Chapter - VIII

CARBON DYNAMICS AND MODELS ON LAND-USE/COVER BASIS

8.1 INTRODUCTION

The relatively large amounts of carbon associated with the world's forests and other land usage attract attention to the terrestrial reservoir as a major component of the carbon cycle. The world forests might even be managed to increase carbon storage (Whittaker & Likens 1973; Olson 1975; Baes *et al.* 1977). Large quantities of carbon are stored for longer periods of time in the soil than in live components of the terrestrial system (Schlesinger 1977). An assessment of the magnitudes of terrestrial carbon pools and associated residence times is difficult because of the large variability in vegetation across landscape. The impact of man's activities on the global terrestrial system, particularly through land-use/cover change, further confounds the issue (Bolin 1977; Woodwell *et al.* 1978).

Allocation and circulation of carbon in different components constitute major characters of ecosystems. In natural terrestrial ecosystems, carbon is assimilated from the atmosphere by photosynthesis and returned by respiration and fire. For natural communities viewed over reasonably long periods of time, net primary production (gross primary production, less plant respiration) is balanced by heterotrophic respiration (from fungi, bacteria and animals) and fire so that no net accumulation of carbon occurs (Emanuel *et al.* 1981). However, any sort of perturbation such as a change in climate or land-use/cover will upset this equilibrium so that particular portions of the terrestrial landscape may act as either source or sink for carbon with respect to atmosphere (Sitaula *et al.* 1995).

A greater difficulty is the current rather than historical nature of information on carbon cycling in the terrestrial biota. Inventories of terrestrial vegetation reflect current conditions. The increasing atmospheric loading of carbon dioxide and consequent increase in global temperature has focused the interest in carbon dynamics of natural ecosystems. This chapter describes carbon dynamics and mathematical compartment model for circulation of carbon on land-use/cover basis. Based on an updated estimate of the inventory of carbon in terrestrial systems, an initial set of rate coefficients for carbon exchange between reservoirs are calculated. The resulting mathematical model is very preliminary, yet it can be used to explore, through simulation experiments, the general dynamic properties of the terrestrial carbon system.

8.2 CARBON DYNAMICS

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.

The results of the study reveal a dynamic picture of changes in land-use/cover. Over the span of thirteen years, forests have decreased by 28%. This has resulted due to an increase in croplands and wasteland. To meet the increasing needs of forest products for fuel and fodder, such changes in land-use was expected. The growth of population in the watershed was on an average rate of 2.84% per year over the period of 1981-1991 and the forest cover decreased at an alarming rate of upto 2.80% per annum, which is excessively high. It has been envisaged that carbon balance and hydrological cycle have been disrupted. A study on land–use/cover basis for one season in the watershed indicated that the soil organic carbon loss ranged between 0.534 to 20 kg ha^{-1}. In the crop fields of the watershed which are highly vulnerable to erosion, a large amount of manure input is required to off set the carbon losses.

Shifts in land-use have a major effect on terrestrial carbon storage. Data on carbon storage and carbon budget in different land-use/cover are summarized in Table 8.1. Most of the ecosystem carbon is stored in the plant biomass in temperate natural forest dense and subtropical natural forest open, the proportion being 48-21%. The net carbon accumulation, generally ranged from 3 to 7 t ha^{-1} yr^{-1}. A comparative account of the nine land-use types showed high carbon stock in soils. Total carbon in soils of different land-uses ranged from 37 to 472 t ha^{-1}. Soil total carbon stock was greater in temperate natural forest dense by 1.8 times that of cardamom based agroforestry and 5.5 times that of open cropped areas of both the belts. As the population grows, more land is required to supply food and fulfill other needs. Besides this, future agricultural demand will strongly affect land-cover patterns and this in turn will affect the flux of CO_2. The total release of carbon to the atmosphere from the watershed was 305×10^3 tC. Reduction in the biomass of the forests as result of conversion was responsible for a net release. The Sikkim Himalaya forests, when unexploited are effective net sink of CO_2.

8.3 DEVELOPMENT OF COMPARTMENT MODEL FOR CARBON CYCLING

To develop mathematical representations of the global carbon cycle, a compartment modeling approach is employed (Emanuel *et al.* 1981). Carbon is distributed over a set of well-mixed reservoirs or compartments connected by fluxes. An ordinary first order differential equation reflecting material balance is associated with each compartment. Functions expressing the dependency of each flux on compartment contents and physical variables such as temperature are substituted in these mass balance equations. The resulting system of differential equations forms a model for the dynamics of the carbon cycle which can be solved, usually by numerical methods, to simulate time courses of the carbon content of each compartment from specified initial levels.

Several compartment model structures for representing terrestrial ecosystems in the global carbon cycle have been proposed. Generally, the terrestrial carbon reservoir has been divided into two compartments. This division has frequently been between live and dead (Erikson & Welander, 1956; Bolin 1970; Gowdy *et al.* 1975). An alternative arrangement which allows greater flexibility in reflecting the range of characteristic response times of the terrestrial biota is the use of rapid and slow compartments corresponding to the mean residence times of carbon (Machta 1971; Keeling 1973; Bacastow & Keeling 1973). Recent emphasis on the fluxes of CO_2 due to land-use/cover change has motivated the further division of these rapid and slow compartments (Chan *et al.* 1979). These approaches share common difficulties. Any two-compartment system provides less resolution of response times than desired. The compartment diagram in Fig 8.1 forms the basis for the model proposed here for circulation of carbon.

Carbon in all live vegetation except trees is lumped into the single compartment that is labeled ground vegetation. Carbon in trees is divided into two compartments, i.e. leaf and the woody. The woody pool contains carbon in branches, bole and roots. On the basis of currently available data, the total carbon in forest ecosystems is assigned to the tree reservoir; carbon in the remaining ecosystems is assigned to the ground vegetation pool. This assumption implies an approximate balance between the carbon in trees in nonforest ecosystems and that in ground vegetation in forest ecosystems may be underestimated, biasing the division of live carbon used here toward the tree pools.

Two compartments are used to lump carbon in dead parts and their decomposers. The detritus/decomposer compartment represents the litter and humus and its decomposers generally at the soil surface. This pool receives the direct input of carbon from deaths of live above-ground parts of vegetation. The soil carbon pool is the carbon in soils and the compartment which is undergoing rapid decomposition. Carbon is transferred into this pool by death and initial decomposition of below-ground parts of vegetation and transport of decomposed material from the actively decaying litter layer. Respiration of organisms decomposing this active soil carbon pool gives it a turnover time in the order of 100 years (Emanuel *et al.* 1981).

The compartment representation for circulation of carbon is viewed as being in equilibrium in 1970. In some instances, this assumed equilibrium has been used to set the numerical value of certain fluxes, particularly those due to respiration. The approach employed here is to use the assumption of 1970 equilibrium for model development and calibration. This equilibrium is then modified or unbalanced, based on alternative ideas of previous system status. This approach will likely stand until methods of inferring past histories of the carbon cycle are perfected. In this study base value of 1970 provided by Emanuel *et al* (1981) is used.

The compartment model for circulation of carbon (Emanuel *et al.* 1981) in the watershed is based on a model structure which parallels the components of these systems more closely than other models. Simulation experiments using this model can therefore be compared more readily with field data. Perhaps more important in resolving the uncertainty about future increases in atmospheric CO_2 concentration resulting from continued anthropogenic pressure is the more detailed treatment of the residence times in various pools of the terrestrial carbon circulation system.

The average fluxes of carbon between compartments for 2000 are collected by direct field measurements. The total respiration of CO_2 from the ground surface has been measured on land-use/cover basis. In developing the model equations corresponding to Fig 8.1, a single first-order ordinary differential equation is used to express material balance for each compartment. The fluxes between compartments are assumed to be linearly proportional to the content of the donor compartment:

$$Fij = Kij\ Ni \qquad (1)$$

Where Fij is the flow of carbon from compartment i to compartment j (tC ha^{-1}); Ni is the standing crop of carbon in the donor compartment i (tC); Kij is the corresponding rate coefficient (yr^{-1}). Utilizing the variables from each land-use/cover, the model equations are:

1. Temperate Natural Forest Dense

(i) $\frac{dN_2}{dt} = 1.61N_3 - 0.829N_2$

(ii) $\frac{dN_3}{dt} = 4.836N_2 - 1.73 \times 10^{-3} N_3$

(iii) $\frac{dN_5}{dt} = 1.73 \times 10^{-3} N_2 + 0.365 N_3 + 0.270 N_4 - 0.030 N_5$

2. Temperate Natural Forest Open

(i) $\frac{dN_2}{dt} = 1.17 N_3 - 0.818 N_2$

(ii) $\frac{dN_3}{dt} = 4.061N_2 - 2.24 \times 10^{-3} N_3$

(iii) $\frac{dN_5}{dt} = 2.24 \times 10^{-3} N_2 + 0.430 N_3 + 0.2075 N_4 - 0.072 N_5$

3. Subtropical Natural Forest Open

(i) $\frac{dN_2}{dt} = 3.76N_3 - 0.953N_2$

(ii) $\frac{dN_3}{dt} = 10.63 N_2 - 2.35 \times 10^{-4} N_3$

(iii) $\frac{dN_5}{dt} = 2.235 \times 10^{-4} N_2 + 0.425 N_3 + 0.217 N_4 - 0.1437 N_5$

4. Cardamom Based Agroforestry System

(i) $$\frac{dN_2}{dt} = 0.445\ N_3 - 0.639\ N_2$$

(ii) $$\frac{dN_3}{dt} = 1.448\ N_2 - 0.022\ N_3$$

(iii) $$\frac{dN_5}{dt} = 0.022\ N_2 + 0.390\ N_3 + 0.0577\ N_4 - 0.0627\ N_5$$

5. Mandarin Based Agroforestry System

(i) $$\frac{dN_2}{dt} = 1.181N_3 - 0.033\ N_2$$

(ii) $$\frac{dN_3}{dt} = 4.14N_2 - 0.026\ N_3$$

(iii) $$\frac{dN_5}{dt} = 0.026\ N_2 + 1.55\ N_3 + 0.270\ N_4 - 0.089\ N_5$$

Many of the transfers of carbon likely depend on the carbon contents of the compartments in a more complex way than captured by the linear assumption (1). Further, rates of carbon transfer are effected by environmental conditions such as temperature. Rodhe & Bjorkstrom (1979) have demonstrated that more complex functional relationships for carbon fluxes in compartment models can lead to significantly different system response. At present however, sufficient data are not available for calibration of more complex expressions for carbon fluxes. Until further refinement is possible, linear differential equations can be used to gain preliminary understanding of the carbon cycle particularly with regard to the implications of different choices of compartmental structure or major changes in relative magnitudes of fluxes between compartments.

8.4 MODEL APPLICATION

The system of differential equations (1) forms a dynamic model for the circulation of carbon in terrestrial ecosystems, which can be coupled to models for circulation of carbon. The ultimate conclusions from adopting the view of the terrestrial carbon subsystem expressed by this model can only be evaluated in a total cycle context; however, it is instructive to carry out a preliminary analysis of this terrestrial module, decoupled from the remainder of the system, to clarify the general response characteristics of this part of the carbon cycle.

For the present model the data of 1970 (Emanuel *et al.* 1981) is used as the base value. Based on these data the present day scenario was evaluated. Maintaining the same ratios among compartment contents implies that increases in atmospheric CO_2 serve only to enhance gross primary production without otherwise changing the structure of the system.

The developed model was used to simulate the total mass of carbon in different land-use/cover. The total mass of carbon in different land-use/cover given by this simulation is presented in Table 8.2. Slight deviations in the model-simulated and estimated carbon storage values are perhaps due to some unaccounted factors.

8.5 DISCUSSION

The simulated result of carbon in different land-use/cover reveals that there were some discrepancies among the observed and simulated values. It is important to establish the propensity of the terrestrial carbon system to act as a sink for carbon from the atmosphere independent of whatever carbon may be released to the atmosphere as a result of land-use/cover change. It is assumed in the model presented here that CO_2 fertilization simply increases gross primary production and therefore the content of the photosynthesizing compartments of the system. Increase in other compartments is then induced by the transfer of carbon from these source pools. The rate coefficients or efficiencies of transfer are assumed to be unaltered. The predicted value shows that there is reasonably good agreement between observed and predicted values except for few land-uses due to some unaccounted factors. To support a larger decrease in the terrestrial soil carbon pool given by these simulations, at least some transfer rates must be changed. The extreme might be to assume that the amount of carbon in photosynthetic material remains constant and that CO_2 fertilization serves to increase the efficiency of transfer to other terrestrial compartments.

This model can be used to know the circulation of carbon due to land-use/cover change in the Himalayan region. The potential approaches to modeling these transfers are on the natural terrestrial carbon circulation. As pointed out by Emanuel *et al.* (1981), the age distribution of dead carbon is more complex than is captured by the two compartments of this model. In reality, decaying material passes through a number of stages, i.e. there is a fair range of turnover times associated with this component. In conclusion, this model can be used to predict the compartment circulation of carbon in different land-use/cover in the Hindu-Kush Himalayan region.■

Table 8.1 Carbon storage and carbon dynamics of different land-use/cover in Mamlay watershed of Sikkim Himalaya.

	TNFD	TNFO	SNFO	CBAS	MBAS	OCAT	OCAS	WLAT	WLAS
Carbon storage (t C ha^{-1})									
Vegetation	191.27	86.13	90.23	46.79	5.47	4.24	3.01		
Forest floor	4.57	2.94	3.03	5.20	1.50				
Humus	1.41	0.87	0.63	1.12					
Soil, 1m depth	472	219	126	255	150	37	48	89	124
Annual carbon budget (t C ha^{-1} yr^{-1})									
Primary productivity	7.43	5.47	5.11	5.91	3.00	4.24	3.01		
Soil, humus and litter respiration	19.32	18.92	21.59	20.04	13.38	20.89	21.67	10.59	13.39
Carbon loss through sediment output (kg ha^{-1})	0.534	0.829	1.046	0.703	1.004	15.912	20.018	0.979	0.836

TNFD=Temperate natural forest dense, TNFO=Temperate natural forest open, SNFO=Subtropical natural forest open, CBAS=Cardamom based agroforestry system, MBAS=Mandarin based agroforestry system, OCAT=Open cropped area temperate, OCAS=Open cropped area subtropical, WLAT=Wasteland area temperate and WLAS=Wasteland area subtropical

Table 8.2 Model-simulated values of carbon (tC ha^{-1}) in different land-use/cover of the Mamlay watershed

Land-use/cover	Woody mass	Soil
Temperate natural forest dense	236.94	465.96
Temperate natural forest open	175.88	141.48
Subtropical natural forest open	198.24	24.99
Cardamom based agroforestry system	137.23	209.82
Mandarin based agroforestry system	19.53	99.01

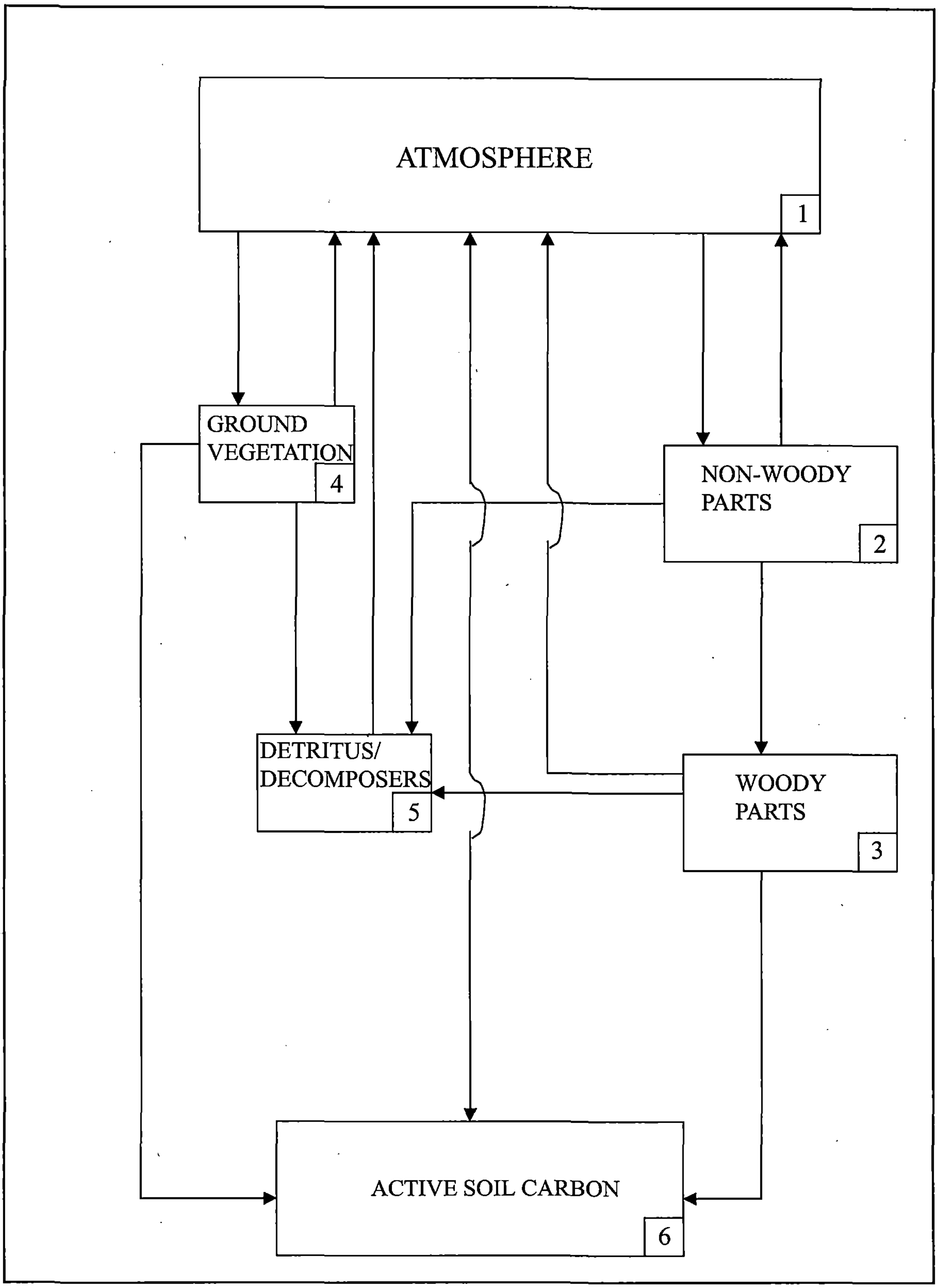

Fig. 8.1 Compartment diagram for the circulation of carbon in the Mamlay watershed. The number of each compartment, corresponding to its variable assignment in the model equations is boxed in each compartment.