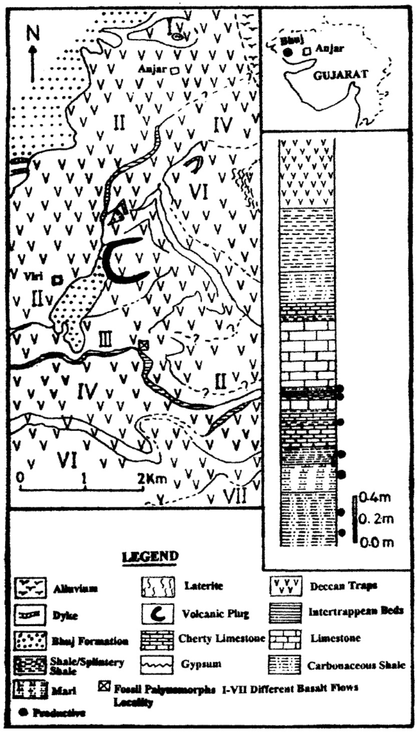

Figure 1. Geological map of Anjar area and lithostratigraphic section at the collecting locality (map after Ghevariya[1]).