ECOLOGICAL LINKAGES OF CARBON DYNAMICS IN RELATION TO LAND-USE/COVER CHANGE IN A HIMALAYAN WATERSHED

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SCIENCE (BOTANY)

By

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I have a great pleasure in forwarding the thesis of Miss Purnima Sharma, M.Sc. (Botany) entitled "Ecological Linkages of Carbon Dynamics in Relation to Land-Use/Cover Change in a Himalayan Watershed" for the degree of DOCTOR OF PHILOSOPHY IN SCIENCE (BOTANY).

This is to certify that the research work presented in the thesis is original and taken up by her under our supervision at the G.B. Pant Institute of Himalayan Environment and Development, Sikkim Unit. I recommend that she has fulfilled all the requirements according to the rules of the University of North Bengal and the Institute regarding the works embodied in her thesis.

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11-05-03

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ACRONYMS AND ABBREVIATIONS

asl	Above Sea Level
BAHC	Biospheric Aspects of Hydrological Cycle
C	Carbon
CBH	Circumference at Breast Height
cm	Centimeter
CO_2	Carbon Dioxide
CPPC	Core Project Planning Committee
DBH	Diameter at Breast Height
ES	Eroded soil
FCC	False Colour Composite
g^{-1}	Per Gram
GAIM	Global Analysis, Integration and Modelling
gC	Gram Carbon
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystem
GDP	Gross Domestic Product
GEC	Global Environmental Change
GTOS	Global Terrestrial Observing System
ha^{-1}	Per Hectare
IHDP	International Human Dimension Programme
IGBP	International Geosphere Biosphere Programme
IGOS-P	Integrated Global Observing Strategy Partnership
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing Satellite
kg	Kilogram
km^{-2}	Per Kilometer Square
LISS	Linear Imaging Self Scanner
LOICZ	Land-Ocean Interactions in the Coastal Zone
$l\ S^{-1}$	Liter Per Second
LUCC	Land-use and Land-cover Change
m	Meter
mg	Mili Gram
mm	Mili Meter

MCT	Main Central Thrust
MRI	Mountain Research Initiative
M t	Metric Ton
NTFP	Non Timber Forest Produce
PAR	Photosynthetically Active Radiation
PAGES	Past Global Change (IGBP)
Pg	Peta Gram
PRA	Participatory Rural Appraisal
PS	Parent Soil
RPPC	Research Programme Planning Committee
SCOPE	Scientific Committee on Problems of the Environment
SIC	Soil Inorganic Carbon
SOC	Soil Organic Carbon
START	Global Change System for Analysis, Research and Training
tC	Ton Carbon
TC	Total Carbon
TOC	Total Organic Carbon
UNCED	United Nations Conference on Environment and Development
WCRP	World Climate Research Programme
yr^{-1}	Per Year

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Chapter - I

INTRODUCTION

1.1 THE CONTEXT

Mountain regions occupy about one fourth of the Earth's terrestrial surface (Kapos *et al.* 2000), they are home to approximately one tenth of the global population, and provide goods and services to more than half of humanity and are in the nearby environs of approximately one fourth of the global population (Messerli & Ives 1997). Accordingly, they received particular attention at the highest level during the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro "Earth Summit" with the inclusion of Chapter 13: "Managing Fragile Ecosystems - Mountain Sustainable Development" in Agenda 21. "Chapter 13" of this document focuses on mountain regions, and states, "Mountain environments are essential to the survival of the global ecosystems, many of them are experiencing degradation in terms of accelerated soil erosion, landslides, and rapid loss of habitat and genetic diversity, hence, proper management of mountain resources and socio-economic development of the people deserves immediate action" (Becker & Bugmann 2001). Unfortunately the capacity of mountain ecosystems to provide continued resources is threatened due to increasing stress of human impact at global level in general and Himalayan region in particular.

The human impact on the global environment has received wide attention in past. Marsh (1864) recognized the deleterious consequences of human activities on the earth's landscape. More recently, Thomas (1956) lent further credence to the notion that one of the most obvious global changes in the last three centuries has been the direct human modification and conversion of land cover. Land-use changes are cumulatively transforming land-cover at an accelerating pace (Turner *et al.* 1994; Houghton 1994). These changes in terrestrial ecosystems are closely linked with the issue of the sustainability of socio-economic development since they affect essential parts of our natural capital, such as climate, soils, vegetation, water resources and biodiversity (Mather & Sodsyuk 1991).

Land cover transformation is significant to a range of themes and issues central to the study of global environmental change. The alterations and its effect on the surface of the earth hold major implications for sustainable development and livelihood systems and also contribute to changes in the biogeochemical cycles of the elements affecting the atmospheric levels of greenhouse and other trace gases.

The land-use change from forest to other usage has been quite conspicuous in the last few decades in the Hindu-Kush Himalayan region (Singh & Singh 1992). It has been envisaged that carbon balance and hydrological cycle have been disrupted. The consequences of land-use transformation from forest to agriculture, in the developing countries of the tropics has aroused international concern for human poverty, loss of plant and animal species, erosion of landscape, siltation of water courses, and flooding (Turner *et al.* 1990). The reduction of original forest cover already amounts to at least 21% in Asia and Australia (Jackson 1983; Rubinoff 1983). These changes have contributed to manifold and massive alterations of fundamental biochemical cycles (e.g., carbon cycle) and have been a major contributory source to increased CO_2 concentration in the atmosphere in the region (Clark 1982; Houghton 1990).

The historical conversion of natural systems to agriculture and other human uses of the land have resulted in a net release of CO_2 to the atmosphere (Houghton *et al.* 1985; Houghton *et al.* 1987; Houghton & Skole 1990). The impact of human land-use on the global carbon cycle through changes in terrestrial vegetation, is a major research concern in understanding the control of global carbon cycle, and therefore, future climatic changes by land and ocean (Houghton *et al.* 1983; Siegenthaler & Oeschger 1987). The global mobilization of carbon from soils and vegetation, estimated at 2-2.8 x 10^{15} g C in 1989 (Houghton 1990), mainly results from changes in land-use in the tropics and represents 25-35% of carbon mobilization from fossil fuels.

Deforestation is still one of the most important sources of CO_2 emissions into the atmosphere. Deforestation accounts for substantial release of carbon, one third of which could be due to oxidation of soil carbon in tropics occasioned by changes in land-use pattern (Singh *et al.* 1991). Deforestation has occurred since the evolution of early settlements and the start of agriculture but over the last decades its rate has accelerated. The resulting net flux from such changes in land-use is difficult to establish because most deforested plots are abandoned after a shorter or longer period of intensive use. This dynamics make the determination of carbon fluxes more complex because during forest re-growth carbon is sequestered again. Carbon dynamics also depend on the dynamics of abandonment, which are complex and depend on a multitude of socio-economic conditions and possibilities for land-use, including suitability for agriculture. The evaluation of carbon dynamics under such land-use change thus requires a detailed description of activities both in time and space. Historic and current land-cover and its land-use have to be portrayed and changes have to be adequately monitored.

Based on the results obtained for Central Himalaya and assuming the same conditions, total net release of carbon in the entire Indian Himalayan forests has been assessed by Singh *et al.* (1985). It is cleared that, because of over exploitation, the Himalayan forests have become a net source of CO_2 to the atmosphere. Most of these forests when unexploited can constitute an effective net sink of CO_2 (Singh *et al.* 1985). Besides this, tropical forests contain as much as 40% of the carbon stored as terrestrial biomass (Phillips *et al.* 1998) and account for 30 to 50% of terrestrial productivity. Therefore a small perturbation in this biome could result in a significant change in the global carbon cycle.

The impact of humans on natural vegetation as the processes of logging and timber removal or conversion of forest to other land-uses has long-term consequences on secondary vegetation, involve gross disruptions of nutrient cycles and water balances (Turner *et al.* 1997). The extent of which these practices result in losses of soil and nutrients affecting subsequent re-growth of vegetation, depends upon the severity of disturbances and the degree to which the differences between the depletion of the capital and plant demands is made up by weathering and or atmospheric inputs (Anderson & Spensor 1991).

Soil erosion is a major environmental threat to the sustainability and the productive capacity of agriculture. During the last forty years, nearly one third of the World's arable land has been lost by erosion and continues to be lost at a rate of more than 10 million hectare per year (Pimental *et al.* 1995). Rivers carry multiple forms of carbon especially in soluble form. This transport has been particularly studied in the 1980s for many major world rivers within the SCOPE-Carbon Programme (Degens *et al.* 1991). Rai & Sharma (1998a) made a study on hydrology and nutrient flux in different land-uses in the Sikkim Himalaya. The importance of hydro-ecological linkages in different land-uses in a watershed has been discussed in greater details (Rai & Sharma 1996). This demonstrates that the changes in land-use/cover may trigger changes in the hydrological cycle which in turn would have significant implications for land-uses.

The importance of land-use/cover change and its role in carbon cycle is duly recognized by the International Geosphere Biosphere Programme (IGBP) and the International Human Dimension Programme (IHDP) on Global Environmental Change (GEC). The IGBP also has a focus on these issues through the programme on Biospheric Aspects of Hydrological Cycle (BAHC), Global Change and Terrestrial Ecosystem (GCTE) and Land-Use/Land Cover Change (LUCC). In order to address the consequences of global change in mountains around the world, an initiative for collaborative research on global change and mountain regions - the Mountain Research Initiative (MRI) - was developed and officially launched in July 2001. It will involve close collaboration between these organizations.

The pace, magnitude and spatial reach of human alterations of the Earth's land surface are unprecedented. To understand recent changes and generate scenarios on future modifications of the Earth System, the scientific community needs quantitative, spatially explicit data on how land cover has been changed by human use over the last 300 years and how it will be changed in the next 50-100 years.

1.2 IMPORTANCE

A large scale land transformation in the past few decades in the Himalayan region may have altered the hydrological cycle and carbon balance of the terrestrial ecosystems. The land-use change from forest to agriculture has been quite conspicuous over the last 40 years in a watershed of Sikkim (Rai *et al.* 1994). The land transformations may have caused tremendous loss of carbon to atmosphere and to streams, which could have both regional and global concerns in terms of climate change. These carbon loss and carbon dynamics in relation to hydro-ecological linkages have not been quantified in understanding functioning of watershed's. Land-use change is expected to cause enormous loss of valuable nutrients from the natural systems. It is also envisaged that the hydro-ecological linkages are distorted in the process of land-use transformation. Such changes in the Himalayan watersheds draw research attention towards understanding the mechanisms of change in the ecosystem processes. Carbon is the most appropriate indicator for studying the mechanisms of change in the ecosystem functioning in a series of land-use transformation from natural forest to plantation forest to different types of agroforestry systems and to open agriculture.

In view of limited information available on watersheds of the Himalaya in general and eastern Himalaya in particular, this work was undertaken to study carbon dynamics in relation to land-use/cover change and hydro-ecological linkages on a watershed level with implications at regional and global biospheric disruptions. The study has been planned with following hypotheses and objectives.

1.3 HYPOTHESES AND OBJECTIVES

Hypothesis-I

The land-use transformation from forest to agriculture and wasteland causes tremendous loss of carbon from the land-cover systems to the atmosphere and streams that disrupts the hydrological cycle and also contributes to climate change in a regional scale.

Objectives to test hypothesis-I

- Dynamic monitoring and systematic analysis of land-use/land-cover change.
- Investigate the hydrological parameters such as overland flow, soil erosion, carbon loss through soil erosion, and sediment concentration in stream water and discharge on land-use/cover basis.
- Study the biogeochemical cycling of carbon i.e. carbon flux between compartments along with carbon fixation, loss through respiration, harvest flux, land cover change loss and agricultural loss and sequestration.

Hypothesis-II

Carbon is the most appropriate indicator for studying the mechanisms of change in ecosystem functioning in a series of land-use transformation.

Objectives to test Hypothesis-II

- Study the land-use sustenance taking the soil carbon level as an indicator.
- Quantify the carbon budget in various ecological compartments and also in humus and litter components in different land-uses.
- Correlate the hydrological processes with ecological dimensions and ultimately develop a mathematical model to quantify ecological linkages especially in relation to carbon dynamics.

1.4 APPROACH

In recent years, high growth rate of human and livestock population has enormously increased the food demand and pressure on natural resources. This has put tremendous pressure on certain land-uses e.g., forests are getting converted to more agricultural lands disrupting support forest system for maintaining agricultural fertility; conversion of pasture land to wastelands and degradation of close canopy forest to open and scrublands has major leading factors for imbalancing hydrological and biogeochemical cycles at a regional and global scale. It is understood that factors leading to unsustainability in mountain system need corrective measures through identification of various resources, their utilization pattern, consequences and quantification of the extent of the problems.

A conceptual frame was developed to understand the main linkages between physical environment, land-use systems and human driving force (Fig 1.1). These linkages related to land-use/cover change are visible at watershed levels but impacts are directly felt at villages and households. It has greater ecological implications at regional and climatic zone levels. Land-use system components such as biodiversity, production systems, practices and soil-water systems are directly impacted by the human driving force, while at the process level it is the alterations of physical environment that has profound impacts. However, at the land-use system, components and processes are inter-effected. These land-use/cover changes at the watersheds show resilience by adjusting and interplaying between components and processes of land-use system as affected by changing physical environment and human driving force (Fig 1.1). This conceptual frame of interactions has been conceived to guide the study approach followed in this thesis.

Varied human driving forces (e.g., population or development), mediated by the socio-economic setting (e.g., market economy, resource institutions) and influences by the existing environmental conditions lead to an intended land-use of an existing land cover through the manipulation of the biophysical conditions of the land. This type of information is necessary to understand properly the land-use/cover change and the carbon input levels and change in physical environment, which control the turnover rate of soil organic matter. This type of conceptual model helps to design and monitor the long term dynamics of carbon and nutrients in natural and managed ecosystems.

It is therefore imperative to study such conversion at least at a watershed level that could be managed properly, since watershed is regarded as a functional unit for analysis of natural resource base and development planning in the hills. It is expected that the results would be replicated partially or fully in other watersheds of the mountain region. This will also help in policy decisions and management of land-uses in the Hindu-Kush Himalayan region.

1.5 DESIGN OF THE THESIS

The present study has been divided into eight chapters dealing with varied but interrelated aspects. Chapter one deals with an introductory outline of the land-use and carbon dynamics, hypotheses, objectives and approaches. Chapter two introduces the review of literature indicating the chronological development and changing content of the land-use/cover. Since not much study has been carried out on the topic in the Indian context, more attention is paid to review studies carried out in other countries. In addition, attempt has been made here to review IGBP initiatives on carbon challenge. The third chapter is devoted to describe the study area, climate and site characteristics. Land-use pattern, land-use/cover change detection, biomass status and community dependence has been examined in the fourth chapter. It is followed by hydrological analyses (chapter fifth). Carbon budget has been discussed in chapter six and carbon flux in chapter seven. Carbon dynamics and models on land-use/cover basis have been described in chapter eight. The end of the study is marked by a summary of basic elements and references.■

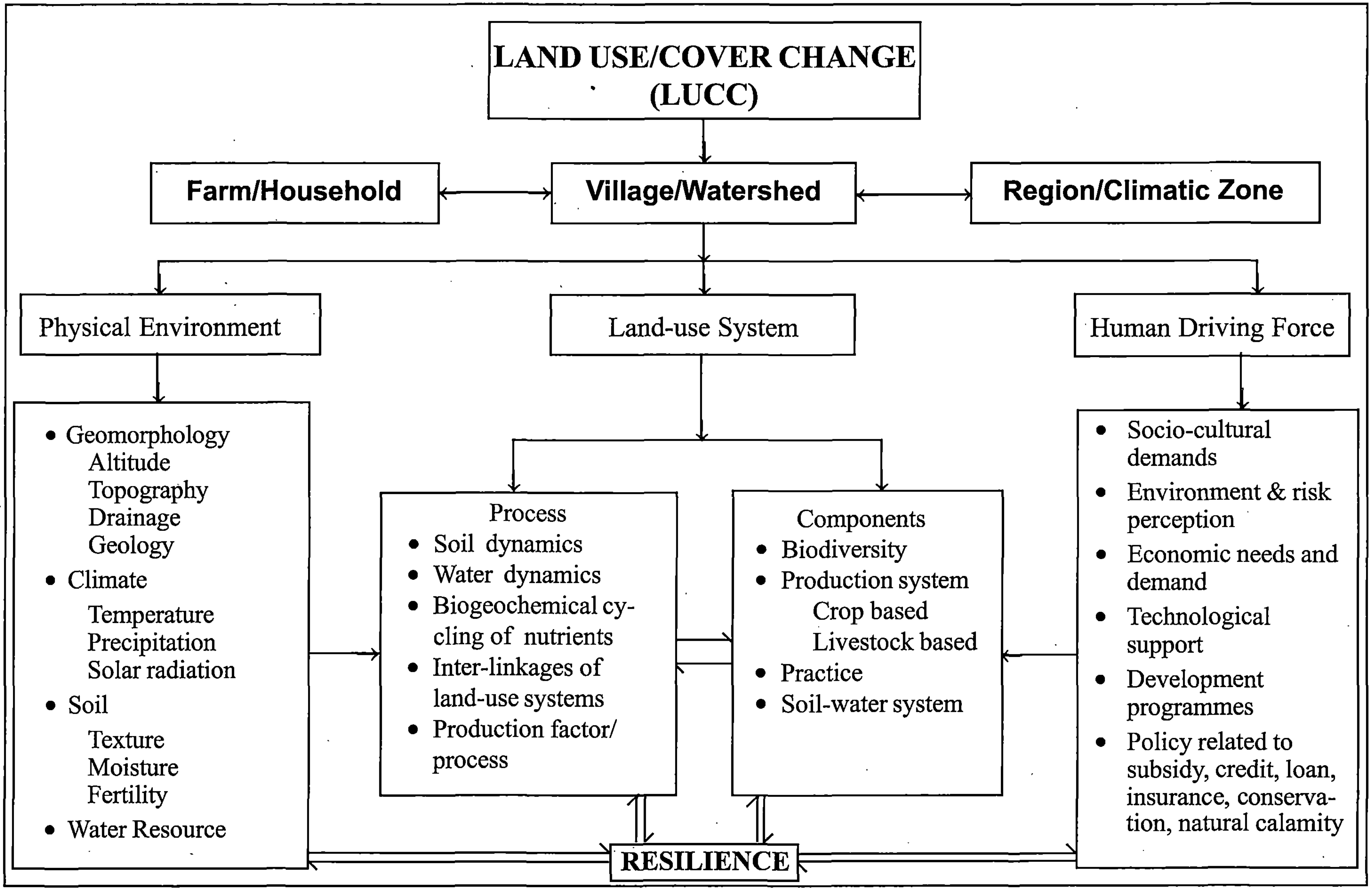

Fig. 1.1 Conceptual frame showing components and processes of land-use system which are influenced by physical environment and human driving force at a watershed level.

Chapter - II

REVIEW OF LITERATURE

2.1 LAND-USE/LAND-COVER CHANGE

The antiquity of land-cover changes is reflected in their prominence in the early classics of environmental science. George Perkins Marsh's *Man and Nature* (Marsh 1864) was a monumental assessment of data and theories, many dating back much earlier, on the effects of land-cover changes, particularly deforestation. Thomas (1956) argued that human driving forces play a key role to altered terrestrial ecosystems since, at least, the use of fire to hunt and the advent of plant and animal domestication. Such changes increased dramatically throughout the agricultural phase of history (Wolman & Fournier 1987), most strikingly in deforestation (Williams 1990) and the transoceanic movement of species (Crosby 1986; Turner *et al.* 1994). These changes were of no small consequences, and yet in spatial scale, magnitude, and pace they pale in comparison to those produced by modern industrial society. Today, land cover change of many kinds are global in spatial scale and magnitude and rapid, if variable, in pace, some of them large enough to contribute significantly to changes in global biogeochemical flow.

At a global scale, land-use changes are cumulatively transforming land cover at an accelerating pace (Turner *et al.* 1994; Houghton 1994). These changes in terrestrial ecosystems are closely linked with the issue of the sustainability of socio-economic development since they affect essential parts of our natural capital such as climate, soils, vegetation, water resources and biodiversity. Today, there is an increased recognition that land-use change is a major driver of global change, through its interaction with environment and natural resources and even more importantly human activities.

Land-use and land-cover change is significant to a range of themes and issues central to the study of global environmental change. Over the course of 20^{th} century, humans have emerged as a primary cause of land cover change around the world (Allen & Barnes 1985; Turner *et al.* 1990; Whitby 1992). The widespread transformation of land is mainly through efforts to provide food, shelter and products for human use. Land-use change is now recognized as an issue that is environmentally significant. The effects of land-use change and management are so significant that collectively they form one of the major environmental changes that are occurring at a global scale (Dale *et al.* 2000). To understand human-induced change in land cover, therefore, requires an understanding of its underlying social causes (Houghton *et al.* 1991; Lugo *et al.* 1987). This is especially true considering that most of the Earth's land is already damaged.

Global inventories of arable land have started date back at least a century (Ravenstein 1890) and those of forest resources almost as far (Zon & Sparthawk 1923). Surveys of global change such as the World Resources Institute reports and the recent volume *The Earth as Transformed by Human Action* (Turner 1990) assemble much historical and statistical material and outline the broad global and regional trend. A SCOPE Volume on *Land Transformation in Agriculture* (Wolman & Fournier 1987) covers the principal agricultural impacts on land cover. Recently, efforts have been made to quantify the nature and extent of land-use/cover changes at a global scale. Richards (1990) estimated that over the last 3 centuries, the total global area of forests and woodlands diminished by 12×10^6 million km^2 (19%), grasslands and pasture declined by 5.6×10^6 million km^2 (8%), and cropland increased by 12×10^6 million km^2 (466%). Such large changes in land cover can have important consequences such as significant changes in regional and global climate (Bonan 1999; Dickinson & Henderson 1988), modification of the global cycles of carbon, nitrogen and water (Houghton *et al.* 1983) and increased rates of extinction and biological invasion (Vitousek *et al.* 1997). Change accelerated globally, in terms of both the conversion of lands to cultivation and the intensification of agriculture on land already cultivated. Despite recent deforestation in parts of the tropics for livestock production, the area of rangeland and pasture has remained virtually the same over the last 300 years (Richards 1990).

Cropland expansion will undoubtedly continue in the near future, but land cover modification, through increasing intensification of agriculture, is likely to be of greater importance than further land-cover conversion (Ruttan 1993). Southgate (1990) provides a simple illustration: rising interest rates or agricultural prices will increase deforestation because they provide an incentive for further clearing. Most of the prime agricultural lands of the world, with the exception of some areas in the tropics, are already cultivated, and major increase in food production are likely to come from yield improvements on these lands through the application of fertilizers, pesticides and herbicides and irrigation. Irrigation of cropland has expanded some 24-fold over the past 300 years, with most of that increase taking place in this century. This practice has increased methane emissions, while the increasing frequency of land tillage world-wide has affected soil carbon (Cole *et al.* 1989; Rozanou *et al.* 1990).

Despite the recognition of the magnitude and impact of global scale changes in land-use and land cover, there have been relatively few comprehensive studies of these changes. Several continental-to-regional scale land-use data sets have been compiled. For example Houghton (1990) presents land-use data for nine continental-scale regions of the world. Richards & Flint (1994) have compiled a very comprehensive land-use data base for south and south-east Asia. But no such data sets are available for the Hindu-Kush Himalayan region except for some patch studies.

A rapid transformation of land-use has led to environmental degradation and economic deterioration in the Himalaya, where majority of people are living just at or below the subsistence level (Thapa & Weber 1990). The ecological consequences and the level of degradation of the fragile ecosystems of the Himalaya are well perceived and addressed by many national and international organizations for promoting more effective conservation of natural resources. But it is disheartening that most of the projects/study have proceeded without adequate knowledge of local land practices and environments and, perhaps even more importantly, without an adequate understanding of the capabilities and limitations of the people within them (Stone 1990).

The Himalaya, a region that holds the largest contiguous tropical to temperate forest in the world is going severe deforestation due to consequences of land-use change (Shah 1982; Asish 1983; Bajracharya 1983; Tiwari & Singh 1983; Fox 1984; Singh *et al.* 1984; Schroeder 1985; Moench & Bandyopadhyay 1986; Tiwari & Singh 1987; Byers 1987a, b, c; Khanal 1992; Rai *et al.* 1994; Byers 1996). Large–scale deforestation in the region started since 1823 when the British decided to expand the amount of arable land, and by the late 1860s in central Himalaya cultivated land had more than doubled. During 1840s and 1850s constituted the first era of large-scale uncontrolled deforestation to meet the timber demands of the people (Trucker 1983). The commercial exploitation of forests has since continued along with the expansion of agriculture. Shah (1982) argue that continued population growth has led to more farming, and as a result the area under cultivation has increased at a rate of 1.5% yr^{-1} and the cattle population at a rate of 0.18% yr^{-1}. Singh *et al.* (1984) estimated that only 28.7% of the Indian central Himalaya is now forested, and that only 4.4% of the area has a forest with greater than 60% crown density. Conditions in neighboring countries are no better. Studies indicate that this will affect the increase of carbon dioxide in the atmosphere, regional hydrology and climate (Singh *et al.* 1985). Therefore, a better understanding of land-use/cover change is required for the carbon dynamics in the Himalayan watershed.

2.2 HYDROLOGICAL STUDIES ON LAND-USE BASIS

Human disturbance of the water cycle is global phenomenons affecting both water fluxes and the transport and processing of sediments, carbon, and nutrients in aquatic ecosystems. Net fluxes of nutrients to the ocean are likely to have increased by a factor of about two (Meyback 1982). Although the riverine fluxes of total organic carbon (TOC), and sediments are known to be heavily affected by human activities at the regional scale, their changes at the global scale remain to be documented. High mountains that are tectonically active yield most sediment (Pinet & Souriav 1988; Milliman & Syvitski 1992; Ludwig *et al.* 1996), and about 70% of the global fluxes is produced in Southern Asia and large Pacific Islands, an area dominated by mountainous source areas, rapidly increasing population, and land cover change (Milliman & Meade, 1983).

Hydrological impacts of land-cover and land-use changes include changes in water quality and water flows. Water pollution due to land-cover change stems from cultivation (by applications of fertilizers and pesticides) and settlement (sewage) (Meyer & Turner 1992). Changes in water quality and flow associated with land transformation result both from deliberate withdrawals and from land-cover changes such as deforestation. It is reported that deforestation, especially in highlands, increases the frequency and severity of flooding downstream and some of the most notable example is the Amazon basin (Sternberg 1987; Richey *et al.* 1989) and the Himalaya Mountains-Ganges Basin (Ives & Messerli 1989). But there is no data available on global scale to indicate its magnitude and depletion rates on a land-use/cover basis (L'vovich & White 1990). Crosson (1990) for instance mentioned that there is very little reliable information about the amount of soil erosion in the developing countries and even less about its impact on productivity and water quality.

Hydrological studies on land-use/cover basis in Himalayan region are very limited. Recently only a few attempts have been made to analyse the impact of land-use change on the hydrological regime of the region (Upadhyaya & Roy 1982; Tiwari & Ali 1987; Bhandare & Pandey 1991; Bhatt & Pathak 1991; Rai & Sharma 1998a, b; Jain *et al.* 2000). There has been little attempt to link the observed data with land-use or land-use change in the Himalayan region.

The hydrological regime of the Himalayan river catchments is seriously affected by the deforestation of hill slopes. This has caused accelerated erosion particularly in areas where human activities have induced drastic changes in land-use pattern (Pandey *et al.* 1983; Singh *et al.* 1983; Carson 1985; Byers 1987a, b; Bartarya & Valdiya 1989; Valdiya & Bartarya 1991, Rawat & Rawat 1994; Rai & Sharma 1995; Collins & Jenkins 1996; Rai & Sharma 1998a, b; Jain *et al.* 2000; Sharma *et al.* 2001). Soil loss and degradation and sediment transport have undoubtedly been increased greatly as a consequence of land-cover change. The recent survey shows that 44% of total land of the Himalayan region is already identified under wastelands (Anonymous 2000). According to one estimate, nearly 85% of all agricultural land already suffers from severe erosion problems (Shah 1982). This problem is aggravated by population growth and land transformation especially road-building activities. The present rate of erosion in the catchment's areas of the Himalayan Rivers (100 cm/1000 years) is five times higher than the rate prevailing in the past 40 million years (21 cm/1000 years) (Singh *et al.* 1984). It can be seen that values of sediment load for the Hindu-Kush Himalayan region exceed the world average by almost two folds (Alford 1992). Therefore, the relationship between land-use/cover change and soil erosion and hydro-ecological process is an imperative for the Himalayan region.

2.3 ECOLOGICAL STUDIES IN FORESTS/ AGRICULTURE / AGROFORESTRY

All over Himalaya, forests have been used traditionally for meeting basic demands (fuel, fodder, timber and NTFPs) of surrounding communities. Disturbance has become a widespread feature in most of the forests all over the Himalaya (Singh & Singh 1987, 1992). During recent times, various forests have been investigated for their structure and function. Estimation of forest biomass is needed especially for the determination of site productivity, nutrient cycling and energy potential (Schmitt & Grigal 1981). The biomass and productive potential of the Himalayan and other forests' reports are available (Rodin & Bazilevich 1967; Singh & Ramakrishnan 1982; Chaturvedi & Singh 1982, 1984; Negi *et al.* 1983; Singh & Singh 1984, 1985; Singh *et al.* 1984; Tiwari & Singh 1984; Rana *et al.* 1989; Sharma & Ambasht 1991; Brown *et al.*

1991; Singh & Singh 1992; Sundriyal *et.al.* 1994a; Sundriyal & Sharma 1996). It is argued that the amount of biomass at different locations in the forest varied due to differences in species composition. In *Pinus roxburghii*, the weight of each component of the tree (i.e., bole, branch, foliage, and root) increases with age, and the total above-ground biomass in a 128-year old tree was 1939 kg (Chaturvedi & Singh 1982). In oak forest the wood biomass is 197.2 to 322.8 t ha^{-1} (Negi *et al.* 1983) in the Central Himalaya. The annual primary production equaled 8% of tree biomass in pine forest and 4% in oak forest (Singh *et al.* 1984). Tiwari & Singh (1984) tried to map the forest biomass using aerial photographs and satellite images. Over a large area, the above-ground tree biomass ranged from less than 80 t to more than 400 t ha^{-1} depending upon the forest type and basal cover. Singh & Singh (1984a, b, c) have reported that in the Central Himalaya the biomass of a majority of forests (163-787 t ha^{-1}) falls well within the range (200-600 t ha^{-1}) given for many mature forests of the world (Whittaker 1966, 1970). Similar results were also reported by Sharma (1993) and Sharma & Ambasht (1986, 1987, 1991) for eastern Himalayan forest. Lieth (1975) and Sharma & Ambasht (1987, 1991) concluded that the biomass is much affected by the age of the dominant plants and since the age differs among the forest, the relationship between productivity and the biomass is rather loose.

Litterfall and its decomposition in the forest ecosystems has been extensively studied in the region (Subba Rao *et al.* 1972; Singh & Ramakrishnan 1982; Chaturvedi 1983; Rawat 1983; Mehra & Singh 1985; Upadhyay & Singh 1985; Upadhyay *et al.* 1985; Sharma & Ambasht 1987). They reported that the annual litter fall ranges between 2.1 and 3.8 t C ha^{-1} yr^{-1}.

In Himalaya, more than 80% of the populations have farming as primary livelihood. There are three basic farming systems, all of which are livestock-based. Settled agriculture predominates at mid-hills between 1000 and 2500 m elevation, and dependent on cattle. The majority of cultivation is rainfed, producing three crops every two years. Since the middle mountains support large number of people, the lands have undergone severe ecological degradation (Pandey & Singh 1984a, c; Singh *et al.* 1984; Rai, 1993). It is reported that the each unit of the agronomic energy produced entails about seven units of energy from the adjacent forests in terms of fodder, firewood and litter. Singh *et al.* (1984) reported that against the requirements of 5.18 ha of forest land per hectare of cultivated land, at the present level of agro-activity, the ratio of agricultural land to forest is only 1:1.66 and the ratio of agricultural land to well- stocked forest is only 1:0.84. Thus, the carrying capacity of the forests has already been far exceeded.

The agroforestry systems in the Sikkim Himalaya can be categorized into two major types viz., large cardamom (*Amomum subulatum Roxb.*) based and multi-tier mandarin-based (Sundriyal *et al.* 1994b). Sharma *et al.* (1994, 1997a, b) have described the large cardamom-based temperate agroforestry specifically with respect to biomass, productivity and nutrient dynamics as an effect of N_2-fixing *Alnus*. At middle hills of eastern Nepal, *Alnus*-cardamom intercrop was studied as a model highland agroforestry system (Zomer & Menke 1993). Large cardamom based agroforestry system is an age old practice and yield reduces substantially on aging of stands (Singh *et al.* 1989; Zomer & Menke 1993). Cardamom is adapted to local soil conditions with very low soil and nutrient loss from the system compared to other cropped area (Rai & Sharma 1998a). Sharma *et al.* (1994) reported that the use of N_2-

fixing *Alnus* as an associate shade tree in cardamom agroforestry has been highly beneficial in terms of stand production, cardamom yield and nutrient cycling.

The other important agroforestry system in the Sikkim Himalaya is mandarin-based agroforestry system in the subtropical belt that comprised trees, mandarin and annual crops. *Albizia* trees are also grown in this agroforestry system. Sharma *et al.* (1995) reported that the stand total biomass, tree biomass and basal area were higher under the influence of *Albizia*. Similar results were also reported by De Bell *et al.* (1989). The contribution of crop biomass was almost the same in both the *Albizia*-mandarin and pure mandarin stands. However, mandarin fruit production was higher (by 1.2 times) in the *Albizia*-mandarin stand (Sharma *et al.* 1995).

Studies on litter production and decomposition dynamics of managed agroforestry systems are limited. Tarrant *et al.* (1969), Binkley *et al.* (1992) and Sharma *et al.* (1997a) have reported much greater litterfall in mixed stands with N_2-fixing associate than in stands containing only non-N_2-fixing trees.

2.4 CARBON DYNAMICS

Carbon dynamics depend on the land-use and land-cover change. The evaluation of carbon dynamics thus requires a detailed description of land-use pattern and change both in time and space. Soil is the largest pool of terrestrial carbon in the biosphere, storing some 1500 Pg of carbon in the upper meter of mineral soils which is about 2.5 times more than is contained in terrestrial vegetation (Houghton *et al.* 1985; Schlesinger 1986, 1997; Eswaran *et al.* 1993; Batjes 1996; Batjes & Sombroek 1997; Jobbagy & Jackson 2000; Singh 2002). World soils constitute one of the five principal global carbon pools. The soil C pool comprises two components, the soil organic carbon (SOC) pool with 1550 Pg of C in the top 1 m depth, and the soil inorganic carbon (SIC) pool containing 950 Pg C. The organic C pool in the soil affects plant production and thus plays a key role in soil fertility and agricultural production management more than a century (Hilgard 1906; Jenny 1941; Tiessen *et al.* 1994).

The conversion of forests to agriculture and other human uses leads to a net release of carbon dioxide to the atmosphere (Likens *et al.* 1970; Clarke 1982; Palm *et al.* 1986; Houghton *et al.* 1985, 1987, 1990, 2000; Houghton & Skole 1990; Singh *et al.* 1991; Sitaula *et al.* 1992, 1995; Wagai *et al.* 1998; Malhi *et al.* 1999). The land-use change that influences soil C storage and release within the tropics can have larger implications for global C cycling (Olson *et al.* 1983; Overpeck *et al.* 1991; Gramer & Solomon 1993; Hannah *et al.* 1994; Houghton 1994; Imhoff 1994). Changes in soil C following deforestation have become an international policy concern in terms of both sustained production at a local or regional scale (Tiessen *et al.* 1994) and the global consequences relating to increased emissions of CO_2 from terrestrial systems (Houghton 1991). Many important global and regional soil C budgets are available for some biomes (Schlesinger 1977; Post *et al.* 1982; Singh *et al.* 1985, 1991; Eswaran *et al.* 1993; Kern 1994; Gupta & Rao 1994; Raich & Potter 1995; Batjes 1996; Woodwell *et al.* 1998; Rastogi *et al.* 2002; Bhadwal & Singh 2002), and a few have directly examined the effect of more subtle land-use changes on soil surface CO_2 flux (Wagai *et al.* 1998). These studies have shown that the carbon content on soils declines under agricultural use. The observed carbon losses in agriculture are caused by low productivity levels, intensive tillage, inadequate fertilization, removal of residuals and erosion and management is important for soil carbon dynamics. Improved land-use management is an essential prerequisite for carbon sequestration. It is estimated that the application of improved management practices could sequester worldwide between 400 and 800 Mt C yr^{-1} (Leemans 1999).

Soil respiration is a major flux in the carbon cycle, second in magnitude to gross primary productivity, which ranges from 100-120 Pg C yr^{-1} and equal to or greater than the estimated global terrestrial net primary productivity of 50-60 Pg C yr^{-1} (Box 1978; Ajtay *et al.* 1979; Bolin 1983; Olson *et al.* 1983; Houghton & Woodwell 1989). Despite its importance in the global carbon cycle, the magnitude of soil respiration as affected by different land-uses is poorly quantified. The global mobilization of carbon from soils and vegetation, estimated at 2-2.8x10^{15} g C in 1989 (Houghton 1990), mainly results from changes in land-use in the tropics and represents 25-35% of carbon mobilization from fossil fuel. Global carbon dioxide concentrations have substantially increased from the mid-eighteenth century to the present day, and CO_2 is expected to reach 600 ppm before the middle of the century (Woodwell 1983; Kimball's 1983). The reduction of original forest cover is one of the most important sources of CO_2 emissions into the atmosphere (Clarke 1982; Houghton 1990). Deforestation accounts for substantial release of carbon, one third of which could be due to oxidation of soil carbon in tropics occasioned by changes in land-use pattern (Sanchez *et al.* 1983; Mann 1986; Dalal & Meyer 1986; Bouwman 1990; Singh *et al.* 1991; Batjes 1992). Deforestation not only transfers carbon stocks directly to the atmosphere by combustion, but it also destroys a valuable mechanism for controlling atmospheric CO_2 (Jeffery 2001).

The CO_2 emission through respiration, both by the vegetation itself and decomposition of organic matter increase with global warming (Grace & Rayment 2000). Deforestation may weaken the carbon sink provided by forests, and in long run the world's forests may eventually become a source of carbon to the atmosphere. Another study, Giardina & Ryan's (2000) results corroborate and extend findings from Finnish soils suggesting that, over long periods of time (decades), decomposition of organic matter is not very sensitive to temperature. But the results of Valentini *et al.* (2000) which come from a network of CO_2 flux measurement stations set across the Europe's forests are even more surprising. Valentini and colleagues showed that respiration is a more important component of the carbon balance in northerly latitudes despite the low temperatures there, and that it is really respiration, not photosynthesis, that varies over the latitudinal band from Iceland to Italy. Grace & Rayment (2000) suspect about the Valentini and colleagues findings. They argued that carbon fluxes in the tropics are larger than those in temperate and northern forests. But there is not enough information yet to comment on the long term effects of temperature on the carbon balance, and further data are needed to complete the global picture.

Soils are sources and sinks of carbon both by changes in the carbon content per unit soil (via assimilation and decomposition) and by the movement of soil itself through erosion and deposition (van-Noordwijk *et al.* 1994). The rate of export of dissolved organic carbon is closely related to biomass productivity. Kabat *et al.* (2001) analyzed that it is not significantly affected by human activity at global scale, and is thus highly dependent on the state of vegetation, in turn directly controlled by humans through land-cover change and global climate. The global system of rivers is increasingly being recognized as a major component of the biogeochemistry of our planet, as demonstrated nearly 30 years ago by the pioneering work of Garrels & Mackenzie (1972). Although riverine C fluxes form a minor component of the global carbon circulation, they are very sensitive to regional and global change as studied for many major world rivers within the SCOPE-Carbon programme (Degens *et al.* 1991; Meybeck & Vorosmart 1991). It is argued that future carbon transfers through river basins will be accelerated with respect to both sources and sinks. However, the final global trend is not yet known and the evolution of regional problems will probably show counteracting tendencies, making for an interesting and challenging global change question. A set of working scenarios for future river response to all global changes has already been proposed by Stallard (1998), taking into account various land-use practices. New global data bases are planned within the IGBP through PAGES, BAHC, and LOICZ programmes to estimate riverine carbon and allied biogeochemical constituent fluxes (Vorosmarty *et al.* 1997).

Possible adverse consequences of climatic changes resulting from increasing levels of atmospheric CO_2 have drawn attention to the inventory and dynamics of carbon in the biosphere (Chan 1982; Kellogg 1982). Carbon exchange between the terrestrial ecosystems and the atmosphere is one of the key processes that need to be assessed in the context of the Kyoto Protocol (IGBP Terrestrial Carbon Working Group 1998).

2.5 IGBP INITIATIVES ON LAND-USE/ COVER CHANGE AND CARBON CHALLENGE

In recent times the land-use and land-cover change is emerging as a central issue within the international communities concerned with global environmental change as it not only has local and regional impacts, but also has important effects at a much larger scale (Richards 1990). For example, man-made changes in land-use over the last 150 years have contributed about as much carbon dioxide to the atmosphere as has come from fossil fuel combustion (Houghton 1999). Therefore, importance of this issue is attested by the emerging International Geosphere-Biosphere Programme and the Human Dimensions Programme's Science agenda on land-use/cover change (IGBP-HDP LUCC) (Turner *et al.* 1993). There are many other international panels, workshops, and symposia devoted to the topic, i.e. 1991 Global Change Institute on Global Land-use/cover Change of the office of Interdisciplinary Earth Studies (Meyer & Turner 1994), the 1993 Symposium on 'Land Use and Land Cover in Australia: Living with Global Change', and the 'South East Asian Global Change System for Analysis, Research and Training' (START) programme. This concern is driven by the facts that land transformations bring about a wide variety of global changes- including greenhouse gases and potential global warming, loss of biodiversity, and loss of soil resources and the regional impacts (IGBP 1998).

The IGBP and IHDP jointly commissioned a core Project Planning Committee/Research Programme Planning Committee for land-use and land-cover Change (CPPC/RPPC LUCC) to create a science/research plan for a jointly sponsored LUCC core project/research programme. Simultaneously with the development of this, the demand for global land-use data base also emerged in the IGBP community. The evaluation of carbon dynamics under such land-use change thus requires a detailed description of activitities both in time and space. Historic and current land cover and its land use have to be portrayed and changes have to be adequately monitored (IGBP 1998). The current availability of comprehensive data sets covering and integrating all these aspects is poor. This is one of the reasons that LUCC, GAIM, GCTE, and PAGES are prioritizing the development of a historic land-cover and land-use database and simulating GCOS/GTOS to develop the necessary observations for monitoring land-use/cover change for future.

IGBP/IHDP-LUCC and IGBP-PAGES came together to take-up the challenge of providing the global change community with historical land-use data sets. PAGES, having participated in the BIOME 6000 projects, have experience with historical reconstructions for 6000 years before present. A new joint PAGES-LUCC initiative, labeled BIOME 300, was created to reconstruct historical land-use/land cover data sets for the last 300 years (1700 to 2000) with coarse time slices in the past (50-100 years) and finer time slices in the later periods (10-25 years) (Ramankutty *et al.* 2001). LUCC is currently recognized as one of critical gaps in our knowledge of the terrestrial carbon cycle which in turn has implications for the rate of greenhouse gas accumulation in the atmosphere and the potential climate change.

The Global change and Mountain Regions Research Initiatives is based on geographical feature- mountain regions that may experience the impacts of the rapidly changing global environment more strongly than others (Purohit 1991). Because of their unique characteristics and opportunities, various aspects of global change interactions with mountainous regions have already triggered significant activity amongst the research community. Within the IGBP the programme elements like

BAHC and GCTE have developed a number of activities related to mountainous regions (Becker *et al.* 1994; Chalise & Khanal 1996). All these developments are related to and confirm the importance of chapter 13 of Agenda 21 (the so-called "Mountain Agenda"), endorsed by the UNCED entitled "Managing Fragile Ecosystems- Sustainable Mountain Development", which also supports the need for further researches (Ives *et al.* 1997). BAHC and GCTE intend to provide the basic understanding of global change impacts on hydrology and terrestrial ecosystems that will underpin the impact studies undertaken by other groups, many of which will be working within the partner IGBP programme elements such as PAGES, LUCC (IGBP/IHDP) and through the START regional networks around the world.

"Greenhouse gases", especially carbon dioxide, are intimately connected to climate change. The international scientific community has responded to this unprecedented carbon challenge by developing a ten-year Global Carbon Cycle Joint Project. This project is co-sponsored by the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP) and the World Climate Research Programme (WCRP). The three programmes already worked together on some areas of carbon-cycle research. WCRP and IGBP work closely together on climate variability and have established a programme of ocean-carbon measurements. Recently, the IHDP and IGBP jointly sponsored a project on land-use and land cover change, including its implications for the carbon cycle. The challenge of obtaining and disseminating global carbon-cycle observations has been taken up by the Integrated Global Observing Strategy Partnership (IGOS-P). The ultimate goal is to understand the system well enough to make reliable projections of carbon-cycle dynamics into the future. In the present study, an effort has been made to assess the impact of land-use and land-cover change on carbon dynamics in a watershed basis, as it is considered as a functional unit in the mountain region with high implications for landscape management ■

Chapter – III

THE STUDY AREA, CLIMATE AND SITE CHARACTERISTICS

The Himalaya is the youngest, tallest and most fragile mountain system of the world, covering an area of approximately 5, 91,000 km^2. Extending for about 2,500 km from east to west, the Himalayan Arc covers more than 10° of latitudinal expanse, i.e. 27° to 38° N. Altitude varies greatly, and tropical and alpine communities may occur within a distance of 300 to 500 km.

The Himalaya has been formed as a result of northward movement of the Indian Plate striking against the Tibetan Plateau and came into existence in the Tertiary-Quaternary period. Since, the Indian Plate continued pushing northward, the Himalaya is still growing and thus its landscape is being reshaped time and again. An "incipient altitudinal zonation" of vegetation was established during the mid-Miocene in the Himalaya, when it was not that high (around 2200-2400 m) as it is today. Wet tropical forests on the lower slopes, wet temperate forests on the higher slopes, and wet sub-tropical types between the two, constituted the vegetation pattern in present time. Owing to its varied topography and climate, the Himalaya supports a variety of forests up to the timber line. However, one's perception of the dense and undisturbed forests in inaccessible valleys and ridges is shattered upon entering the Himalaya, whereas the fact remains that in most parts the forests are degraded and interspersed with deforested open 'blanks' and village settlements. The Hindu Kush Himalayan terrain is inhabited by about 150 million people with a multiple ethnic composition which further has an impact on its ecosystem making it more fragile.

The Himalaya constitutes a unique geographical and geological entity comprising diverse social, cultural and environmental set-up. It extends from the Indus Trench below Naga Parbat (8125 m) in the west to the Tsangpo (Bramhaputra) gorge below Namcha Barwa (7756 m) in the east, covering the political administrative regions of Afghanistan, Pakistan, India, Nepal, Bhutan, Myanmar, Tibet and China. Although it covers only 18% of India's geographical area, the Himalaya accounts for more than 50% of the country's forest cover and 40% of the species endemic to the Indian subcontinent (Myers 1990; Khoshoo 1992).

Generally three broad geographical divisions are recognized for the Indian Himalaya, viz., the western Himalaya that include Jammu & Kashmir and Himachal Pradesh; the central Himalaya consisting of Kumaon and Garhwal regions; and the eastern Himalaya extending from Sikkim to Arunachal Pradesh. Physiographically and geologically, four distinctive terrains are recognized in the Himalaya. From south to north, these are: Outer Himalaya, Lesser Himalaya, Higher Himalaya and Tethys Himalaya. The western and eastern flanks of the Himalaya are different in climate and vegetation. The western Himalayan ranges are much wider and colder with drier climate and vegetation is cold and drought resistant. In contrast, eastern ranges are among the wettest regions having rich diversity of vegetation. It is so because the highly precipitous hilly terrain of the eastern Himalayan amphitheatre happens to be at a closer proximity to the Bay of Bengal to receive more rainfall than the central and western Himalaya.

3.1 THE SIKKIM HIMALAYA

Sikkim or Sukhim (means New House), a small hilly state (27° 3' 47" to 28° 7' 34" N and 88° 03' 40" to 88° 57' 19" E) of India in the eastern Himalayan biogeographic zone that harbors largest number of endemics and endangered species in the Indian subcontinent, is recognized as one of the biodiversity 'Hot Spot' of global significance (Khoshoo 1992). The State is exceptionally rich in biodiversity. It extends approximately 114 km from north to south and 64 km from east to west. The State is bounded in the north by the Tibetan Autonomous Region of the People's Republic of China, in the east by Bhutan and the Chumbi Valley of Tibetan Autonomous Region of the People's Republic of China, in the west by Nepal and in the south lies Darjeeling Gorkha Hill Council of West Bengal State (Fig. 3.1). The entire Sikkim Himalaya constitutes a mountainous terrain spreading over 7096 km^2 and is a quite well-known in terms of its resplendent flora and faunal aggregation. It beholds one of the most magnificent ranges of snow clad mountains popularly known as the Khangchendzonga (8598 m) groups. The elevation of the State ranges between 300-8598 m above mean sea level.

Administratively the State is divided into four districts, viz., North, South, East and West and is a cornucopia of four major ethnic groups', viz., Lepchas, Nepalese, Bhutias and Limbus. The Lepchas are the aboriginal of Sikkim and are predominantly Buddhists. The Bhutias are the people of Tibetan origin. The people of Nepalese origin have migrated to Sikkim in large number from middle of the nineteenth century. The majority of the population is Nepalis (67%) who are Hindus by religion, followed by Buddhists (29%) and others (4%). The main livelihood option in the State is agriculture which earns about 47% of its GDP from this sector. There are 447 villages, out of which 440 are inhabited. A total of 540493 populations were recorded in 2001 with an average density of 76 persons km^{-2}. The rich natural and cultural heritage of Sikkim makes this small Himalayan State an attractive destination for international and domestic tourists (Rai & Sundriyal 1997).

The State has a good drainage network. The entire State is drained by the Tista and the Great Rangit through its numerous tributaries and innumerable sub-tributaries. The most important tributaries include the Zemu Chhu, the Rangyong Chhu, the Lachung Chhu, Ranthong Chhu, and the Ramam Chhu. The combined course of the Ramam and the Great Rangit marks the southern boundary of the State. The entire State is divided into two catchments, i.e., the Tista and the Rangit catchment. Further, the Rangit catchment comprises 51 micro-watersheds, including the Mamlay Watershed, which has been selected as the study area of the present work.

3.2 THE MAMLAY WATERSHED

The Mamlay Watershed is situated in the South District of Sikkim, which is the most populated zone. It extends from 27°10' 8" to 27° 14' 16" N and 88° 19' 53" to 88° 24' 43" E, embracing an area of 30.14 km^2. It has an elevational range of 300-2650 m above mean sea level, encompassing nine revenue blocks including 34 settlements (Fig 3.1).The population of the watershed was 4522 in 1991 census with an average density of 200 persons km^{-2}. There are five perennial streams (Tirikhola, Rangrangkhola, Sombareykhola, Pockcheykhola and Chemcheykhola) forming five micro-watersheds. All these streams finally merge into Rinjikhola, which is the outlet of the Mamlay Watershed. It has a dendritic pattern where each micro-watershed has a mosaic distribution of land-use practices.

3.2.1 Topography

The watershed area under study lies entirely in the mountainous zone. The area is characterized by varied lithology and folded structure. The elevation of the watershed varies from 300 m near Rangit River in the west to more than 2650 m near Tendong peak in the north-east ridges.

The topography progressively becomes rugged from the Rangit River to the Tendong peak.

Physiographically, the watershed has been divided into three geomorphic divisions viz., (i) Lower hill slope (<1000 m), (ii) Middle hill slope (1000-2000 m) and (iii) Upper hill slope (>2000 m) based on geology, land use and natural vegetation cover. Some landslips and gullies are also observed. The vegetation changed remarkably with variation in micro-climate in a gradient of altitude. About 50% area of the watershed is under the middle hill slope, 40% in the lower hill slope, and just 10% in the upper hill slope. Medium to dense natural forest covers are found in the sub-tropical and temperate belts. A major portion of the watershed faces the east-west direction.

3.2.2 Geology

The Mamlay Watershed falls under the Lesser Himalayan Zone. Four major litho-tectonic units exist in Sikkim Himalaya, viz., the Gondwana Group, Buxa Group, Daling Group and Darjeeling Group. The Precambrian high-grade crystalline rocks of Darjeeling Group are thrusted over the Daling Group of rocks of Late Precambrian to Middle Palaeozoic age along the Main Central Thrust (MCT). These rocks are exposed in large part of Sikkim; whereas, the rocks of Buxa and Gondwana groups are mostly exposed in a tectonic window, known as "Rangit Window" that exists in South Sikkim.

In Mamlay Watershed area, which falls in the Rangit Window, mostly the rocks of Buxa and Gondwana groups are exposed, though a few exposure of Daling Group are also present mostly along the periphery of the Window (Fig. 3.2). Apparently, the rocks of Daling Group form nearly NNE-SSW trending large-scale and elongated domal structure that overlie the sediments of Gondwana Group with a thrust (Gangopadhyay & Roy 1979).

The Gondwana sediments are represented by pebble slate, inter-bedded sandstone and carbonaceous shale, slaty-shale and thin layers of coal. Sahni & Srivastava (1956) have described marine fossils, mainly bivalve and brachiopods, such as *Eurydesma*, *Ambikella*, *Spirifer*, *Syringothyris*, etc., from Kamrang and Wak in South Sikkim. Further, well-preserved plant fossils, viz., *Glossopteris*, *Phyllotheca*, *Vertebraria*, etc., are also known to occur in the slaty-shales of the Gondwana sediments exposed in the Rangit Window (Singh & Bajpai 1990). These fossils indicate a Permian age to the Gondwana sediments. The Buxa Group is predominantly represented by variegated colour limestone and slate, impure carbonate phyllites and quartzite. It shows good organo-sedimentary structures. Sinha & Roy (1972) has reported algal stromatolites from the rocks of Buxa Group in the Rangit Window. The Gondwana and Buxa Groups of rocks are surrounded by typical greenish phyllites, quartzites and low-grade schists and gneisses of Daling metamorphites.

Several metallic and non-metallic minerals are known to occur in the area, of which coal and dolomite are the most dominant and important. Besides these, sporadic occurrences of sulphide mineralization are also present.

During the early period of the geological history, deep water marine sediments exhibiting considerable facies variation were deposited in the major part of the area and were later subjected to repeat fold, fault and thrust movements. It bears the evidences of several persistent thrusts in the Rangit Window, viz., the Sikkip Thrust and the Tendong Thrust (Fig. 3.2).

3.3 CLIMATE

The climatic data for the present study was collected at the Jaubari village (2000 m) and Kamrang village (800 m) covering temperate and subtropical belts respectively of the watershed during 1999 and 2000. The climate of the area is typically monsoonic having the three main seasons: winter (November-February), spring (March-May) and rainy (June-October) and rainfall varies from area to area, and over 80% of the rain occurs through June to September.

3.3.1 Rainfall

The rainfall in the watershed varies rapidly with elevation. The watershed experiences high rainfall in the temperate region and has shadowed rainfall in the valleys which fall in the sub-tropical region. Monthly rainfall data were collected from both the regions in two consecutive years (1999 and 2000). The mean annual rainfall was much higher at the temperate site 2992 mm, while it was 1295 mm at the sub-tropical site during the same period. At both the sites low rainfall was received between November to February while fairly good rainfall was received every month from March to October and highest was recorded in the month of August in both the sites (Fig. 3.3). In the sub-tropical site very little rainfall was recorded between November to April except February.

3.3.2 Temperature

The temperature was measured at Jaubari in the temperate zone and Kamrang in the sub-tropical zone of the watershed and it was observed that the temperate zone experiences a mean monthly maximum temperature of 18^0 C while the mean monthly minimum temperature reaches up to 11^0 C. The record shows that the temperate zone of the watershed experienced a temperature as high as 21^0 C in June whereas it scaled as low as 5^0 C in the month of January. The sub-tropical zone of the watershed on the other hand experienced a mean monthly maximum temperature of 30^0 C and a mean monthly minimum temperature of 15^0 C (Fig. 3.3). Air temperature was distinctly much lower in the temperate site than the sub-tropical site.

3.3.3 Evaporation

Daily evaporation was measured at temperate and sub-tropical belts of the watershed and data were pooled on monthly basis. Mean monthly measured value ranged from 2 to 10 mm in temperate belt and 3 to 12 mm in sub-tropical belt. The highest monthly evaporation was recorded in July and lowest in December at both the belts (Fig. 3.4).

3.3.4 Relative Humidity

The relative humidity of temperate and subtropical belts was recorded during 1999-2000. Mean monthly relative humidity ranged between 66-77% in temperate belt and 73-88% in subtropical belt. Rainy season had the highest relative humidity followed by winter and short summer season.

3.3.5 Photosynthetically Active Radiation

Photosynthetically active radiation (PAR) was recorded during 10.30 to 12.00 hours in temperate and subtropical belts of the watershed. Minimum and maximum value of PAR in a month varied widely in all the months in both the belts. Mean PAR ranged from 68 to 1168 μ mol m^{-2} s^{-1}, which was lower during winter and rainy seasons, but peaked during spring season.

3.4 SITE CHARACTERISTICS

Twenty seven sites from nine dominant land-use/cover types were selected for the study covering slope, aspect and altitude i.e., three forest types (temperate natural dense mixed forest, temperate natural open mixed forest, and sub-tropical natural open forest), two agroforestry system types (large cardamom based agroforestry systems and mandarin orange based agroforestry systems), two agricultural area types (open cropped area temperate and open cropped area sub-tropical) and two wastelands types (wasteland area temperate and wasteland area sub-tropical) (Table 3.1). All sites were located within a geographic distance of more than 3 km in a designated watershed area. Though the species composition varied with sites, *Castanopsis tribuloides* and *Quercus lamellosa* dominated at most of the sites. Other dominating canopy species were *Alnus nepalensis, Quercus lineata, Juglans regia, Cryptomeria japonica, Michelia excelsa* and *Symingtonia populnea* at temperate natural forest dense and open, whereas *Schima wallichii, Castanopsis indica, Castanopsis tribuloides*, and *Shorea robusta* in sub-tropical natural forest. Large cardamom based agroforestry were dominated by *Alnus nepalensis*, *Bellschmedia sp., Nyssa sp., Erythrina sp.*, and in mandarin agroforestry systems, *Citrus reticulata* and *Albizia stipulata* etc. were the dominating species. The dominating subcanopy species in temperate forests were *Eurya acuminata, Symplocos theaefolia, S. sumuntia, Leucosceptrum canum* etc.

Altitudes, slope, soil pH, soil moisture, and dominant tree species of the sites are given in Table (3.1). Soil texture of different forest and agroforestry types are also outlined in Table 3.1, which is either sandy loam, silty loam, or clay loam varying at different physiographic divisions and land-use/cover types of the watershed. The texture of the open cropped area in temperate and subtropical field soils was sandy loam. Soil temperature of different land-use/cover was recorded seasonally. The higher soil temperature was observed in rainy season in comparison to spring and winter seasons. On land-use/cover basis, highest soil temperature was recorded in open cropped and wasteland areas of sub-tropical belt and lowest in forest and agroforestry systems of the temperate belt.

Most soils are acidic (pH ranged from 5.02 to 6.43) due to cations accumulation in biomass causing anionic disbalance in soil and anion leaching loss due to heavy rainfall. Average soil moisture levels ranged from 17% in subtropical wasteland to 34% in temperate natural forest dense.

3.4.1 Bulk Density

The bulk density of the soil horizon (0-100 cm) in different land-use/covers varied distinctly with higher values in temperate natural forest dense and lower in open cropped area subtropical (Table 3.2). The bulk density in the lower depths of all the land-use/covers showed higher values indicating the most compact soil in this horizon. Bulk density varied significantly ($P<0.0001$) within land-use and soil depths. Interactions between the land-use and depths were also significant ($P<0.0001$).

3.4.2 Soil Nutrient Status

In order to assess the effect of change in land-use/covers on soil fertility, the nutrient levels of soil at two depths (0-15 cm and 15-30 cm) from different land-use/covers were estimated following standard methods (Anderson & Ingram 1993).

3.4.2.1 Organic carbon

Organic carbon concentrations of both the soil depths varied significantly (P<0.0001) between land-use and depths. Interactions between land-use and depth were significant (P<0.01) (Table 3.3). Pairwise mean difference probabilities showed significant differences between temperate natural forest dense with other land-use (P<0.05). Mean difference between subtropical natural forest open, mandarin based agroforestry system, open cropped area subtropical and wasteland area subtropical showed no significant difference (P>0.05) (Table 3.3). Between the depths also the mean differences was significant (P<0.05). At higher soil depth percentage of organic carbon was smaller than the surface layer.

3.4.2.2 Total nitrogen

Soil total-N varied significantly between land-use, seasons and depths. Interaction between land-use and depth were also significant (Table 3.3). Pairwise mean difference probabilities were significantly higher in temperate natural forest dense than other land-uses (P<0.05). Pairwise mean differences between other land-uses were not significantly different (P>0.0.5). Between the seasons, differences were significant for winter with rainy and spring with rainy (P<0.05). Soil total-N was always higher in 0-15 cm depth compared to 15-30 cm depth in all the land-uses.

3.4.2.3 Total phosphorus

The range of total-P concentration was 0.02-0.12% in the 0-15 cm and 0.01-0.09% in 15-30 cm soil depths in different seasons and land-use/covers. Highest values were recorded in winter and lowest in spring season. Significant variation was obtained between land-use and depths. Interaction between land-use and depth (P<0.005), were significant.

Pairwise mean difference probabilities showed significantly higher value in subtropical natural forest open with other land-uses ($P<0.05$) (Table 3.3).■

Table 3.1 Site characteristics of different land-use/cover selected for study

Land-use/cover	Altitude (m)	Slope (^{0})	Soil texture	Soil pH	Moisture (%)	Dominant tree species/crops
Temperate natural forest dense	1900-2650	30-52	Sandy loam	5.10±0.10	33.5±5.2	*Alnus nepalensis, Juglans regia, Quercus lamillosa, Michellia lanuginosa*
Temperate natural forest open	1700-2200	35-42	Sandy loam	5.02±0.07	30.3±5.1	*Cryptomeria japonica, Alnus nepalensis, Beilschmedia sp., Nyssa sp., Erythrina sp.*
Subtropical natural forest open	800-1000	30-35	Silty loam	5.16±0.05	20.2±4.1	*Schima wallichii, Castanopsis indica, C. tribuloides, Shorea robusta*
Cardamom based agroforestry	1000-2000	25-30	Silty/clay loam	5.44±0.04	28.9±3.4	*Alnus nepalensis, Beilschmedia sp., Nyssa sp., Erythrina sp.*
Mandarin based agroforestry	400-1600	20-25	Silty loam	6.11±0.18	16.6±3.3	*Citrus reticulata*
Open cropped area temperate	1000-2000	25-30	Sandy loam	6.43±0.04	27.8±4.2	Maize
Open cropped area subtropical	300-1000	20-25	Sandy loam	6.02±0.10	17.1±3.1	Maize, Pulses, Rice
Wasteland area temperate	1000-2000	25-30	Sandy silt	5.21±0.05	26.4±3.7	
Wasteland area subtropical	300-1000	20-25	Sandy soil	5.90±0.16	16.5±3.8	

Table 3.2 Bulk density (g cm^{-3}) of different land-use/cover with depth

Land-use/cover	Depths (cm)						
	0-15	15-30	30-45	45-60	60-75	75-90	90-100
Temperate natural forest dense	1.31	1.33	1.37	1.40	1.47	1.55	1.60
Temperate natural forest open	1.14	1.16	1.17	1.28	1.31	1.35	1.37
Subtropical natural forest open	0.64	0.67	0.72	0.78	0.80	0.84	0.93
Cardamom based agroforestry system	0.86	0.87	0.89	0.95	0.97	1.03	1.07
Mandarin based agroforestry system	0.84	0.86	1.10	1.33	1.39	1.40	1.41
Open cropped area temperate	0.57	0.60	0.86	0.89	0.90	0.92	1.00
Open cropped area subtropical	0.46	0.51	0.67	0.70	0.71	0.83	1.07
Wasteland area temperate	0.62	0.64	0.78	0.83	0.87	0.88	0.92
Wasteland area subtropical	0.72	0.76	0.92	0.95	1.10	1.11	1.18

ANOVA: Land-use, $F_{8,\ 126}$= 804.82, P<0.0001; Depth $F_{6,\ 126}$= 319.70, P<0.0001; Land-use x Depth $F_{48,\ 126}$= 9.46, P<0.0001.

Table 3.3 Soil nutrient status (%) in different land-use/cover. Means in each column with different letters denotes significant difference at (P<0.05, n=3) (Tukey's honestly significant difference test)

Land-use/cover	Organic carbon	Total nitrogen	Total phosphorus
Temperate natural forest dense	2.770^{f}	0.254^{b}	0.076^{a}
Temperate natural forest open	2.290^{e}	0.219^{a}	0.060^{a}
Subtropical natural forest open	1.256^{a}	0.207^{a}	0.160^{b}
Cardamom based agroforestry system	1.871^{c}	0.212^{a}	0.067^{a}
Mandarin based agroforestry system	1.401^{a}	0.172^{a}	0.067^{a}
Open cropped area temperate	1.988^{d}	0.182^{a}	0.069^{a}
Open cropped area subtropical	1.182^{a}	0.180^{a}	0.066^{a}
Wasteland area temperate	1.617^{b}	0.178^{a}	0.042^{a}
Wasteland area subtropical	0.968^{a}	0.134^{a}	0.043^{a}

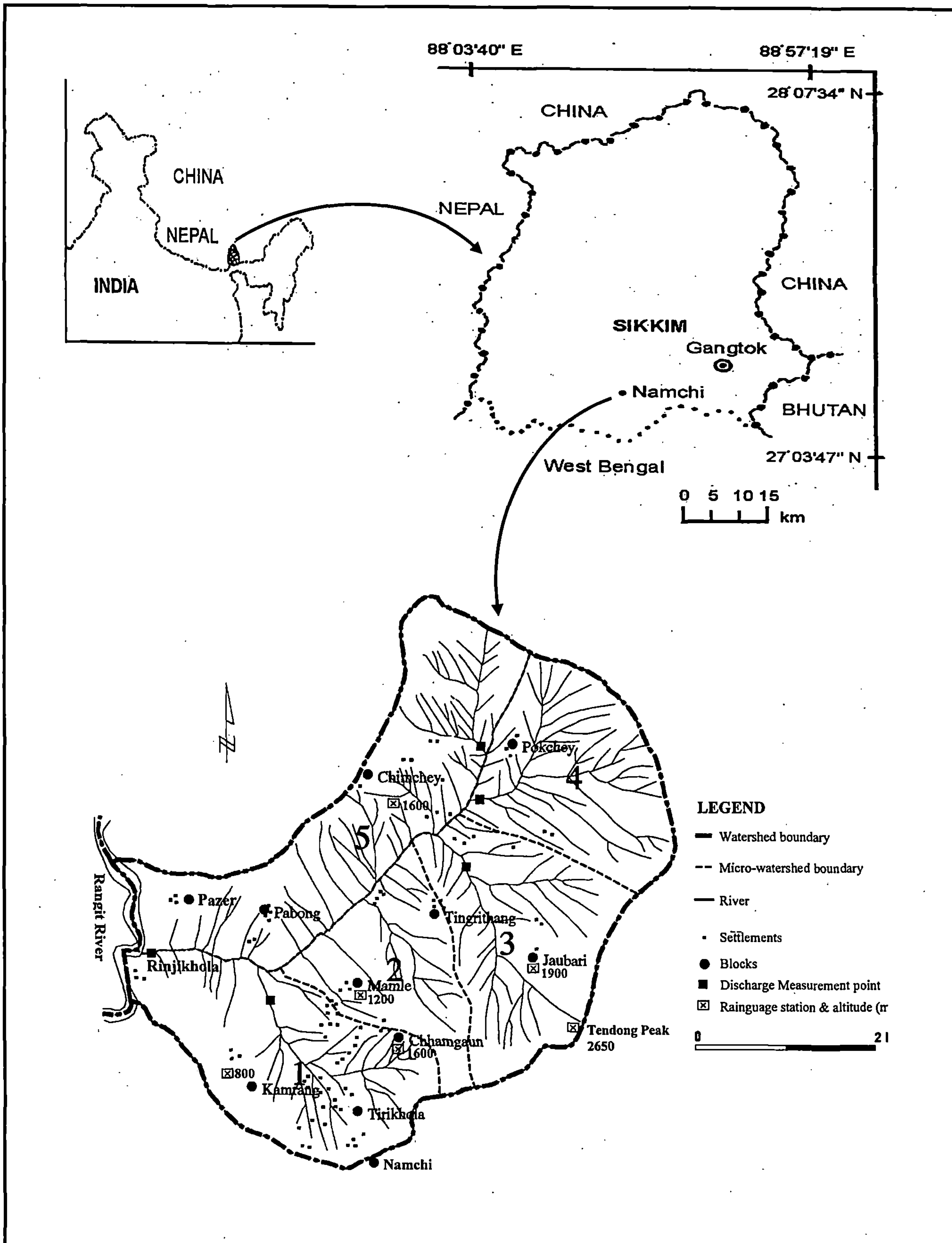

Fig. 3.1 Location map of Mamlay Watershed showing drainage pattern and settlements

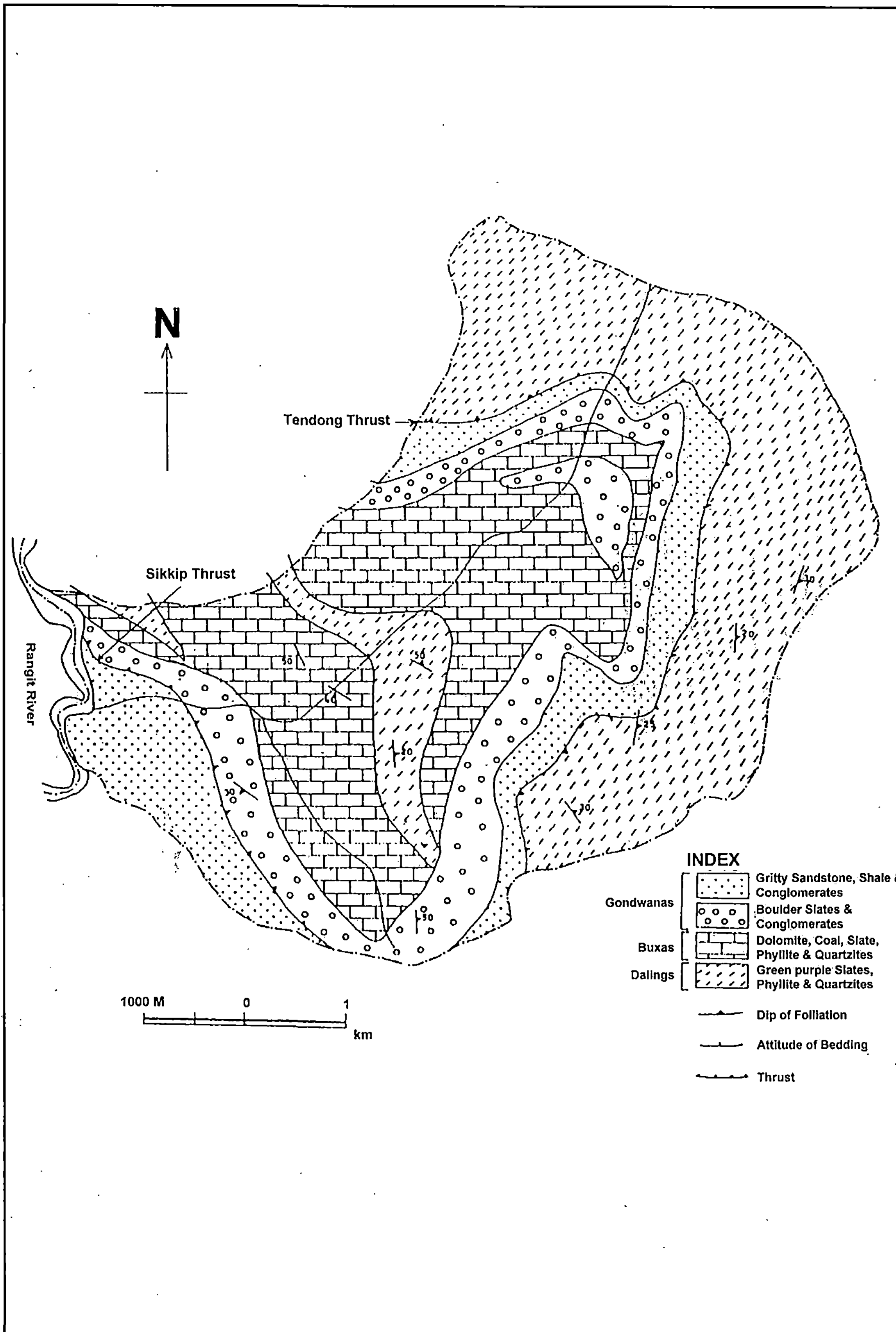

Fig. 3.2 Geological map of Mamlay watershed.

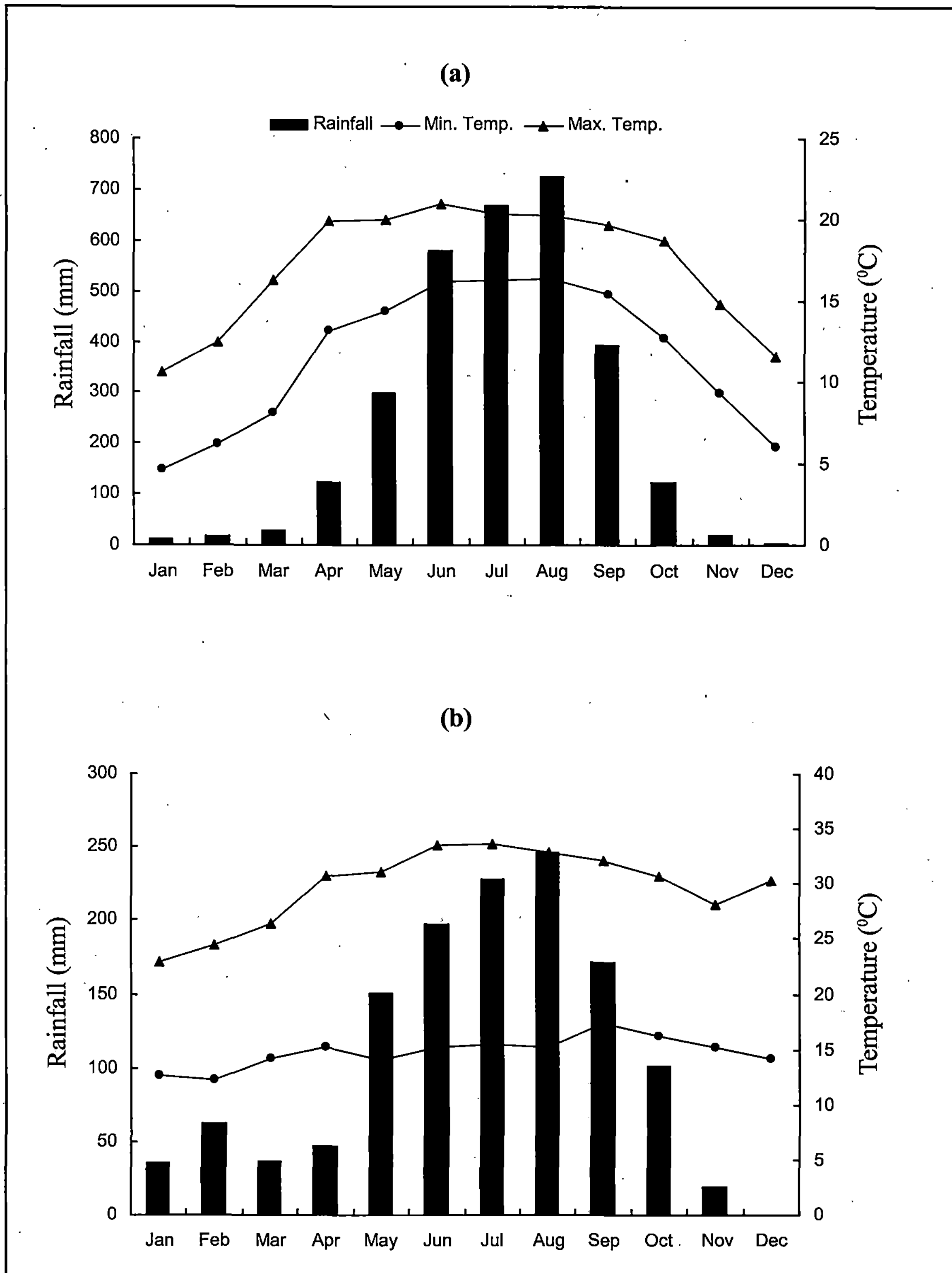

Fig. 3.3 Mean monthly rainfall (mm) and temperature (^{0}C) in **(a)** temperate belt and **(b)** subtropical belt of the Mamlay watershed recorded during 1999 and 2000 (n = 6).

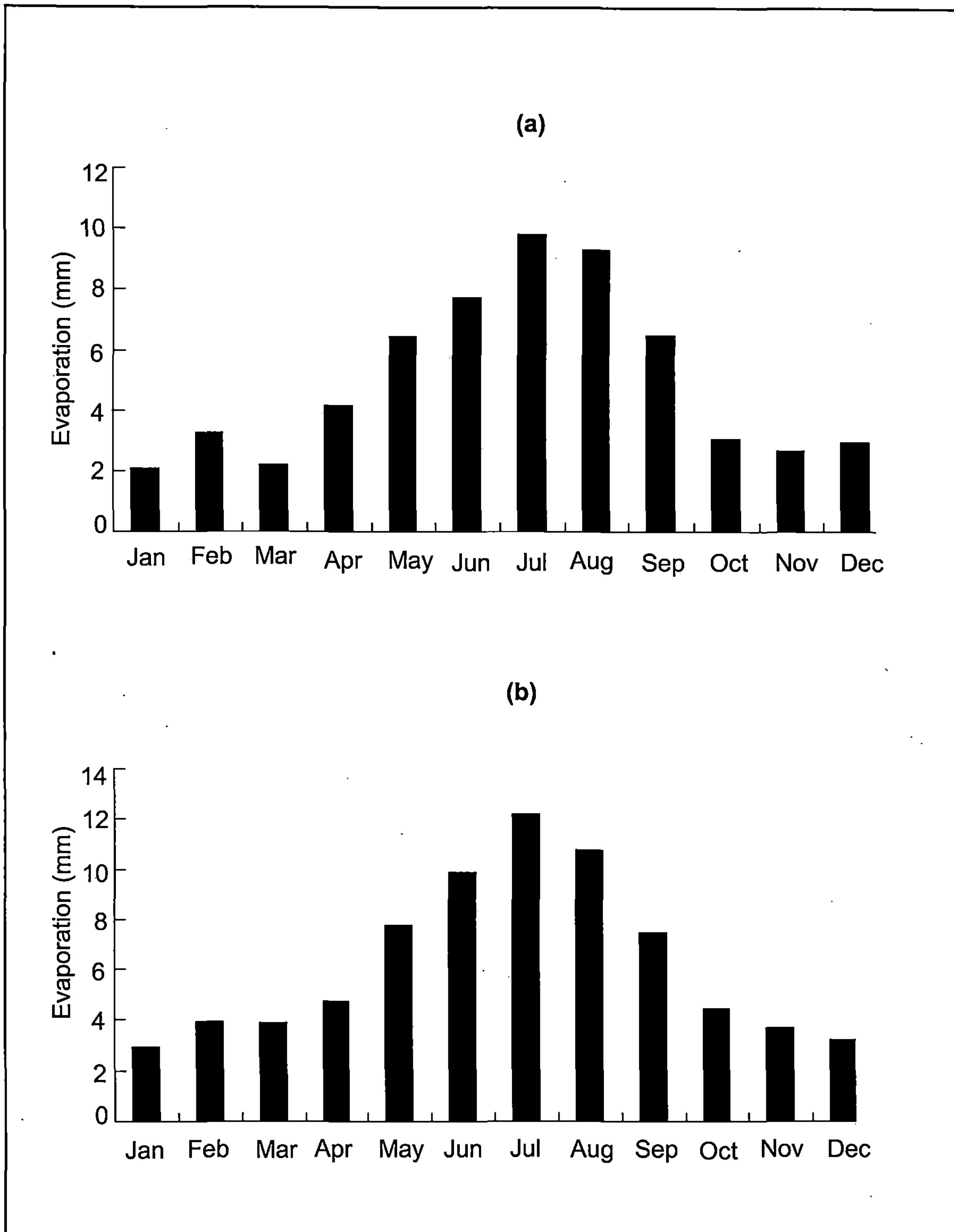

Fig. 3.4 Mean monthly evaporation (mm) in **(a)** temperate belt and **(b)** sub-tropical belt of the Mamlay watershed recorded during 1999 and 2000 (n = 6).

Chapter – IV

LAND-USE/LAND-COVER DYNAMICS, BIOMASS STATUS AND COMMUNITY DEPENDENCE

4.1 INTRODUCTION

Land is the most important natural resource which embodies soil, water, vegetation and other productive resources upon which all terrestrial biosystems are dependent. The science of land-use/cover change comprised of identifying and quantifying changes in the landscape, requiring and understanding of that existed (or currently exist) in the landscape, how the landscape will look in near future (prognostic component), and socio-economic forces that drive changes. In the recent time advancement of the technological inputs has made land-cover change monitoring platforms more complex. There has been a new earth observation system, satellites with very fine resolution that has helped new opportunities to advance the frontier of land-use/cover change researches. Over the years there has been frequent concern of land resource degradation due to increasing human and bovine population that leads to put high pressure on certain resources and thus changes land-use/cover, leading to loss of soil fertility and depletion of forest resources (Milas 1984; Toit 1985; Pimental *et al.* 1986; Soule 1986; Whitlow 1988). Other factors contributing to resource degradation include the breakdown of traditional resource management systems (Swift 1976; Sinclairs & Fryxell 1985; Rai *et al.* 1994), inequality in access to natural resources (Repetto & Holmes 1983; Baker 1984; Whitlow 1988) and commercialization (Owen 1976; Singh *et al.* 1984).

Land-cover change stemming from human land-uses represents a major source and a main element of global environmental change. Land-use/cover changes contribute to globally systematic changes because of greenhouse gas accumulation in the troposphere and stratospheric ozone depletion (Turner *et al.* 1993). The quest for fast economic development and expanding agricultural activities has increased the exploitative pressure on the forests in the Himalaya (Singh *et al.* 1984). Himalayan forest loss is recognized as a regional and global problem, a little is known about the link between resource use and effects on forest fragmentation and loss. Knowledge of the dynamics and patterns of land-use/cover and forest fragmentation inventories are needed for the long-term sustainability of human-forest interactions and for developing management policies that protect and enhance Himalayan forests. Information on forest composition and association, biotic pressure and type of species surviving and the extent of biomass removal can help to rejuvenate depleting forest through silvicultural practices and community involvement (Ramakrishnan & Toky 1981; Singh & Singh 1987 and Sundriyal & Sharma 1996).

Forest constitutes about 42% of the total area of the Sikkim State. Records show that the area under closed canopy was only about 14% (Sudhakar *et al.* 1998). The forests of the State have suffered a serious set back during recent years due to tremendous pressure arising out of ever increasing demand for fuel wood, fodder and timber coupled with diversion of forest lands to non-forest uses in the name of developmental processes. A rapid depletion of forest resources has led to environmental degradation and economic deterioration all too widely in the Himalaya, where the majority of people are living just at or below the subsistence level (Thapa & Weber 1990). There is a vital need for protecting and scientifically managing the valuable land resources of the Himalayan region.

A better understanding of land-use and land-cover dynamics is of crucial importance to the study of carbon dynamics because changes in land- cover are caused by land-uses, which, in turn, are governed by human driving forces. Therefore, comprehensive information on the spatial and temporal distribution of land-use and land-cover categories and the pattern of their change is a prerequisite for understanding the optimum utilization and management of land resources on watershed basis because watershed approach in the Himalayan region has become acceptable in undertaking land improvement measures. Land, water and vegetation are the most important natural resources of mountain regions and these are much more degraded today than they were in the past. Considering the above issues, this chapter examines the overall pattern of land-use and land-cover change in a watershed focusing; (a) land-use/cover pattern; (b) land-use/cover change detection; (c) biomass, productivity and litter production and (d) fuel, fodder and timber extraction.

4.2 MATERIALS AND METHODS

4.2.1 Land-use/cover

The potential of satellite data as a basis for generating valuable information for land-use/land-cover is by now widely recognized, although initial efforts were made since mid seventies for application of different interpretation techniques in land-use/cover mapping (Anderson *et al.* 1976; Colwell 1983).

The land-use/cover pattern of the Mamlay watershed was analyzed based on a combination of surveys carried out in phases, using a combination of conventional and remote sensing techniques. The first phase consisted of collection of conventional data and their evaluation.

The second phase involved collection of satellite imageries IRS-1A, LISS-II of 1988 and IRS-1C, LISS-III of 2001, Geocoded FCC of bands 2, 3, 4 in the scale of 1:50000 in conjunctions with the survey of India topographical map on 1:50000 scale. Preparation of land-use/cover map is based on visual interpretation of satellite imageries by employing a photo interpretation key, tone, texture, pattern, shape, size, shadow, site, and association (Anonymous 1989). Interpreted details from the imageries were transferred to a base map 1:50000 scales having micro-watershed boundaries prepared from a topographical map. Each forest type was subdivided on the basis of crown-cover into three classes ≤20% (degraded), 21-40% (open) and ≥ 40% (dense). Both the visual interpretation and ground truth survey were employed for the extraction of various land-use/cover features.

Ground check studies were carried out for each theme to verify image interpretations. A traverse survey was undertaken from Gangtok to Mamlay watershed via Damthang and Namchi. On the way, observations were taken for the field features at several places. These were correlated with the satellite imagery information. Based on the ground truth data, modifications were effected and the classified features as well as their boundaries redefined. Image interpreted maps were finalized based on the ground truth and collateral data/information. This information is transferred to the base map and final thematic maps were prepared. Information on various features derived from satellite and collateral data were integrated and analyzed. Areas of different land-use and forest types under each crown class were estimated by using digital planimeter to complete the watershed land-use/land-cover statistics.

The only limitation encountered during this interpretation was the shadow effect of the hills. This is quite usual phenomenon in case of the satellite imageries of the Himalaya. Because of the total data acquisition time of the IRS satellite, which is 10.25 AM, the western and north-eastern slopes of the watershed are shadowed to some extent. This was overcome with the field verifications of the doubtful features of the shadow zone and modified suitably in the final interpretations.

4.2.2 Biomass, Productivity and Litter Production

A set of sample sites for each forest and agroforestry system comprising sub-tropical to temperate belts was selected from the map and these sites were marked on the ground. On each site, woody biomass standing state, woody biomass production, stand density and basal area were analyzed on 20x30 m quadrats. Sample consisted of 15 randomly placed permanent quadrats. Within each quadrat, each tree >10 cm DBH was identified, marked at 1.3 m for measurement of annual increment. Litter production and agronomic yield (in case of agroforestry systems) were estimated in the above quadrat. The volume of standing tree woody biomass in different forests and agroforestry systems were computed as product of volume and specific wood density (Ruark *et al.* 1987; Sundriyal *et al.* 1994a and Sundriyal & Sharma 1996), using species-specific regression equations developed by Sundriyal *et al.* (1994a) and Sundriyal & Sharma (1996). This was further confirmed with the measurement of fallen tree (cut by villagers and forest department) volume and biomass. Estimation of woody biomass of tree was extrapolated for each plot using the above relationship. Allometric relationships of tree component biomass on DBH developed by Sharma (1995) for *A. nepalensis, Albizia stipulata, Citrus reticulata* and mixed tree species for temperate and subtropical belts of the study area were used. The component weight data of each tree in the sample plots were extrapolated using the allometric relationship and then expanded to stand values. Mean annual increments of aboveground and belowground component of the individuals in the sample quadart were obtained by DBH increment measurement. The net change in the component biomass over one year period yielded annual biomass accumulation and the sum of the different components gave net production of tree strata. Monthly sampling of forest floor herbaceous biomass was done using 50×50 cm quadrat in replicates.

Litter production was studied in these sample plots. Monthly tree litterfall was recorded in each of the plots over a 2-year period (1999 and 2000), using three litter traps representing 1 m^2 collecting area in each plot. Accumulated litter on the floor was randomly sampled in triplicate from each stand and extrapolated to stand values. In the sample plots of large cardamom agroforestry total numbers of understory cardamom bushes were recorded. Average number of tillers per bush was calculated using data of 20 bushes for each plot. Total tillers for the plots were extrapolated using average number of tillers per bush and total number of bush per plot. About 200 tillers from each plot were harvested and height, leaf dry weight, pseudo-stem dry weight and bush root/rhizome dry weight measured for calculating mean values. The cardamom tillers that have fruited in any year are slashed after the harvest as a management practice because it does not fruit again. Therefore, the cardamom crop residue at the time of harvest was estimated for its annual contribution to the floor. Similarly, the above-ground crop residue in the mandarin based agroforestry system was estimated at the time of harvest of each crop.

4.2.3 Fuel wood, Fodder and Timber

Villagers were interrogated about the uses they made of different tree species, i.e., house construction, for agricultural field implements, volume of timber needed for house construction and amount of fodder collected from the forest and agroforestry area. The fuel wood, fodder and timber use and extraction of species by different communities were based on a detailed primary survey in randomly selected 100 households during the study period. To provide proportionate representation to every socio-economic segment, the community households were stratified on the basis of the size of land holding, income status, ethnicity and caste reflecting social status. Community wise fuel wood fodder and timber consumption per day, supply of fuelwood, fodder and timber from different sources, time taken for collection and distance covered were collected through questionnaire survey.

The questionnaire is the most widely adopted method for gathering data on collection and consumption quantities of fuel wood and fodder. The wide use of questionnaires is probably due to the limitation of time, resources and logistic facilities (Uma Shanker *et al.* 1998). Although extensively used, the questionnaire method generates highly biased data, because most of the respondents do not give accurate information due to lack of interest, inadequate knowledge of the subject, and intentional distortion of information. Inadequate knowledge of quantities might also lead to incorrect reporting (Malhotra *et al.* 1991). However, the questionnaire method is useful for a rapid assessment and to collect qualitative information such as the name of species used for fuel wood and fodder. To avoid the biases, estimation of the actual quantity of fuel wood and fodder requirement/consumption by each household was worked out on the basis of personal observation over a period of 24 hours by adopting a weight survey method. Simultaneously observations were also made in each sample to quantify fuel wood and fodder use for various tasks such as cooking, water heating and other purposes. During the survey the interviewer visited each sample household and requested the head person of the family to monitor the amount of fuel wood and fodder that would be burnt during that particular day. The wood and fodder was weighed using spring balance and then left in the kitchen (35 kg wood bundle and 50 kg fodder leaves) of each household with instruction to use wood and fodder only from bundle. On the next day, interviewer returned to each sample household, the remaining wood and fodder leaves were weighed again and deducted from the original bundle to calculate the actual consumption per day. Time spent for collection was noted when the members of the households went to the forests.

Participatory Rural Appraisal (PRA) techniques were also used to collect information of preferred species for fuel wood and fodder consumption. People's responses to the resource pressure faced by them, were considered the most accurate indicators of fuel wood and fodder shortage and were used to examine the severity of the problem.

4.3 RESULTS

4.3.1 Land-use Pattern

The land-use/cover pattern of the Mamlay watershed varies considerably depending upon the ecological conditions, altitude, lithology and slope aspect. Apart from these factors, technological and institutional influences also affected the land-use/cover pattern. The land-use/cover data generated through satellite imagery has been classified into four major classes of level I category i.e., (i) forests (ii) agroforestry (iii) agricultural land, and (iv) wasteland, and further sub-division has led to 9 sub-classes at level II. The spatial distribution pattern of the land-use/cover map of the watershed as interpreted from the imageries for the year 1988 and 2001 are shown in Figure 4.1 and 4.2 and area of different land-use types are given in Table 4.1, 4.2 and 4.3.

4.3.1.1 Forests

Forest is the most important land cover on higher steep slopes and ridges. The forest land includes temperate natural forest dense, temperate natural forest open and sub-tropical natural forest open (Plate 1a & b). The total forest land in the watershed accounts for 69% and 49% of the total areas of the watershed in 1988 and 2001, respectively (Table 4.1). The spatial distribution pattern shows that the northern, western and eastern parts of the watershed area are dominated by dense mixed and open mixed forests. Some forest blanks are also found in the reserved forest categories, this indicates the high human and livestock pressure in the area. Micro-watershed wise, Pockcheykhola and Sombareykhola were dominated by temperate natural forest dense and open, whereas Tirikhola by subtropical natural forest open in both the assessment years (Table 4.2 and 4.3). Figure 4.1 and 4.2 reveals that the Pockcheykhola, Sombareykhola, and Chemcheykhola micro-watersheds were dominated by forest at the ridge tops, agroforestry in the middle and agriculture in the valley areas.

4.3.1.2 Agroforestry systems

The agroforestry practices in the watershed are traditional and promising for higher economic returns. Two types of agroforestry systems are very common in the watershed, i.e., (i) large cardamom based and (ii) mandarin orange based (Plate 2a & b). About 4% areas came under agroforestry practices in 1988 and 2001, respectively (Table 4.1). Sombareykhola micro-watershed is dominated (3%) by large cardamom based agroforestry system whereas Tirikhola and Rangrangkhola by mandarin based agroforestry system (Table 4.2 and 4.3) in both the years.

4.3.1.3 Agricultural land

This class includes built-up land, rainfed and irrigated land. About 14.39% and 30.53% area was under this category in 1988 and 2001 respectively. The land-use/cover pattern in the watershed as a whole showed about 2% area under built-up land in both the years. This includes only cluster settlements. In the Mamlay watershed, the distribution pattern of settlements is scattered (R_n= 1.19 and Di= 54%). So, it is very difficult to demarcate the whole built-up land area through satellite imageries because of limitations of resolution. The low lands along the river bed, commonly known as *khet*, are irrigated and paddy cultivation is the common practice in this land. The whole watershed had only about 2% of its area under irrigation in both the assessment years. Rainfed known as *pakho* cultivation (Plate 3a) covered about 12 and 28% area in 1988 and 2001, respectively. This land is suitable for cultivation of mainly maize, ginger and pulses (Plate 3b).

The dominant land-use/cover in each of the micro-watersheds has been also worked out in the watershed. The highest agricultural coverage was recorded in Chemcheykhola (4.17%), followed by Tirikhola (3.96%) and Pockcheykhola (3.11%) of the total watershed area in 1988, while in 2001, the highest coverage was observed in Tirikhola (13.11%), followed by Chemcheykhola (8.58%) and Rangrangkhola (3.69%) respectively (Table 4.2 and 4.3). The spatial distribution pattern of the agricultural land revealed that the central and north-western part of the watershed were under intensive agricultural practices (Fig. 4.1 and 4.2).

Four types of crop rotations are found in the watershed viz., maize-pulse/maize-potato/maize-ginger-pulse, these are practiced in rainfed conditions and one type (maize-paddy-fallow) in irrigated areas of the watershed. The maize-pulse crop combination is quite common and maize is harvested much earlier than pulses. Potatoes are becoming more popular as a cash crop. They are usually grown in triple cropping rotations after monsoon maize and relay-cropped with pulses or ginger. The intensity of cropping varies from farm to farm and from household to household due to differences in socio-economic conditions, particularly inputs and products, dependence on land and tenurial system etc.

4.3.1.4 Wastelands

This category of land cover includes rock outcrops, landslides, forest blanks, degraded forests and scrublands. The wasteland covered about 11 and 15% of the total area of the watershed in 1988 and 2001, respectively (Table 4.1). In 2001 about 9 ha area was under landslides whereas no landslides were observed in 1988. Micro-watershed wise, Chemcheykhola, Pockcheykhola and Sombareykhola were dominated by wasteland area temperate, while Tirikhola by wasteland area subtropical in both the assessment years (Table 4.2 and 4.3).

The surface water bodies include river, streams and springs. Owing to vegetation cover over the major drainage channels of the watershed, satellite imagery does not show a clear response for these channels in terms of the spectral signature of the water bodies. This is compounded by the fact that during the acquisition of image, the season was such that the channels were dry to a great extent. Therefore, in terms of land-use/cover interpretation, it was not possible to quantify the surface water bodies of the watershed.

4.3.2 Land-use/cover Change

The land-use/cover change detection was generated by the multi-date satellite data. Monitoring of land-use/cover reflected that changes were greater in extent over the span of 13 years in the land under different categories. Table 4.1 is a summary of changes in land-use between 1988 and 2001. The most dramatic changes are the increase in agricultural area and decrease in forest cover area. The open cropped area sub-tropical increased by more than 166% for the thirteen years period, while wasteland subtropical increased by about 117%. The total forests cover comprising temperate dense mixed, open mixed, and sub-tropical open mixed forest decreased by 28% during 1988-2001 (Table 4.1). Micro-watershed wise, major land-use/cover changes were observed in Tirikhola, Chemcheykhola and Pockcheykhola (Table 4.4). Figures 4.1 and 4.2 reflect the conversion of dense mixed forest to open mixed forest to degraded forest and dense mixed forest with agroforestry to open mixed forest with agroforestry and further to open cropped area. Ground-truth verification supports the finding that the depletion of closed forest or its conversion into other categories is the result of maximum anthropogenic pressure on the limited forest resources.

4.3.3 Biomass, Productivity and Litter Production in Different Land-Uses/Cover

Basal tree-trunk cover, total biomass (above-ground and below-ground), productivity, floor litter, annual litter production and humus content for different types of forest and agroforestry systems are given in Tables 4.5 and 4.6. Mean basal tree-trunk cover among different forest and agroforestry types ranged from 2 m^2 ha^{-1} (mandarin based agroforestry systems) to 50 m^2 ha^{-1} (temperate natural forest dense) (Table 4.5). The pattern of biomass (aboveground+belowground) was similar to that of basal cover. The total biomass varied from 12 t ha^{-1} in mandarin based agroforestry system to 448 t ha^{-1} in temperate natural forest dense (Table 4.5). The total biomass of large cardamom based agroforestry system was 103 t ha^{-1}, while it was 22 t ha^{-1} in open cropped area temperate. The total biomass was 22 times higher in temperate natural forest dense than open cropped area. Of the total biomass, over 95% is contributed by aboveground component in forest ecosystems, up to 98% in mandarin based agroforestry and 52% in cardamom based agroforestry systems.

The productivity of forest and agroforestry systems were estimated and presented in Table 4.5. Highest (16.93 t ha^{-1} yr^{-1}) net primary productivity was estimated in temperate natural forest dense and lowest (6.93 t ha^{-1} yr^{-1}) in mandarin based agroforestry system.

The floor litter biomass was measured in different forests and agroforestry systems. The floor litter biomass was recorded maximum (13 t ha^{-1}) in temperate natural forest dense and the mandarin based agroforestry system had the minimum (3.8 t ha^{-1}) (Table 4.6). The annual litter production was recorded highest in temperate natural forest dense (4.57 t $ha-^{1}$ yr^{-1}) and lowest in subtropical natural forest open (2.82 t ha^{-1} yr^{-1}).

The humus content was measured in temperate natural forest dense, temperate natural forest open, subtropical natural forest and cardamom based agroforestry system only, as mandarin based agroforestry contained no differential humus. It followed the similar trend as floor litter biomass with highest value recorded in temperate natural forest dense (6.7 t ha^{-1}) and the lowest in subtropical natural forest open (3.3 t ha^{-1}) (Table 4.6).

4.3.4 Fuel wood, Fodder and Timber Utilization

Field checks, interviews and detailed households survey in the watershed revealed that a large number of woody species are utilized for fuel, fodder and timber for house construction and in making agricultural implements (Plate 4a, b, c & d). Most of these species are collected from the forest and agroforestry systems. Each household on an average is composed of 6 persons and consists of 4 cattle. Fuel wood consumption per house hold is as much as 21 kg per day, through a minimum of 4000 kg (range 4000-5800kg) of dry firewood annually (Table 4.7). Annual consumption of firewood was greater for cooking (69%) followed by animal food preparation (9%), water heating (7%), house warming (6.7%), local wine /beer preparation (6%) and use for festivals (2%).

Each family maintains four animals consisting of cattle, pig and goat. Fodder is collected mainly from the forest (65%) and from agricultural fields (35%). Average fodder collection per household varies from 5000-6500 kg yr^{-1} (mean 5700 kg per household yr^{-1}) from the forest area (Table 4.7). Most of the tree sprouts as well as ground herbaceous vegetation are removed for fodder purposes. In addition, unpalatable species and leaf litter are used for animal bedding.

Family fragmentation every 20-25 years leads mostly to construction of many new houses and almost all houses are made of wood (Plate 4b). Generally a space of two rooms needs 3-6 m^3 wood, depending upon the socio-economic condition of the farmers, and thus a huge amount of wood is collected each year. Field observations revealed that a tree of 50-90 cm and 90-125 cm CBH produces about 0.3-0.4 and 0.8-1.0 m^3 wood respectively. Generally large timber poles are harvested for making ceilings, doors, windows and beams. Medium size poles are used in making furniture and repairs, whereas small size poles for making cattle sheds or temporary huts (Table 4.7).

4.4 DISCUSSION

Human and livestock population pressure on the limited land resources has increased in recent years. This has resulted from the construction of road, fuel, fodder and timber extraction, encroachment into forests and more land utilization for agricultural expansion. Increased pressure on forests has brought tremendous changes in the pattern of land-use including reduction in forest cover. The expansion of agricultural land can be mainly attributed to fragmentation of upland farm families, which has led to expansion of the agricultural area. A bulk of settled agriculture fields in the watershed occurs on sloping terraces along the steep hill sides. Slopes of some agricultural land exceed 40° but most of them fall in between 20 to 35° (Rai *et al.* 1994).

The overall pattern of the forest and agroforestry revealed that all sites are under increasing biotic pressure from the neighboring villages. The forest stand shows high species diversity. Similarly, the density and basal area of the forest is towards the top of the range for most studied Himalayan and other forests (Saxena & Singh 1982; Ralhan *et al.* 1982; Sargent *et al.* 1985; Upreti *et al.* 1985; Singh & Singh 1987; Sundriyal *et al.* 1994a; Sundriyal & Sharma 1996). Now there are trends/evidences of indiscriminate cutting and mismanagement during recent years which has resulted in more damage of some species than others.

The biomass and productivity potential of the studied forest and agroforestry system is within the comparable range of values published for Himalayan and other forests and agroforestry (Singh & Ramakrishnan 1982; Shukla & Ramakrishnan 1984; Sharma & Ambasht 1991; Sundriyal *et al.* 1994a; Sundriyal & Sharma 1996; Sharma *et al.* 1997). Amount of biomass at different locations varied due to differences in species composition. Greater biomass was mainly due to the presence of canopy trees of larger girth classes, viz., *Castanopsis tribuloides, Quercus lamellosa, Symingtonia populnea* and *Nyssa sessiliflora* etc.

The forest and agroforestry systems has been meeting and satisfying the material needs of the majority of the population of the watershed, but now evidence of decline in species number and composition are emerging and it is apparent that local subsistence needs are causing much of the degeneration in the forests. Indiscrimate cutting by people, selective felling by Forest Department, plantation of exotic species like *Cryptomeria japonica*, and use of enormous amounts of wood in house construction and large scale cardamom curing are the most common causes of forest destruction. Field visits revealed that the cutting process is highly irregular in both space and time and a huge amount of wood is wasted. Nearly 40-50% and 20-30% is wasted in the processes of timber and fuel collection, respectively. Generally, smaller dry and dead, and fallen logs and branches are not collected and trees of smaller girth classes are preferred due to easy extraction.

Interviews with the residents of the watershed revealed that previously the forest had a good number of individuals of *Michelia excelsa, M. lanuginosa, Juglans regia, Cedrela toona*, and various other timber trees. The most significant extraction of these species was done after 1970 due to construction of more luxurious house throughout the State. In Sikkim as well as in the Mamlay watershed it has been observed that the rate of immigration into the area was high during 1971-1991. Most of the immigrants were traditionally cultivators (personal observation). The growth of population in the watershed was at 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. A similar trend was observed in the Central Himalayan region at 1.5% per year (Shah 1982; Singh *et al.* 1984). Thus the family fragmentation and population pressure is continually taking place within the watershed, which indicates that the man-land ratio is likely to further decline in the near future. Considering all these factors, it can be said that this natural forest stand is at severe risk of reduction which may lead to the disappearance of many species in the near future.

Lack of effective land-use planning and uncontrolled population growth has contributed to the present deplorable state of affairs. In general, the area shows increasing environmental degradation and resource depletion, while very little conservation efforts are being made to reverse the trend. These results indicate that a sustainable land-use/cover management plan is urgently needed for the area.■

Table 4.1 Area under different land-use/cover and change detection of the Mamlay watershed based on remote sensing data, 1988-2001

Land-use/cover	Year				Variation	
	1988		2001		(1988 - 2001)	
	(ha)	(%)	(ha)	(%)	(ha)	(%)
Forest						
Temperate natural forest dense	606.81	20.13	160.00	5.32	-446.81	-73.63
Temperate natural forest open	815.09	27.04	982.24	32.59	167.15	20.51
Sub-tropical natural forest open	681.54	22.61	362.25	12.03	-319.29	-46.85
Agroforestry						
Cardamom based agroforestry	114.78	3.81	114.78	3.81	--	--
Mandarin based agroforestry	17.42	0.58	17.42	0.58	--	--
Agriculture*						
Open cropped area temperate	243.89	8.09	413.62	13.72	169.73	69.59
Open cropped area sub-tropical	189.96	6.30	506.33	16.81	316.37	166.55
Wasteland**						
Wasteland area temperate	341.99	11.35	451.92	14.99	109.93	32.14
Wasteland area sub-tropical	2.5	0.08	5.42	0.18	2.92	116.80
Total	3014	100	3014	100		

* Irrigated area, rainfed area and built-up area

**Degraded forest, scrub land, forest blanks, rock out crops, land slides

-- denotes no change

Table 4.2 Area under different land-use/cover on micro-watershed level of the Mamlay watershed based on remote sensing data, 1988

Land-use/cover	Micro-watersheds									
	Pockcheykhola		Chemcheykhola		Tirikhola		Sombareykhola		Rangrangkhola	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Temperate natural forest dense	372.13	12.35	43.13	1.43	0.00	0.00	189.97	6.30	1.58	0.05
Temperate natural forest open	245.70	8.15	375.04	12.44	0.00	0.00	194.35	6.45	0.00	0.00
Sub-tropical natural forest open	0.00	0.00	14.94	0.50	381.85	12.67	0.00	0.00	284.75	9.45
Cardamom based agroforestry	11.74	0.39	4.24	0.14	0.00	0.00	98.80	3.28	0.00	0.00
Mandarin based agroforestry	0.00	0.00	3.94	0.13	7.96	0.26	0.00	0.00	5.52	0.18
Open cropped area temperate	93.88	3.11	125.63	4.17	0.00	0.00	24.38	0.81	0.00	0.00
Open cropped area sub-tropical	0.00	0.00	0.00	0.00	119.32	3.96	0.00	0.00	70.64	2.34
Wasteland area temperate	64.38	2.14	150.11	4.98	0.00	0.00	127.50	4.23	0.00	0.00
Wasteland area sub-tropical	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.50	0.08
Total	788	26.11	717	23.79	509	16.89	635	21.07	365	12.11

0.00 = not present

Table 4.3 Area under different land-use/cover on micro-watershed level of the Mamlay watershed based on remote sensing data, 2001

Land-use/cover	Micro-watersheds									
	Pockcheykhola		Chemcheykhola		Tirikhola		Sombareykhola		Rangrangkhola	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Temperate natural forest dense	92.50	3.07	5.00	0.17	0.00	0.00	62.50	2.07	0.00	0.00
Temperate natural forest open	498.76	16.55	195.78	6.50	0.00	0.00	287.70	9.58	0.00	0.00
Sub-tropical natural forest open	0.00	0.00	14.94	0.50	103.50	3.43	0.00	0.00	243.81	8.09
Cardamom based agroforestry	11.74	0.39	4.24	0.14	0.00	0.00	98.80	3.28	0.00	0.00
Mandarin based agroforestry	0.00	0.00	3.94	0.13	7.96	0.26	0.00	0.00	5.52	0.18
Open cropped area temperate	102.50	3.40	258.62	8.58	0.00	0.00	52.5	1.74	0.00	0.00
Open cropped area sub-tropical	0.00	0.00	0.00	0.00	395.04	13.11	0.00	0.00	111.29	3.69
Wasteland area temperate	82.50	2.74	234.48	7.78	0.00	0.00	132.50	4.40	0.00	0.00
Wasteland area sub-tropical	0.00	0.00	0.00	0.00	2.50	0.08	0.00	0.00	4.37	0.14
Total	788	26.11	717	23.79	509	16.89	635	21.07	365	12.11

0.00 = not present

Table 4.4 Land-use/cover change detection on micro-watershed level of the Mamlay watershed based on remote sensing data, 1988-2001

Land-use/cover	Micro-watersheds									
	Pockcheykhola		Chemcheykhola		Tirikhola		Sombareykhola		Rangrangkhola	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Temperate natural forest dense	-279.63	-75.43	-38.13	-88.41	0.00	0.00	-127.47	-67.10	0.00	0.00
Temperate natural forest open	253.06	102.99	-179.26	-47.79	0.00	0.00	94.35	48.55	0.00	0.00
Sub-tropical natural forest open	0.00	0.00	--	--	-278.35	-72.89	0.00	0.00	-40.94	-14.38
Cardamom based agroforestry	0.00	0.00	--	--	0.00	0.00	--	--	0.00	0.00
Mandarin based agroforestry	0.00	0.00	--	--	--	--	0.00	0.00	--	--
Open cropped area temperate	8.62	9.18	132.99	105.86	0.00	0.00	28.12	115.34	0.00	0.00
Open cropped area sub-tropical	0.00	0.00	0.00	0.00	275.72	231.08	0.00	0.00	40.65	57.55
Wasteland area temperate	18.12	28.14	84.37	56.21	0.00	0.00	5.00	3.92	0.00	0.00
Wasteland area sub-tropical	0.00	0.00	0.00	0.00	2.50	250.00	0.00	0.00	1.87	74.80

0.00 = not present;

-- = no change

Table 4.5 Estimation of density, basal area, biomass and productivity in different land-use/cover of the Mamlay watershed

Land-use/cover	Components	Density (trees ha^{-1})	Basal area ($m^2\ ha^{-1}$)	Biomass (t ha^{-1})	Productivity (t $ha^{-1}\ yr^{-1}$)	Removal (t $ha^{-1}\ yr^{-1}$)
Temperate natural forest dense	Tree	422	50			3.15
	Bole + Branch			425.94	10.37	
	Leaf + Twig			2.07	4.57*	
	Root			19.49	0.74	
	Tree Total			447.50	15.68	
	Herbaceous					1.95
	Aboveground Biomass			0.69	1.00	
	Belowground Biomass			0.17	0.25	
	Herbaceous Total			0.86	1.25	
	Stand Total			448.36	16.93	5.10
Temperate natural forest open	Tree	239	31			2.75
	Bole + Branch			188.70	7.39	
	Leaf + Twig			1.73	3.31*	
	Root			10.05	0.42	
	Tree Total			200.48	11.12	
	Herbaceous					2.03
	Aboveground Biomass			1.00	1.06	
	Belowground Biomass			0.25	0.27	

	Herbaceous Total			1.25	1.33	
	Stand Total			201.73	12.45	4.78
Sub-tropical natural forest open	Tree	189	10			4.35
	Bole + Branch			184.45	6.63	
	Leaf + Twig			0.60	2.82*	
	Root			2.85	0.05	
	Tree Total			187.90	9.50	
	Herbaceous					2.45
	Aboveground Biomass			0.82	0.90	
	Belowground Biomass			0.20	0.23	
	Herbaceous Total			1.02	1.13	
	Stand Total			188.92	10.63	6.80
Cardamom based agroforestry system	*Alnus* + Mix Tree	330	42			
	Branch			13.64	1.13	
	Bole			35.07	2.23	
	Leaf +Twig			5.63	3.69*	
	Root			12.76	1.35	
	Catkin			0.50	0.53	
	Tree Total			67.60	8.93	
	Cardamom					
	Leaf			2.33	0.42	

	Pseudostem			6.98	1.25
	Capsule			0.31	0.18
	Root/Rhizome			25.30	2.01
	Cardamom Total			34.92	3.86
	Stand Total			102.52	12.79
Mandarin based agroforestry system	Mandarin + Mix Tree	128	2		
	Branch			1.15	0.11
	Bole			3.99	0.41
	Leaf + Twig			0.46	1.08*
	Root			1.56	0.17
	Orange Fruit			0.65	0.65
	Tree Total			7.81	2.42
	Crops				
	Aboveground Residue			2.12	2.12
	Belowground Residue			0.79	0.79
	Agronomic Yield			1.60	1.60
	Crop Total			4.51	4.51
	Stand Total			12.32	6.93
Open cropped area temperate	Crops				
	Aboveground residue			4.84	4.84
	Belowground Residue			1.57	1.57

	Agronomic Yield	3.57	3.57
	Crop Total	9.98	9.98
	Weed	11.85	-
	Stand Total	21.83	9.98
Open cropped area sub-tropical	Crops		
	Aboveground Residue	4.77	4.77
	Belowground Residue	1.19	1.19
	Agronomic Yield	1.23	1.23
	Crop Total	7.19	7.19
	Weed	12.05	-
	Stand Total	19.24	7.19

* Tree leaf and twig production estimated on standing trees was corrected using annual litterfall data

- not measured

Table 4.6 Annual litter production, floor litter and humus content of different land-use/cover

Land-use/cover	Annual litter production ($t\ ha^{-1}\ yr^{-1}$)	Floor litter ($t\ ha^{-1}$)	Humus content ($t\ ha^{-1}$)
Temperate natural forest dense	4.57	13.00	6.70
Temperate natural forest open	3.31	8.30	4.10
Sub-tropical natural forest open	2.82	7.50	3.30
Cardamom based agroforestry system	4.11	11.70	5.90
Mandarin based agroforestry system	3.2	3.80	-

Table 4.7 Per household consumption of fuel wood, fodder and timber in the Mamlay watershed.

Fuel wood consumption	
Daily requirement per household	15-21 kg
Annual requirement per household*	4000-5800 kg
Fodder collection	
From forest**	5700 kg $household^{-1}$ $year^{-1}$
From agricultural fields**	2630 kg ha^{-1}
Timber (on per household basis)	
Small size poles (bamboo)	
Purpose	cattleshed, baskets, mats, minor repairs
No. of poles required	100+
Average size of poles (CBH***)	<30 CM
Time interval of need	5 - 7 years
Medium size pole	
Purpose	house repairs, furniture etc.
Wood volume required	2.5 – 4.2 m^3
Time interval of need	15 – 20 years
No. of trees required	20-40
Average size (CBH)	30-90 cm
Large size poles	
Purpose	new house construction
Wood volume required	5 - 7 m^3
No. of trees required	7 – 10
Average size (CBH)	90 – 125 cm
Time interval of need	20 – 30 years

*large cardamom growers use an additional 70 to 80 kg of fuel wood (dry weight) for curing per 100 kg of cardamom.

** on dry weight basis (fresh weight-dry weight ratio is 3:1)

*** CBH is pole's circumference at breast height

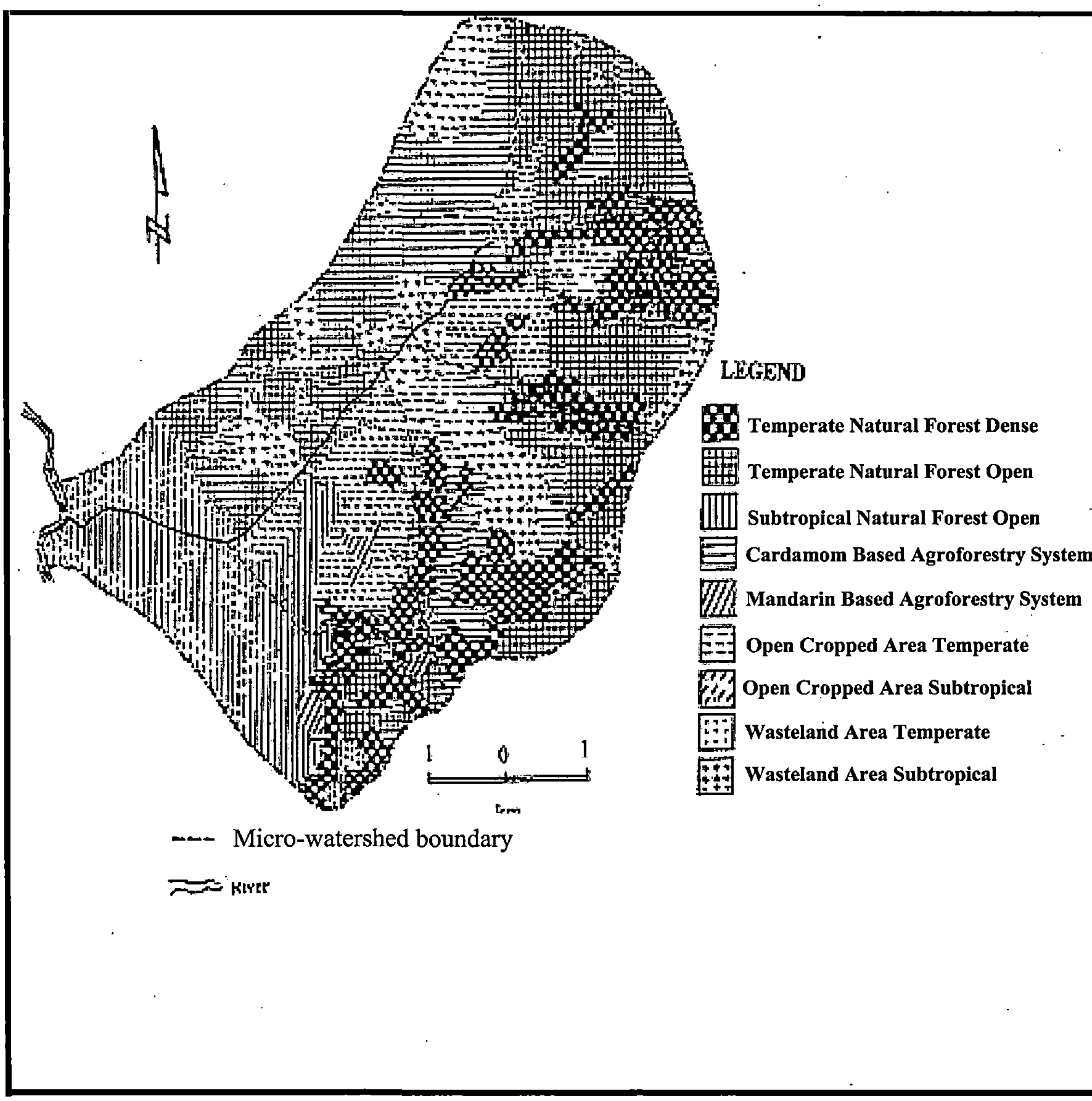

Fig. 4.1 Land-use/cover map of the Mamlay watershed, 1988

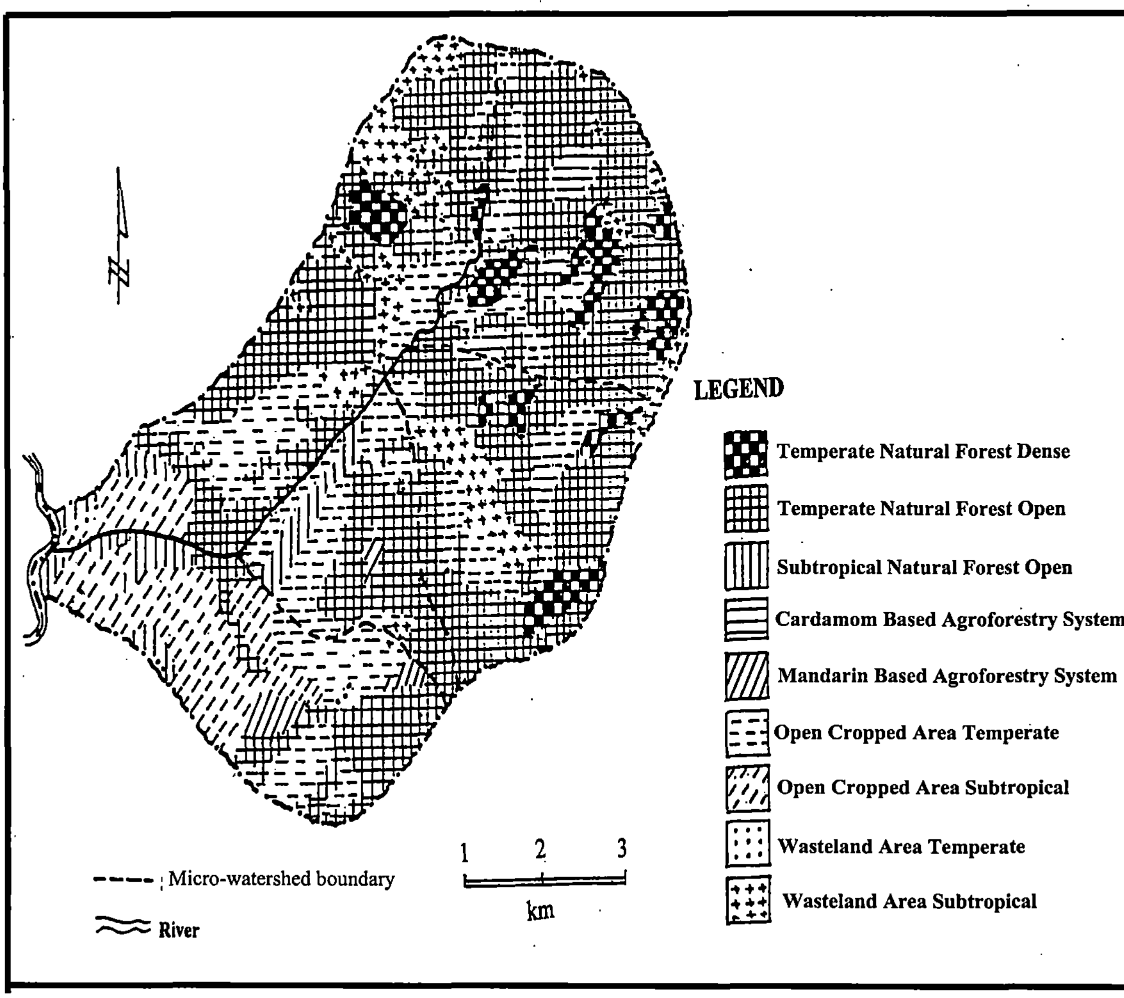

Figure 4.2 Land –use/cover map of the Mamlay watershed 2001

Chapter - V

HYDROLOGICAL ANALYSES

5.1 INTRODUCTION

The Himalayan massif is a relatively young and geo-morphologically unstable region. It is a major contributor of run-off and sediment in the principal rivers of South Asia. Conventional wisdom holds that widespread deforestation and population pressure have exacerbated erosion and led to increased down-stream flood hazards. The Himalayan Mountain range is the source of the major river systems of India. Because of the accelerated silting of these rivers and catastrophic floods in the adjoining plains, the soil loss from Himalaya has attracted considerable attention in recent years.

Eighty per cent of the sediments delivered to the World's oceans each year come from Asian rivers and amongst these the Himalayan Rivers are the major contributors (Stoddart 1969). The Himalaya contributes 500-1000 t km^{-2} yr^{-1} of sediment (Milliman & Meade 1983) and Sikkim in the eastern Himalaya as also shows similar value of 794 t km^{-2} yr^{-1} (Sharma *et al.* 2001). It is estimated that the river Brahmputra alone carries a suspended load of 800 million tones, the average sediment-yield from its catchments being of the order of 26000 ha meters (Raina *et al.* 1980). River systems are also the major means of transport of dissolved materials, including inorganic nutrients and contaminants, which depend on riverine geochemical and hydrological processes. It is estimated that current rates of erosion are five times as great as the rates prevailing in the geological past (Singh *et al.* 1983). Mass wastage and spectacular landslides have occurred owing to tectonic stresses (Raina *et al.* 1980) and road construction, but they form a class among themselves.

The problem of erosion is still more acute in the high-sesmicity areas, which are geo-dynamically sensitive thrust areas.

The rapidly increasing population is seen to be fuelling the expansion of agricultural land on steep and marginal slopes, thereby increasing the destruction of forest cover to make way for agricultural terraces and this has resulted in land degradation. To meet the increasing needs of forest products for fuel and fodder, such change in land–use was expected to lead a dramatic environmental degradation with important consequences for soil erosion, reduced productivity, and deterioration of fragile natural ecosystems (Danida 1988). Soil erosion is a major environmental and agricultural problem worldwide. Although erosion has occurred throughout the history of agriculture, it has intensified in recent years. The loss of soil degrades arable land and eventually renders it unproductive. Worldwide, about $12x10^6$ ha of arable land are destroyed and abandoned annually because of unsustainable farming practices and only about $1.5x10^9$ ha of the land are cultivated (Pimental *et al.* 1995).

Hydrologically linked ecosystems interact through the flow of nutrients through water. Nutrients discharged from uplands pass through low lands on their way to the sea. Understanding the dynamics of such nutrient flows requires knowledge of the effect of land-use on nutrient discharge and of the effects of uphill ecosystems on downhill ecosystems. Therefore, information on the hydrological cycle in the hills is very important for considering management strategies at a watershed level. The relationship between land-use/cover change and soil erosion and hydro-ecological process is a key element in understanding the little known local, regional and global biospheric disruptions. Unfortunately, there were no such hydrological studies of carbon flow through different land-uses for the Himalayan region. In this chapter investigation was undertaken to understand the different hydrological processes involving carbon flow in a hilly watershed. The present chapter was divided to consider the following (i) stream discharge and carbon loss; (ii) sediment concentration; (iii) precipitation and overland flow; (iv) soil erosion and carbon loss and (v) precipitation pathways and carbon flow. The land-use change and hydrology of these on micro-watersheds and total watershed have been analyzed to determine the effect of land-use on sediment and carbon flux from the system.

5.2 MATERIALS AND METHODS

5.2.1 Stream Discharge and Sediment Concentration

Precipitation was recorded on a monthly basis since 1999 in a non-recording rain gauge located in sub-tropical and temperate belts of the watershed area. The collectors were located at elevations ranging from below 1000 m to 1900 m a.s.l.

Stream flow grab samples were taken at six locations i.e., Pockcheykhola, Chemcheykhola, Sombareykhola, Tirikhola, Rangrangkhola and at the outlet of the watershed at Rinjikhola. Samples were taken after rainfall events or at least every two weeks between events and the data pooled into seasonal values, viz., summer, rainy and winter between 1999 and 2000. The year 1999 had a normal monsoon season but 2000 was marked by a failure of the rains and droughts. Stream sampling sites for Pockcheykhola, Chemcheykhola and Sombareykhola were predominantly occupied by agriculture with agroforestry and the other two were dominated by agriculture, agroforestry and forest land-uses. Out flow from the main outlet were also collected on these dates. Total suspended sediment content of each stream flow sample was determined by filtering the sediment from collected water samples.

5.2.2 Overland Flow and Soil Loss

Overland flow and soil loss were estimated from 27 experimental plots under different land-use during 1999 and 2000 on three monsoon (pre-monsoon, mid-monsoon and post-monsoon) seasons. Three rainfall events were considered for each monsoon period totaling 18 events during two years of study. These were estimated using natural shallow surface run-off channels and artificially delineated plots (Pandey *et al.* 1983; Singh *et al.* 1983; Rai & Sharma 1998). The delineated plot size was 10x3 m^2 for estimations of overland flow and soil loss, and three plots were laid in each type of land-use/cover practice. These plots were delineated with aluminum sheets (inserted in soil for about 6 cm and remaining 15 cm exposed in air) from all sides to prevent water likely to enter from adjacent areas. The plots were selected with 25 to 30° slope in all the land-uses as majority of the area in the watershed fall in this slope category. The overland flow and soil loss along the slope were estimated from the collecting tank after each rainfall event. Soil samples were collected from surroundings of each of the delineated plots in replicates up to 30 cm depth and samples were mixed together for a representative composite parent soil. These samples were collected just before the rainy season at the time of plot delineation. The eroded soil was sampled in the form of bed-load sediments and suspended clay materials from the collecting tank. The suspended clay material was separated by filtration through whatman filter paper size 41 from the sample water. The soils for carbon analyses comprised of both bed-load sediment and suspended clay materials for eroded soils. Total organic carbon of the soil was estimated following modified Walkley-Black method (Anderson & Ingram 1989).

Total area of each sub-divided land-use in the watershed was calculated, and overland flow and soil loss from each of the land-use were estimated. The run-off water samples were analyzed for soluble carbon (Anderson & Ingram 1989).

5.2.3 Precipitation Partitioning Pathways

Partitioning of incident precipitation into throughfall, stemflow, canopy interception; floor leachate and floor interception was made. Trees were marked for stemflow measurement in each of the sites, temperate natural forest dense, temperate natural forest open, sub-tropical natural forest, cardamom based agroforestry and mandarin orange based agroforestry systems. Stemflow was collected by attaching aluminum collars to five trees of different diameter classes in each stand. Stemflow was sampled over almost the whole range of size classes for the dominant tree species in each plot. Within each plot five throughfall collectors and five floor leachate collectors were established. Throughfall, stemflow, and forest floor leachate volumes were measured frequently to prevent over flowing. The floor leachate collectors were covered by 2 mm mesh nylon net on the top on which rested the litter, carefully removed from the bottom of the collectors. Floor leachate collectors were inserted into the soil such that the rim of the container was horizontal and level with the surface of the litter. Throughfall collectors rested on the soil surface such that their upper rims were also horizontal and about 20 cm above the surface. All throughfall and floor leachate collectors were set out in a random pattern and measurements were made at different times during the rainy season. Following each sampling, all throughfall and floor leachate collectors were randomly relocated. This technique is likely to produce more accurate estimates of annual volumes than fixed collectors (Kimmins 1973). Throughfall and floor leachate volumes were calculated considering the width of the upper rim of collecting vessels and converted to mm. Average stemflow volumes per tree for each species for a sampling period was calculated. These volumes were then multiplied by number of trees present to obtain the total stemflow volume for each plot and then converted to mm. Canopy interception was calculated by subtracting throughfall and stemflow value from incident precipitation. Forest floor interception was derived from the difference of the forest floor leachate with the added value of throughfall and stemflow.

Throughfall, stemflow, and floor leachate samples were determined in the field on bimonthly basis in different stands of forest and agroforestry and brought to the laboratory and processed for soluble carbon analyses following Anderson & Ingram (1993).

5.2.4 Statistical Analysis

All statistical analyses were conducted within the framework provided by the statistical analysis system (Systat 1996). The 0.05 level of probability was used as the criteria for accepting or rejecting null hypotheses pertaining to all data sets.

5.3 RESULTS

5.3.1 Stream Discharge and Carbon Loss

The Mamlay watershed is a part of the catchment of the Rangit River, the second largest river of the Sikkim Himalaya. The drainage network of the watershed is dendritic type and the texture is fine in the upper part of the watershed. The outlet for the watershed is the Rinjikhola which feeds the River Rangit, a main tributary of the River Tista. The watershed has a total area of 30.14 km^2 and the total stream length is 82.6 km. The drainage density of the watershed is very high, having a value of 2.74. The total number of channels are 80, 18 and 7 in the first, second and third order streams, respectively. The bifurcation ratio (ratio between the number of streams of a particular order and that of the streams of the next higher order) of the first order stream was 4.44 and the second order stream 1.14.

All the streams attain significant sizes during the rainy season. Seasonal streams dry up by January-May in the watershed. The highest discharge of 4143 l s^{-1} was recorded in the rainy season in 1999 followed by 4137 l s^{-1} in 2000 and the lowest of 850 l s^{-1} and 840 l s^{-1} in summer season, in the respective years, in the Rinjikhola, the outlet of the watershed (Fig. 5.1). For the different streams the discharge was in order Pockcheykhola > Sombareykhola > Chemcheykhola > Tirikhola > Rangrangkhola and the significant variation was observed only in rainy season. The discharge in various streams showed high seasonality and direct relationship with precipitation. Most of the precipitation was received in the monsoon and consequently discharge was highest in this season. Analysis of variance showed that streams, season and stream×season varied significantly (P<0.0001).

Across the micro-watersheds and total watershed, the carbon loss through runoff and sediment was analyzed. Organic carbon loss through sediments ranged from 0.014 to 136 t yr^{-1} in micro-watershed, while the annual loss from the outlet of the watershed was 833 t yr^{-1} (Table 5.1). The loss of soluble carbon through runoff water ranged between 0.96 to 814 t yr^{-1} for the micro-watersheds and was about 2025 t yr^{-1} at the watershed outlet. Streamflow concentrations of soluble carbon showed the most distinct seasonal trend. On seasonal basis highest loss was recorded during rainy season (Table 5.2) and it varied significantly (P<0.0001). All the streams showed highest concentration in the rainy season. On micro-watershed wise, mean yearly stream water soluble carbon concentration for the two years study period was recorded highest at Pockcheykhola (814 t yr-1) compared to mean concentration values with other micro-watersheds.

5.3.2 Sediment Concentration

The sediment concentration varied distinctly with seasons in different streams and the outlet of the watershed. The sediment concentration during 1999 and 2000 ranged from 9-61 mg l^{-1} in winter, 8-59 mg l^{-1} in summer, and 14-399 mg l^{-1} in the rainy season (Fig. 5.2). Analysis of variance showed significant variation between streams and seasons and its interaction was also significant ($P<0.0001$).

The highest sediment concentration in the rainy season was mainly because of high precipitation and extensive agricultural practices followed in this season. Seasonal and yearly soil loss value was recorded in stream waters of the micro-watersheds and total watershed for the two year period 1999-2000 are presented in Table 5.3. The soil loss from different micro-watersheds ranged from 0.001-7.48 t ha^{-1} in 1999 and 0.001-6.62 t ha^{-1} in 2000. The soil loss rate from the total watershed ranged between 6 to 7 t ha^{-1} yr^{-1} during the two years of the study. The total soil loss from the watershed with an area of 30.14 km^2 is significant, ranging from 18295 t yr^{-1} in 1999 to 21953 t yr^{-1} in 2000.

5.3.3 Precipitation and Overland Flow

Precipitation was recorded at two locations representing different slope and aspects in the watershed covering sub-tropical and temperate belts for the period of two years from 1999-2000. The average annual precipitation for the two years period was 2992 mm in temperate belt and 1295 mm in sub-tropical belt of the watershed.

Overland flow (percentage of rainfall during rainy season) was recorded to be highest in open cropped area sub-tropical (10.86%) and lowest in cardamom based agroforestry (2.80%) (Table 5.4). Usually the non-forested sites had a greater overland flow of water compared with adjacent forested and agroforestry sites. Overland flow was a function of the size of the rain-shower. Nevertheless, the magnitude of overland flow was too small to play a significant role in the wider context of flooding. The overland flows involve subsurface systems and that most of the water is transmitted to streams by lateral down slope flow within the soil.

5.3.4 Soil Erosion and Carbon Loss

In most areas, raindrop splash and sheet erosion are the dominant forms of erosion. Erosion is intensified on sloping land, where more than half of the soil contained in the splashes is carried downhill. The sediment movement from the temperate natural forest dense was 16 kg ha^{-1} during the monsoon period and this is 17 times lower than the values recorded from open cropped area of the sub-tropical belt (Table 5.4). There is a dramatic rise in sediment output from the landslide and newly constructed road sites consequent to the formation of channels. Erosion increased dramatically on steep cropland. Soil loss was recorded highest in open cropped area sub-tropical (525 kg ha^{-1}) when compared to forests and agroforestry systems.

Total organic carbon concentration in parent soil and eroded soil was estimated during the rainy season in different land-use/covers and the values are presented in Figure 5.3. Concentration of total organic carbon content was higher in eroded soil than the parent soil. Total organic carbon content in the parent soil upto 30 cm depth ranged from 10 to 26 mg g^{-1}, highest being recorded in temperate natural forest dense and very little variation was observed in other land-use/covers. But the highest organic carbon concentration in eroded soil was recorded in wasteland area temperate (40.8 mg g^{-1}) and lowest from temperate natural forest dense (32.2 mg g^{-1}). An ANOVA test on organic carbon concentration between eroded and parent soils and between land-uses shared a statistically significant variation ($P < 0.0001$).

5.3.5 Precipitation Pathways and Carbon Flow

Incident precipitation is initially partitioned into throughfall, stemflow and interception by a forest canopy. Some of the throughfall and stemflow reaching the forest floor is intercepted by the litter, the remainder flows into the mineral soil as forest floor leachate. Partitioning of incident precipitation into various pathways in temperate natural forest dense, temperate natural forest open, sub-tropical natural forest open, large cardamom based agroforestry system and mandarin orange based agroforestry system of the watershed were analyzed. The quantities of water moving through these pathways are given in Table 5.5. In temperate natural forest dense, precipitation partitioned into 77.71% throughfall, 9.92% stemflow and 11.40% intercepted by canopy. About 45% of the water was collected as leachate and the floor interception was 55%. In the case of temperate natural forest open, 52.71% canopy interception was recorded. In the large cardamom based agroforestry system, throughfall was recorded 54.58% of total precipitation, canopy interception was 40% and stemflow was just 5%. In the sub-tropical natural forest, throughfall was about 55.67%, canopy interception was 42% and the stemflow was negligible that amounted 0.23%. The floor leachate was 38% and the remaining 62% was recorded to be the floor interception. Stemflow in the mandarin agroforestry system was higher (5%) than that recorded from sub-tropical natural forest open. The total amount of water on the floor partitioned as 70% as leachate and remaining as floor interception in the mandarin based agroforestry system (Table 5.5).

In temperate natural forest open a significant reduction in throughfall (P<0.05) was observed in open canopy and cardamom agroforestry stand probably because of less rainfall intercept by these than dense forest stand. Higher canopy interception was recorded in open forest stand but canopy interception in between open forest stand and cardamom agroforestry stand did not vary significantly (P>0.05) because of similar canopy coverage (Table 5.5). Floor leachate also did not vary significantly. In floor interception significant reduction was observed (P<0.05) due to more floor litter and herbaceous biomass. No significant variation was observed in throughfall, stemflow, canopy interception, floor leachate and floor interception between subtropical natural forest and mandarin based agroforestry system (all P>0.05) because of sparse canopy coverage (Table 5.5).

Soluble carbon flow was analysed in throughfall, stemflow and floor leachate in different forest and agroforestry stands in sub-tropical and temperate belts of the watershed (Table 5.6). The soluble carbon concentration in throughfall was highest in cardamom based agroforestry system (34.43±4.89 mg l^{-1}) and lowest in sub-tropical natural forest (25.27±4.31 mg l^{-1}). In stemflow water also, soluble carbon was recorded highest (54.13±7.91 mg l^{-1}) in cardamom based agroforestry system, while soluble carbon in floor leachate was recorded highest (51.40±4.70 mg l^{-1}) in sub-tropical natural forest open (Table 5.6).

5.4 DISCUSSION

The drainage texture is fine on the higher elevation and gradually becomes coarse at the valley. Fine drainage texture is vulnerable for high rates of erosion under extensive cultivation. In the Mamlay watershed all high hill areas are located under forest cover where fine drainage texture is prevalent experiencing minimum soil erosion. Because of the fine texture and dense forest, this zone has high underground water potential. In spite of coarse drainage texture, erosion was greatest in the middle hills because of dense population and extensive cultivation. The discharge in various streams showed high seasonality and direct relationship with precipitation. About 90% of annual precipitation was received in the monsoon and the discharge was highest in this period. Many streams dried completely during the summer season mainly in the mid hills because of deforestation and extensive human activities. This belt is located between two major thrusts of the watershed where water percolates from upper thrust and appears in the lower thrust through sub-surface flow. Sediment concentration also showed seasonality similar to discharge. The sediment concentration in different seasons at all streams showed direct relationship with precipitation. The highest sediment concentration in rainy season was attributed to (i) high rainfall during this period, (ii) steep slopes and (iii) extensive cultivation of the soil practices in this season. The soil loss rate from the total watershed ranged from 6 to 7 t ha^{-1} yr^{-1} during the two years of study. Rawat & Rawat (1994) reported about 2 t ha^{-1} yr^{-1} soil loss in a normal rainfall year from a watershed in the Central Himalaya where the rainfall is comparatively low. The two year average of the annual sediment flux from the watershed was 667 t km^{-2} yr^{-1}. This is within the range of 500-1000 t km^{-2} yr^{-1} reported for the Himalayan region by Milliman & Meade (1983). Soil loss as high as 3005 t km^{-2} yr^{-1}, was recorded in an agro-ecosystem less than 5 years of shifting cultivation (Toky & Ramakrishnan 1981).

Mean annual estimates of organic carbon export via stream flow differ somewhat with micro-watersheds. Carbon in soluble form was lost more through runoff than sediment movement. The higher concentration values at stream water are related to the mean annual discharge.

Rainfall was distributed seasonally and more than 90% was received during May to October. The overland flow in the open cropped area was highest because of intensive cultivation and steep aspect of the land. It takes between 200 and 1000 years to form 2.5 cm of top soil under cropland conditions, and even longer under forest conditions (Pimental *et al.* 1995). About 80% of the World's agricultural land suffers moderate to severe erosion, and 10% suffers slight to moderate erosion (Speth 1994). Croplands are most susceptible to erosion because their soil is repeatedly tilled and left without a protective cover of vegetation. A survey of agricultural fields on unterraced slopes showed more than 60% pebbles/stones. Participatory inventory with farmers also revealed high soil erosion problem and the indicators as observed by farmers were exposure of red soil and stones of deeper soil profile. The overland flow decreased in mandarin orange based agroforestry as a result of protection by trees. In the sub-tropical forest relatively high amount of overland flow was recorded because of high biotic pressure. Prior to the year of experimentation this forest was totally in degraded condition and devoid of ground vegetation and understory species. This has contributed to greater overland flow and soil loss. Overland flow and soil loss from the wasteland was low compared to open cropped area as it was not disturbed and was covered by ground vegetation. Similar observations on fallow lands were also made in shifting agriculture system in North-Eastern India by Toky & Ramakrishnan (1981). According to an estimate made by Shah (1982) nearly 85% of all agricultural land already suffers from severe erosion problems. The overland flow and the soil loss in large cardamom based agroforestry system were lower because of good tree canopy and under-story thick large cardamom bush coverage. Temperate natural forest dense showed relatively lower overland flow and soil loss. In the Central Himalaya, comparatively less overland flow was recorded from the temperate forest but the soil loss was more than the temperate forest of the present study (Pandey *et al.* 1983; Singh *et al.* 1983; Negi *et al.* 1998). The high overland flow in the present study located in the eastern Himalaya was the consequence of higher rain intensity and more annual precipitation. In spite of more overland flow in the temperate natural forest in the present study, soil loss was less than the Central Himalaya because of complete ground vegetation, thicker forest floor litter and more stratification of the forest. Large cardamom based agroforestry is a traditional practice of the region and is regarded to be profitable and sustainable farming system. The less overland flow values in temperate natural forest and large cardamom based agroforestry indicate that the catchment areas under these land-uses encourage high infiltration and subsurface flow. Bren & Turner (1979) and Bren (1980) studied the surface runoff on steep forested infiltrating slopes in Australia and reported that overland flow was very low (0.005% of the rainfall). The hydrological response of a forested hill slope to rain is often dominated by the lateral down slope movement of water within the soil system. Overland flow may be a rare occurrence on such forested watershed.

Soil and organic carbon losses from open cropped area was more than 90% of total watershed indicating that agriculture practice without agroforestry in such unterraced sloping land and in high rainfall areas are highly vulnerable. Therefore, strong agroforestry based agriculture such as mandarin, cardamom and horti-agri-silvi system is recommended in the watershed for conservation of soil, water and nutrients in such a fragile upland farming system. Reliable and proven soil conservation technologies include ridge planting, no-till cultivation, crop rotations, strip cropping, grass-strips, mulches, living mulches, terracing, contour planting, cover crops and windbreaks (Pimental *et al.* 1995). Although the specific processes vary, all conservation methods reduce erosion rates by maintaining a protective vegetative cover over the soil, which is often accompanied by a reduction in the frequency of ploughing. Ridge planting, for example, reduces the need for frequent tillage and also leaves vegetative cover on the soil surface year round, and crop rotations ensure that some part of the land is continually covered with vegetation. Each conservation method may be used separately or in combination to control soil erosion. To determine the most advantageous combination of appropriate conservation technologies, the soil type, specific crop and climate (rainfall, temperature and wind intensity), as well as the socioeconomic conditions of the people living in a particular site must be considered.

The implementation of appropriate soil and water conservation practices has the potential to reduce erosion rates from 2 to 1000 fold and water loss from 1.3 to 21.7 fold. Conservation technologies also significantly reduce organic carbon loss. By substantially decreasing soil and nutrient loss, conservation technologies preserve the soils fertility and enable the land to sustain higher crop yields. In many instances, the use of conservation technologies may actually increase yields (Faeth 1993; Sharma *et al.* 2001).

Organic carbon content was high in temperate natural forest dense as a result of humus accumulation and high organic matter input. The organic carbon of the cropped area was also high which has resulted from application of organic manure in the system. Organic carbon loss could be more in the cropped area because of the high soil loss. The higher loss of organic carbon through soil erosion in the sub-tropical forest compared to temperate natural forest dense and temperate natural forest open is mainly attributed to higher soil loss in the sub-tropical forest. Nutrient discharge from watersheds increases as percentage of cropland increases (Jordan *et al.*1986; Omernik 1976; Likens & Borman 1974) and high carbon loss from the open cropped area in the present study is consistent to this finding. However, the amounts of nutrients released by croplands differ greatly even among lands with the same crop. This is partly due to the variety of farming methods. Carbon release by forests is generally thought to be related to age and amount of disturbance. Young or highly disturbed forests release the most nutrients, old forest release less and intermediate aged forests release the least (Bormann & Likens 1979). Soil type may also influence organic carbon discharge. Dillon & Kirchner (1975) found that watersheds with soils of sedimentary origin, like the present watershed, discharge more nutrient than those with soils of igneous origin. The ranking of land-use vulnerable to soil erosion with respect to loss of organic carbon was open cropped area> mandarin orange based agroforestry>sub-tropical natural forest> wasteland> cardamom based agroforestry>temperate natural forest dense. In the crop fields of the Himalayan catchments which are highly vulnerable to erosion, a large amount of manure input is required to off set the carbon losses. This can be appreciated by the fact that for a potato crop field of Poland it was reported that particulate input of only 263 g C m^{-2} resulted in an increase of 103 g C m^{-2} (Melillo 1985), while in the maize field in Central Himalaya, similar amount of organic matter input could not even off set the decline in the carbon status of the soil (Singh & Singh 1992), where deforestation leads to an agricultural land-use, higher rates of erosion will be maintained indefinitely (Rapp 1975) unless practices of soil conservation are especially followed (Doran 1980).

The throughfall, stemflow, and canopy interception results are similar to that of forests of the Central Himalaya (Pathak *et al.* 1983; Negi *et al.* 1998; Jain *et al.* 2000). Throughfall in the temperate natural forest dense was highest as a result of more canopy coverage and broad leaf nature of natural forest species than the mixed open forest. Throughfall of similar magnitude has been reported by Henderson *et al* (1977). Stemflow was more in open forest because of *Cryptomeria japonica* dominating which has conical canopy architecture and stream lining of water through stemflow. Our data on canopy interception corroborate that broad-leaved forest intercepts less rainfall than do coniferous species. Pathak *et al* (1983) reported positive relationship of interception with canopy cover in the Oak forest of the Central Himalaya. Waring *et al* (1980) argued that the surface area of the forest is an important determinant in interception processes. Floor interception of precipitation was directly related with the floor litter composition and quantity. Broad-leaved litter composition showed higher floor interception and relatively smaller floor leachate. Precipitation partitioning was studied only in systems where there was tree cover. Comparisons between forest types and agroforestry systems showed that totality of canopy and floor interception is very important determinant for water availability with respect to floor leachate. Forests showed more floor interception as result of thick litter layer. Mandarin orange based agroforestry have smaller floor interception and showed fairly high soil erosion indicating inverse relationship.

In the partitioning of precipitation the soluble carbon on the leaf surface, stem bark, and floor litter are mobilized. Our study shows different levels of mobility of soluble carbon in different pathways of partitioning. Soluble carbon loss through floor leachate was highest in cardamom based agroforestry system. Soluble carbon loss through floor leachate was almost similar from different land-uses except for temperate natural forest open that showed relatively lower value. This may be because of slow decomposition rates in temperate natural forest open.■

Table 5.1 Carbon loss (tons) through sediment in different streams water of Mamlay watershed

Season	Micro-watersheds					Total watershed
	Pokchey khola	Chemchey khola	Tiri khola	Sombaray khola	Rangrang khola	Rinji khola*
Winter	1.2	1.6	3.9	0.2	0.003	17.8
Summer	0.4	0.7	1.1	0.0003	0.00	3.0
Rainy	45	28	131	34	0.014	812
Total ($t\ yr^{-1}$)	46.6	30.3	136	34.2	0.0143	833

*Watershed outlet

ANOVA: Streams $F_{4,30} = 427.65$, $P<0.0001$; Season $F_{2,30} = 1769.40$, $P<0.0001$; Streams x Season $F_{8,30} = 382.901$, $P<0.0001$.

Table 5.2 Soluble carbon (tons) loss through different streams water of Mamlay watershed

Season	Micro-watersheds					Total watershed
	Pokchey khola	Chemchey khola	Tiri khola	Sombara y khola	Rangrang khola	Rinji khola*
Winter	74	77	74	14	0.06	51
Summer	7	14	16	0.2	0.00	148
Rainy	733	559	388	401	0.9	1826
Total (t yr^{-1})	814	650	478	415	0.96	2025

*Watershed outlet

ANOVA: Streams $F_{4, 30} = 5650.89$, $P<0.0001$; Season $F_{2, 30} = 46064.92$, $P<0.0001$; Streams x Season $F_{8, 30} = 3980.46$, $P<0.0001$.

Table 5.3 Seasonal and yearly soil loss (tons) estimated using discharge and sediment concentration of micro and total watershed

Parameter		Micro-watersheds					Total Watershed
		Pokchey khola	Chemchey khola	Tiri khola	Sombaray khola	Rangrang khola	Rinji khola*
Area (ha)		788	717	509	635	365	3014
1999	Winter	48	47	284	10	0.03	744
	Summer	13	30	33	0.01	0.00	87
	Rainy	1235	854	3491	977	0.44	17464
	Total	1296	931	3808	987	0.47	18295
	Soil loss ($t\ ha^{-1}$)	1.64	1.30	7.48	1.55	0.001	6.07
2000	Winter	33	43	98	7	0.01	500
	Summer	10	19	28	0.01	0.00	83
	Rainy	1118	793	3242	948	0.4	21370
	Total	1161	855	3368	955	0.41	21953
	Soil loss ($t\ ha^{-1}$)	1.47	1.19	6.62	1.50	0.001	7.28

*Watershed outlet

Table 5.4 Overland flow (% of rainfall) and soil loss (kg ha $^{-1}$) in different land-use/cover of Mamlay watershed

Land-use	Overland flow	Soil loss
Temperate natural forest dense	2.57	16
Temperate natural forest open	3.92	22
Subtropical natural forest open	4.56	27
Cardamom based agroforestry system	2.80	18
Mandarin based agroforestry system	4.77	31
Open cropped area temperate	10.25	480
Open cropped area subtropical	10.86	525
Wasteland area temperate	3.78	24
Wasteland area subtropical	3.90	25

ANOVA: Overland flow – Land-use $F_{8, 18} = 104.14$, $P<0.0001$; Soil loss – Land-use $F_{8, 18} = 1131.52$, $P<0.0001$.

Table 5.5 Partitioning of incident precipitation into various pathways in different land-use/cover of Mamlay watershed (n=6). Values in parentheses are ± se. Means with same superscript in each row are not significantly different to each other at $P<0.05$ (Tukey's honestly significant test)

Parameters	Land-use				
	Temperate region			Subtropical region	
	Temperate natural forest dense	Temperate natural forest open	Cardamom based agroforestry system	Subtropical natural forest open	Mandarin based agroforestry system
Throughfall (mm)	2355^{c} (96)	974^{a} (48)	1633^{b} (54)	721^{a} (26)	746^{a} (50)
Stemflow (mm)	297^{c} (19)	441^{d} (26)	162^{b} (13)	32^{a} (7)	68^{a} (5)
Canopy interception (mm)	341^{a} (76)	1577^{b} (22)	1197^{b} (67)	541^{a} (19)	481^{a} (55)
Floor leachate (mm)	1195^{b} (105)	1226^{b} (71)	1215^{b} (68)	290^{a} (36)	573^{a} (26)
Floor interception (mm)	1456^{c} (31)	189^{a} (49)	580 (135)	464^{a} (54)	241^{a} (29)

Table 5.6 Carbon content (mg l^{-1}) in throughfall, stemflow and floor leachate in forests and agroforestry land-uses of Mamlay watershed

Land-use	Throughfall	Stemflow	Floor leachate
Temperate natural forest	27.42±3.42	37.43±3.02	24.57±3.68
Subtropical natural forest open	25.27±4.31	29.60±8.86	51.40±4.70
Cardamom based agroforestry system	34.43±4.89	54.13±7.91	36.93±5.45
Mandarin based agroforestry system	27.03±7.60	48.20±4.58	20.27±4.85

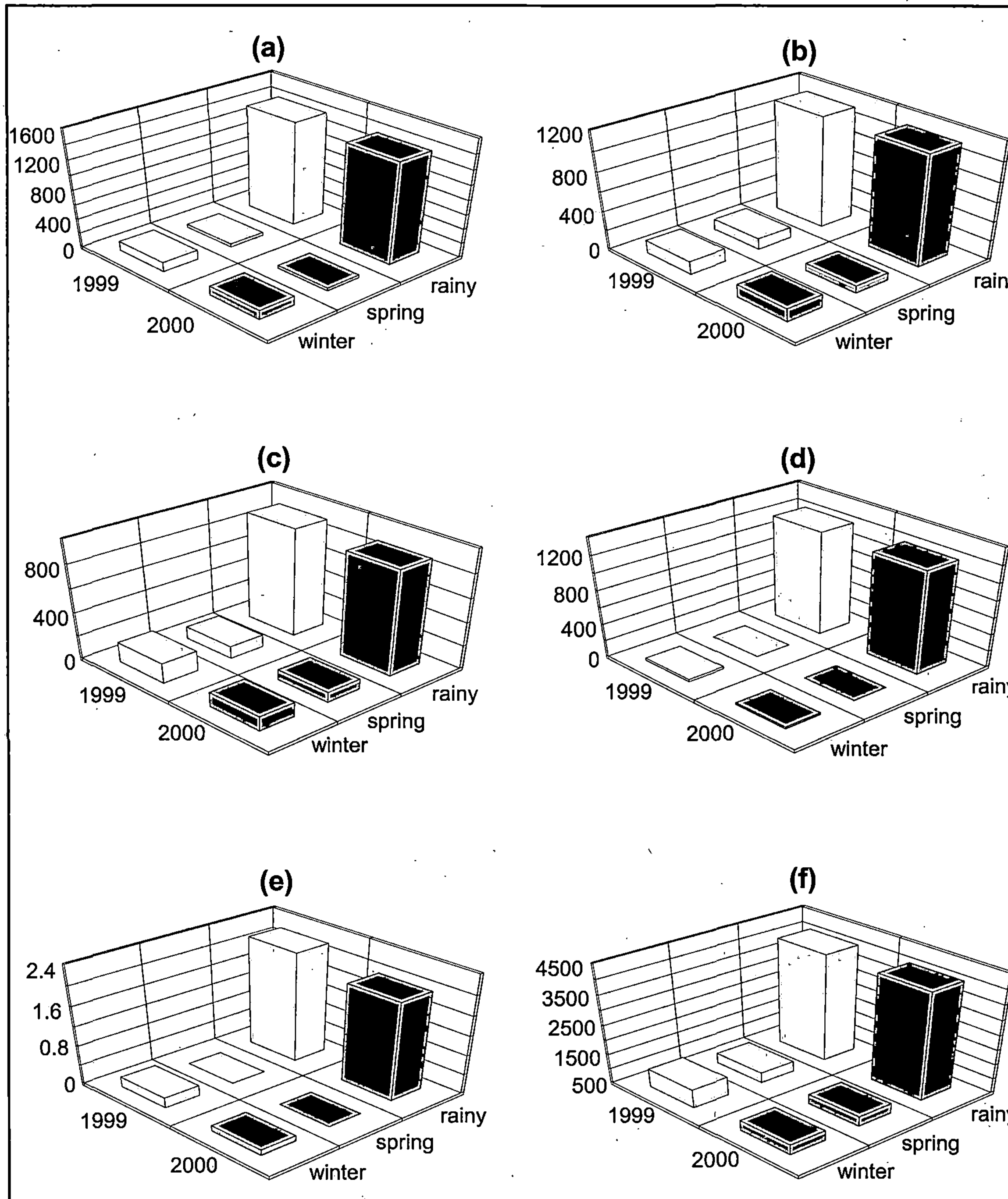

Fig. 5.1 Seasonal stream discharge (ls^{-1}) for 2 years in different streams and the outlet; **(a)** Pokcheykhola, **(b)** Chemcheykhola, **(c)** Tirikhola, **(d)** Sombareykhola, **(e)** Rangrangkhola and **(f)** Rinjikhola (watershed outlet).

ANOVA: Discharge-streams $F_{4,60}$=15213, P<0.0001; year $F_{1,60}$=69.71, P<0.0001; season $F_{2,60}$=150076, P<0.0001; streams x year $F_{4\ 60}$=12.18, P<0.0001; stream x season $F_{8,60}$=11040, P<0.0001; year x season $F_{2,\ 60}$=0.229, NS; stream x year x season $F_{8,\ 60}$= 7.14, P<0.0001; LSD (0.05) = 3.66.

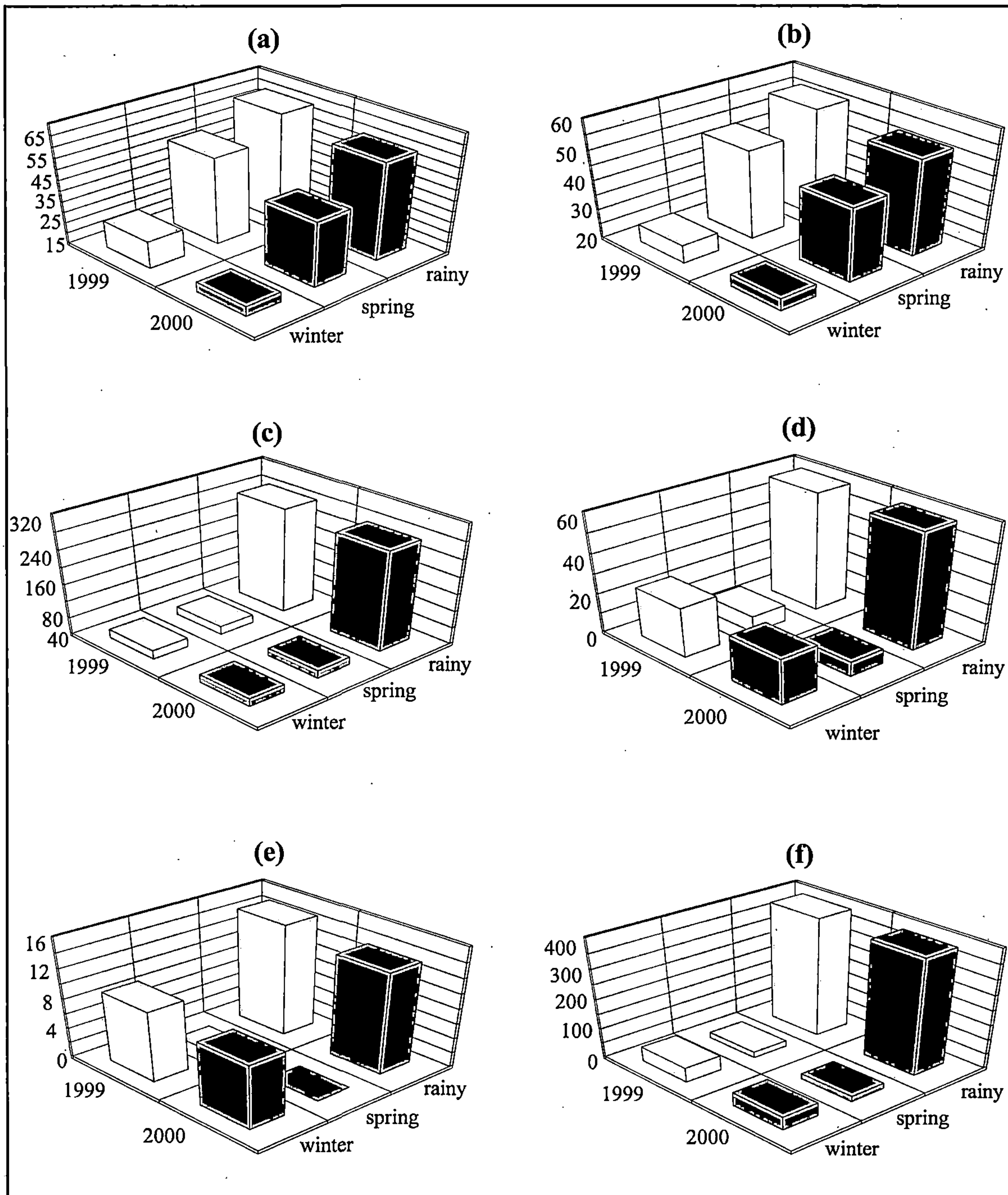

Fig. 5.2 Seasonal sediment concentration (mg l^{-1}) for 2 years in different streams and the outlet; **(a)** Pokcheykhola, **(b)** Chemcheykhola, **(c)** Tirikhola, **(d)** Sombareykhola, **(e)** Rangrangkhola and **(f)** Rinjikhola (watershed outlet). ANOVA: Sediment concentration-streams $F_{4,60}$=3733, P<0.0001; year $F_{1,60}$=25.98, P<0.0001; season $F_{2,60}$=3675, P<0.0001; streams x year $F_{4,60}$=3.15, P<0.05; stream x season $F_{8,60}$=1480, P<0.0001; year x season $F_{2,60}$=0.48, NS; stream x year x season $F_{8,60}$=1.31, NS.

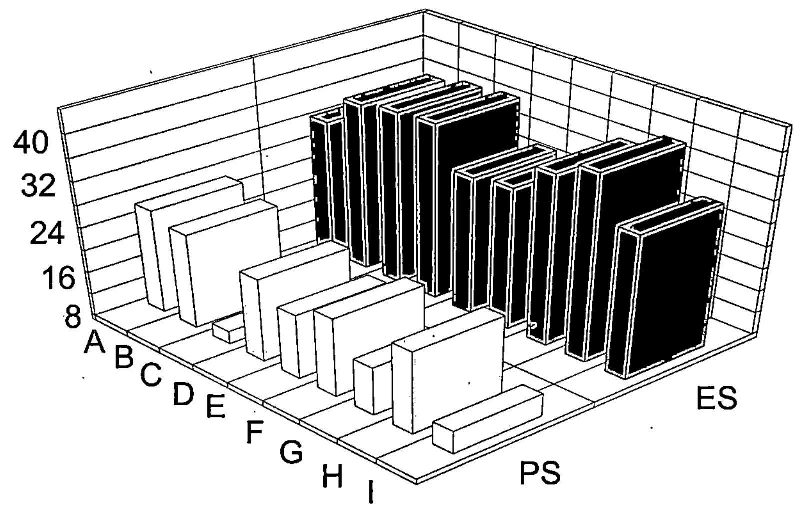

Fig 5.3 Organic carbon (mg g^{-1}) in parent soil (PS) and eroded soil (ES) in different land-use/ cover, A=Temperate natural forest dense, B = Temperate natural forest open, C = Subtropical natural forest open, D = Cardamom based agroforestry system, E = Mandarin based agroforestry system, F = Open cropped area temperate, G = Open cropped area sub-tropical, H = Wasteland temperate and I = Wasteland subtropical.
ANOVA: Organic carbon – Land-use $F_{8,36}$ = 311.53, P<0.0001; soil type $F_{1,36}$ = 19039, P<0.0001; Land-use x soil type $F_{8\,36}$ = 316.41, P<0.0001. LSD (0.05) = 0.299

Chapter -VI

CARBON BUDGET

6.1 INTRODUCTION

Recent years have seen a spectacular increase in the per capita food production worldwide. At the same time forest ecosystems have also shown progressive deterioration with increasing conversion of forests to other uses, and degradation of soil by nutrient depletion and erosion. The conversion of forest to agricultural land has varying influence on terrestrial C inventories, depending on the type of land-use/covers undergoing change and the post conversion land management. The forest-dominated watersheds are consequently converted into agrarian watersheds which lead to a considerable loss of soil organic matter and microbial biomass (Hass *et al.* 1957; Adams & Laughlin 1981; Bauer & Black 1981). Deforestation accounts for an annual net release of carbon between 0.9×10^{15} and 2.5×10^{15} g, one third of which could be due to oxidation of soil carbon in the tropics occasionally by changes in land-use patterns (Houghton *et al.* 1985). Changes in land-use through anthropogenic and climatic forcing result in vegetation conversion, which is likely to influence the balance of storage and flux of carbon in terrestrial ecosystems (Global Change Report No. 4 1988).

Humans have significantly caused changes in species composition, structure and function of terrestrial ecosystems. Forest conversion to agriculture or pastureland causes functional shifts from woody canopy to the herbaceous ground stratum. This may lead to altered carbon storage/flux relationships and therefore will have implications for global carbon budget. Besides the living phytomass, the most important carbon reservoir of the biosphere is the litter from dead plant materials which is also responsible for the large organic carbon pool in the soil.

Estimating shifts of carbon due to land-use/cover change is a key process in determining impacts of disturbance on C storage in ecosystems. Allocation includes the pool of C in biomass components, and the fluxes of C between atmosphere, plants and soil. Possible adverse consequences of land transformation have drawn attention to the inventory and dynamics of biospheric carbon (Chan 1982). Land-use/cover change may contribute to the loss of soil carbon by changing the balance between biomass production and decomposition. Intensive cultivation can also decrease soil carbon, contributing to terrestrial net fluxes of carbon to the atmosphere and decreased net primary productivity (Burke *et al.* 1989; Johnson 1992).

Soil is the largest pool of terrestrial C, more than three times the C in land vegetation, and, depending on the land-use (Houghton *et al.* 1987; Schlesinger 1997), this pool may be a source or sink of carbon both by changes in the carbon content per unit soil (via assimilation and decomposition) and by the movement of soil itself through erosion and deposition (Van-Noordwijk *et al.* 1994). Soil carbon is the major constituent of the soil organic matter and thus, is the index of soil fertility and productivity. Soil organic carbon is intricately linked to the cycling of soil nutrients that influence ecosystem productivity (Van Cleve & Powers 1995). The soil carbon storage is controlled by the balance of C inputs from plant production and outputs through decomposition (Jenny *et al.* 1949; Schlesinger 1977). Soil microbial biomass constitutes a transformation matrix for all the natural organic materials in soil and act as a labile reservoir of plant available nutrients (Jenkinson & Ladd 1981; Singh *et al.* 1989; Srivastava & Singh 1991).

The patterns and controls of soil carbon storage are critical for understanding of the biosphere, given the importance of different forms of soil carbon for ecosystem processes and the feedback of this pool to atmospheric composition and the rate of climate change (Raich & Potter 1995; Woodwell *et al.* 1998). Although many important global and regional carbon budgets are available (Schlesinger 1977; Post *et al.* 1982; Eswaran *et al.* 1993; Kern 1994, Bashkin & Binkley 1998; Rhoades *et al.* 2000; Jobbagy & Jackson 2000, Srivastava, 1994 and Batjes, 1996), and for some biome, like temperate grasslands, major environmental controls of SOC have been described (Parton *et al.* 1987; Burke *et al.* 1989; Brye *et al.* 2002), the effects of large-scale land-use changes on the carbon (C) cycle are poorly understood. However, no information is available on carbon budget and pool i.e., plant allocation above and belowground, vertical distribution in the soil and accompanying relationships with land-use/cover in a Himalayan watershed.

This chapter quantifies the carbon budget as a function of land-use/covers. For the convenience of the study, the whole chapter has been divided into (a) carbon content in vegetation, (b) carbon in floor litter, (c) carbon in humus, (d) soil carbon pool, (e) compartmental distribution of carbon and (f) watershed carbon budget.

6.2 MATERIALS AND METHODS

6.2.1 Plant Carbon Analyses

Carbon content in different parts of plant was determined on land-use/cover basis. Plant materials viz., bole, branch, leaf, twig, root, fruit, herbaceous biomass, weed and crop residue were collected from different land-use/cover types from the watershed and oven dried in the laboratory. Oven dried plant materials were ground and made a composite sample for each component on land-use/cover basis. Percent carbon was analyzed using a Heraeus CHN-O Rapid Elemental Analyzer. The powdered samples were dried at 105±2 °C in an air oven upto constant weighting. About 15 to 25 mg sample from each plant component was placed in a Tin boat and injected into oxygen filled quartz combustion tube for oxidative decomposition using copper oxide catalyst. Pure Helium served as carrier and scavenging gas. Interfering substances like volatile halogens or sulphur compounds were removed from the gas stream by silver wool.

The total carbon content in different components of plant biomass was estimated by multiplying biomass value with the carbon per cent.

6.2.2 Sample Collection and Processing

6.2.2.1 Soil sampling

Seasonal soil sampling (winter, spring and rainy) was carried out in replicate from the marked sample plots at each of the nine selected land-use/covers, numbering 27 plots altogether during 1999-2000 at two depths interval i.e., 0-15 cm and 15-30 cm for soil organic carbon analysis. In each land-use/cover, soil cores were taken along the altitudinal gradients to see the vertical distribution of carbon stock upto 1m depth. The cores were divided into seven (0-15, 15-30, 30-45, 45-60, 60-75, 75-90 and 90-100 cm) depths. Soil samples were transported to laboratory for analyses. Bulk density of soil (mass per unit volume in g cm^{-3}) in all the experimental plots were determined from random cores taken at different depths. Samples were oven dried at 80 ^{0}C to constant weight.

6.2.2.2 Soil carbon analyses

Soil samples were air dried and passed through a 2-mm sieve to remove coarse fragments and roots. Soil organic carbon was analyzed at seven depths. Seasonal organic carbon was analyzed at two depths only (0-15 cm and 15-30 cm). Organic carbon of soil samples was measured after the partial oxidation with an acidified dichromate solution following modified Walkley-Black method (Anderson & Ingram 1993).

Per cent total carbon at different soil depths was determined using a Heraeus CHN-O Rapid Analyzer. The soil samples were homogenized and were dried at 105±2 °C in an air oven upto constant weighting. A composite 15 to 25 mg samples were taken for analyses.

6.2.2.2.1 Microbial biomass carbon

At each site, three soil samples were collected randomly from the upper 15 cm. Large pieces of plants and stones were removed and each sample was sieved through 2 mm mesh screen and divided into two parts. One part in the field moist condition was used to determine microbial biomass carbon and the other part was air-dried for the rest of the analyses.

The field-moist soils were stored for 7 days at room temperature (25 - 28°C) to stabilize the respiration (Srivastava & Singh 1988). Microbial C was determined by fumigation-extraction in which soils were extracted after fumigation (Anderson & Ingram 1993). For microbial biomass carbon analysis two subsamples of 10±0.01 g were weighed into 150 ml beaker and the first subsample was extracted with K_2SO_4. This extract was analyzed for organic carbon (Ct_0). The second subsample was fumigated with 30 ml alcohol free liquid chloroform. The chloroform was evaporated applying the vacuum pump and the dried sample was stored in the dark for 5 days at 25°C. After 5 days the soil was extracted with same K_2SO_4 solution and the extract was analyzed for organic carbon (Ct_1). Microbial biomass carbon was calculated by the formula (Ct_1-Ct_0) x 2.64, where 2.64 is a constant (Vance *et al.* 1988). All data reported in this study are means for three seasons (winter, spring and rainy), three replicate sites of each land-use/cover and two years (1999-2000 and 1999-2001).

Soil total carbon (TC), total organic carbon (TOC) and microbial biomass carbon mass (t ha^{-1}) was calculated by multiplying carbon concentration by depth-wise bulk density.

6.2.3 Statistical Analysis

Statistical analyses were conducted using SYSTAT version 6.0 (SYSTAT 1996) and SPSS version 6.0. Statistical analysis between land-use, depths, seasons and their interactions was based on analysis of variance (ANOVA). The difference between means of different parameters in different land-uses were compared with Tukey's honestly significant difference test ($P<0.05$) (SPSS version 6.0), using land-use, seasons and depths as independent variables. Simple regression analyses were employed to compare the strength of relationships between different parameters as a function of land-use/covers.

6.3 RESULTS

6.3.1 Carbon Content in Vegetation

Per cent carbon in different plant materials are summarized in Table 6.1. Most of the ecosystem carbon is stored in the plant biomass. Per cent carbon in woody biomass of temperate natural forest dense, temperate natural forest open, sub-tropical natural forest open, cardamom based agroforestry system and mandarin based agroforestry system were

42.53, 42.53, 47.79, 45.50, and 45.95 respectively. Similarly in leaf, it was 47.33, 50.24, 47.07 and 44.93% and in root, 45.01, 46.63, 45.50 and 44.98% respectively. In crop residue the mean carbon was 40.97%.

The total vegetation C varied significantly with land-use ($P<0.0001$). Tukey's pairwise mean difference showed significantly higher total vegetation C in temperate natural forest dense compared to other land-uses ($P<0.05$). Pairwise mean differences were not significant between agroforestry systems and open cropped area of subtropical and temperate belts ($P>0.05$) (Table 6.2). The total carbon storage ranged from 5.47 to 191 t C ha^{-1} (Table 6.2). Weed biomass in open cropped area temperate and subtropical belts contributed more (54-63%) C storage compared to crop residue. The belowground biomass in the cardamom based agroforestry system contributed more (37%) to total C storage compared to that in temperate natural forest dense (5%). Share of herbaceous vegetation in total stored-vegetation C was only 0.19%, 0.62% and 0.51% for temperate natural forest dense, temperate natural forest open and subtropical natural forest, respectively.

6.3.1.1 Allocation of C in above-ground plant biomass

The C in aboveground plant biomass varied significantly with land-use ($P<0.0001$). Tukey's pairwise mean difference of aboveground biomass C showed significant differences between temperate natural forest dense with other forests and agroforestry stands ($P<0.05$). Pairwise 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 ($P<0.05$). Mean difference were also not significant between sparse vegetation stands such as temperate natural forest open and subtropical natural forest open. Mean values for aboveground biomass C ranged between 4 to 182 t C ha^{-1}. More than 80% C was recorded in aboveground biomass in all the stands except cardamom based agroforestry system (Table 6.2).

6.3.1.2 Allocation of C in below-ground plant biomass

The C of belowground plant biomass varied significantly with land-use ($P<0.0001$). Tukey's pairwise mean difference probabilities showed significant differences between cardamom based agroforestry systems and other stands ($P<0.05$). Temperate natural forest dense had significantly higher belowground biomass C than other stands ($P<0.05$). Pairwise mean difference between temperate natural forest open with other stands were also significant but variations between similar stands were not significant ($P>0.05$). Belowground biomass C in agroforestry stands contributed more (30%) to total C storage compared to different types of forest stands (4%) (Table 6.2).

6.3.1.3 Short-term vs. long-term vegetation carbon

Mean values for short-term and long-term C in standing vegetation are calculated for each land-use/cover (Table 6.3). Long-term vegetation C comprised of woody (bole+branch) components and coarse roots, and short-term vegetation C comprised tree leaves, ground vegetation and fine roots. Long-term vegetation C varied significantly with land-use ($P<0.0001$). Tukey's pairwise mean difference showed significant difference between temperate natural forest dense and other stands ($P<0.05$). Stands with sparse vegetation i.e., temperate natural forest open and subtropical natural forest open had significantly higher long-term carbon than agroforestry stands. The long-term vegetation C was 62 times higher in temperate natural forest dense in comparison to mandarin based agroforestry system, whereas it was only 4 times higher than cardamom based agroforestry system.

Short-term vegetation C also varied significantly with land-use ($P<0.0001$). Pairwise mean difference showed significantly higher short-term C concentration in open cropped area temperate and subtropical belts than other land-use/covers ($P<0.05$). Cardamom based agroforestry system had significantly higher short-term carbon over other land-uses. Mean difference between similar type of stands did not show significant difference ($P>0.05$).

The ratio of standing crop of carbon in short lived components of vegetation to that of C in long lived components increased. Thus temperate natural forest dense had this ratio equal to 0.007, temperate natural forest open had a mean ratio of 0.016, the cardamom based agroforestry system 0.096 and mandarin based agroforerstry 0.79 (Table 6.3).

Relationship between basal area and vegetation carbon are presented in Fig 6.1. In the forested and agroforestry stands, tree basal cover was linearly related ($r^2 = 0.73$, $P<0.0001$) with long-term carbon and total vegetation carbon ($r^2 = 0.85$, $P<0.0001$) (Fig 6.1 a, b). Total stand carbon (total vegetation + soil) was also linearly related ($r^2 = 0.70$, $P<0.0001$) with basal area (Fig 6.1 c), while short-term C did not show any relationship with basal area. Standing biomass was also linearly related ($r^2 = 0.99$, $P<0.0001$) with stand total carbon (Fig 6.2a).

6.3.2 Carbon in Floor Litter

Per cent carbon in floor litter ranged from 35% to 44% (Table 6.1). The carbon mass in floor litter of different forests and agroforestry systems are presented in Table 6.4. The total carbon content in floor litter ranged from 1.50 to 5.20 t C ha^{-1}. Floor litter C varied significantly with land-use ($P<0.0001$). Cardamom based agroforestry system had significantly higher C concentration than other stands ($P<0.05$). Temperate natural forest dense had also significantly higher floor litter C in comparison to other stands but significantly lower than cardamom based agroforestry stand. Stands having sparse vegetation did not show significant difference in floor litter C content ($P>0.05$). Floor litter carbon was positively related to floor litter biomass with high significance level ($r^2 = 0.93$, $P<0.0001$) (Fig 6.2b).

6.3.3 Carbon in Humus

Humus C varied significantly with land-use ($P<0.01$). Tukey's pairwise mean difference test showed significant variation between temperate natural forest dense with other forests and agroforestry systems ($P<0.05$). Other land-uses did not show significant difference in between them ($P>0.05$). Per cent carbon in humus of different forest and agroforestry systems ranged from 18.91 to 21.25% (Table 6.1). The total C mass in humus ranged from 0.63 to 1.41 t C ha^{-1} (Table 6.4). In the forested and agroforestry areas, humus biomass was linearly related ($r^2 = 0.98$, $P<0.0001$) with humus C storage (Fig 6.2c).

6.3.4 Soil Carbon Pool Analysis

6.3.4.1 Total carbon

Total carbon (TC) content in soil varied significantly between land-use and depth. Interactions between land-use and depths were highly significant ($P<0.0001$) (Fig 6.3). Tukey's pairwise mean difference probabilities within land-use/cover and depths as independent factors are presented in Table 6.5a & b. Soil TC content was significantly greater in the temperate natural forest dense and cardamom based agroforestry system (P<0.05) than the other land-use types, but did not differ significantly between temperate natural forest open, subtropical natural forest open and mandarin based agroforestry system (P>0.05), while in these three systems TC was significantly greater than the cropped and wasteland areas of temperate and subtropical belts. Mean difference test of wasteland area temperate and subtropical showed significantly higher TC content than open cropped areas (P<0.05). Similar type of land-uses did not show significant difference in total carbon content (P>0.05).

Surface layer had significantly higher TC content over the increasing depths (P<0.05). The soil C content did not change significantly between deeper depths (30-100 cm) (P>0.05) in all the land-uses. The TC concentration for the soils ranged from 1.75 to 6.16% in the surface layer (0-15 cm), slightly decreased to 0.22 to 4.01% in 15-60 cm, and then drastically decreased to 0.08 to 2.05% at 1 m depth (Fig 6.3).

Soil TC content upto 1 m depth in different land-use/covers ranged from 37 t ha^{-1} in open cropped area temperate to 472 t ha^{-1} in temperate natural forest dense (Table 6.6). As observed TC storage decreased with increasing depth. In between different land-uses, the storage of TC in the surface layer ranged from 13 t ha^{-1} to 121 t ha^{-1}. The vertical distribution of TC was deeper in temperate natural forest dense and shallowest in open cropped area of both the belts (Table 6.6).

6.3.4.2 Organic carbon

Total organic carbon (TOC) distribution was higher (0.96 to 4.22%) in surface layer (0-15 cm), slightly decreased (0.30 to 2.55%) in 15-60 cm and then drastically decreased (0.067 to 1.16%) at 90-100 cm depth in all the land-use/covers (Fig 6.4). The highest TOC concentration was recorded in temperate natural forest dense and lowest in open cropped area temperate in all the depths. An ANOVA test on TOC showed a significant variation between the land-use and depths ($P<0.0001$). Interaction between land-use and depths were also significant ($P<0.0001$). Tukey's pairwise mean difference probabilities within land-use/cover and depths as independent factor are given in Table 6.7. TOC content was significantly higher in temperate natural forest dense and cardamom based agroforestry system ($P<0.05$) than the other land-use/covers. Mean variations between these were not significant ($P>0.05$). TOC content did not differ significantly for the temperate natural forest open, subtropical natural forest open and mandarin based agroforestry system ($P>0.05$) but these had significantly greater TOC content than open cropped and wasteland areas of subtropical and temperate belts ($P<0.05$). TOC content was significantly higher in the wasteland areas of both the belts ($P<0.05$) than the open cropped areas but mean variations in between croplands and wastelands of both the belts were not significant.

Surface layer (0-15 cm) had significantly higher TOC concentration over the increasing depths ($P<0.05$). Mean difference between deeper depths (45-100 cm) was not significant difference in TOC concentration ($P>0.05$).

Soil organic carbon storage upto 1 m depth ranged from 19 t ha^{-1} in open cropped area temperate to 292 t ha^{-1} in temperate natural forest dense. Surface layer stored more TOC (7-83 t ha^{-1}) in comparison to deeper depth (0.3-14 t ha^{-1}) (Table 6.6).

6.3.4.2.1 Seasonality in organic carbon

The organic carbon level in soil was estimated at two depths (0-15 cm and 15-30 cm) on seasonal basis (Table 6.8). Organic carbon concentrations of both the soil depths varied significantly ($P<0.0001$)

between land-use, seasons and depths. Interactions between land-use and depth and land-use and season were significant ($P<0.01$) but interactions between depth and season and depth × land-use × season were not significant (Table 6.8). Pairwise mean difference showed significant variation between temperate natural forest dense, temperate natural forest open, cardamom based agroforestry system, open cropped area temperate and wasteland area temperate ($P<0.05$), while subtropical natural forest, mandarin based agroforestry system, open cropped area subtropical and wasteland area subtropical showed no significant differences in between them ($P>0.05$). Pairwise mean difference within season was significant between winter and rainy and rainy and spring ($P<0.05$). Between the depths also the mean difference was significant ($P<0.05$). Pooled data showed a highest concentration value in winter season and lowest in spring season in all the land-use/cover types. At higher soil depth percentage of organic carbon was smaller than the surface layer.

Figure 6.5a revealed a strong positive correlation between C stock in vegetation and soil organic carbon ($r^2 = 0.85$, $P<0.0001$), however relation between C stock in floor litter and soil organic carbon was significantly positive but feeble ($r^2 = 0.55$, $P<0.005$) (Fig 6.5b).

In all land-use/covers, C N ratio ranged from 1.05-34.32 at different soil depths and season. C N ratio in all the land-use/covers was higher at 15-30 cm depth compared to 0-15 cm depth in all the seasons. The ratio was comparatively higher in the spring and lower in rainy season. Mean C N ratio was lowest in subtropical natural forest and highest in wasteland area temperate.

6.3.4.3 Microbial biomass carbon

Across the land-use/covers, mean annual microbial biomass C ranged from 219 to 864 $\mu g\ g^{-1}$, increasing to a peak in temperate natural forest dense and declining to a minimum in the wasteland area subtropical (Table 6.9). Analysis of variance showed significant variation in land-use and season ($P<0.0001$). Interaction between the land-use and seasons were not significant. Tukey's pairwise mean difference showed significant variation between temperate natural forest dense and other land-uses ($P<0.05$). Pairwise mean variations between open cropped areas and wasteland areas of subtropical and temperate belts were not significantly different ($P>0.05$). Mean difference within seasons was significant between winter and spring, rainy and spring and rainy and winter ($P<0.05$).

The land transformation from forest to other usage led to several changes in soil organic carbon and microbial biomass carbon (Table 6.10). The highest percentage decline of organic carbon (92%) and microbial C (88%) were estimated in open cropped area subtropical compared to temperate natural forest dense. Microbial biomass carbon contributed 1.69 to 4.33% to the total soil organic carbon (Table 6.10). Relationship between organic carbon to microbial biomass carbon was significantly positive but feeble ($r^2= 0.42$, $P<0.0005$) (Fig.6.6). Microbial C of different land-use/covers was highly seasonal (Fig 6.7). The seasonal pattern of microbial C was similar in all land-uses, the value being minimum (growing period) in rainy season and gradually increased as dryness increased during winter and spring. Microbial C in different land-use/covers ranged from 0.14 to 2.04 tC ha^{-1} (Table 6.11).

6.3.5 Compartmental Allocation of Carbon

Compartmental allocation showing the distribution of carbon mass in different land-use/covers are presented in Figure 6.8a, b ,c, d, e & f. Values in the compartments are carbon net pool. Most carbon enters ecosystems via leaves, and carbon accumulation is most obvious when it occurs in aboveground biomass, more than half of the assimilated carbon is eventually transported belowground via root growth and turnover, exudation of organic substances from root, and incorporation of fallen dead leaves and wood (litter) into soil. A comparative account of the nine land-use types showed high carbon stock in soils. 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. Component allocation of carbon in the tree layer of temperate natural forest dense was more than that of the subtropical natural forest in the case of bole+branch, floor litter and root etc. In the case of cardamom based agroforestry, all the components except bole+branch, such as leaf and root showed higher carbon content in comparison to temperate natural forest open and subtropical natural forest. About 86% of the mean total C was allocated to bole+branch components of all the forests and agroforestry systems, highest being recorded in subtropical natural forest and lowest in mandarin based agroforestry system.

6.3.6 Watershed Carbon Budget

Area-weighted standing crop values for vegetation, litter, humus and soil are calculated on each land-use/cover type in the entire watershed and presented in Table 6.12. Total vegetation C in forested land-use ranged between 30.6 and 84.6×10^3 t C. In the agroforestry this value ranged from 0.01 to 4.91×10^3 t C. The overall range of soil C was 45.6 to 215×10^3 t C in forested land area, between 2.61 to 29×10^3 t C in agroforestry systems, between 8.5 to 40×10^3 t C in wastelands and between 15 to 24×10^3 t C in open cropped areas of subtropical and temperate belts. Total stand carbon in the studied watershed area (3014 ha) was 624×10^3 t C, total C stored in the soil to a depth of 1 m was 456×10^3 t. Total vegetation C was 161×10^3 t, litter C 5.33×10^3 t and humus C 1.44×10^3 t in the whole watershed.

6.4 DISCUSSION

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. Forests contain 20 to 100 times more biomass C per unit area than agriculture land so that conversion of forest to crop land generally reduces the amount of carbon on land (Houghton 1990). Brown & Lugo (1990) reported that in wet and moist life zones, sites cultivated after deforestation typically loss 60-70% of the initial carbon contained in mature forests. Similar results were found in the present study where dense forest had significantly higher total C in comparison to other land-uses. Total vegetation carbon in forested and agroforestry systems depended considerably on component biomass. The standing state of nutrients in different components increased with increase in their biomass and the role of nutrient concentration was minimized (Sharma 1993; Rawat & Singh 1988). Total vegetation C in the forested and non-forested land-uses ranged between 5 to 191 t C ha^{-1}, fall within the range reported by Raghubanshi *et al.* (1991), Brown & Lugo (1982), Vogt *et al.* (1995) and Homan (1996). Houghton (1999) reported slightly high estimates of carbon in vegetation for tropical Asia moist forest. Total vegetation C was significantly higher in open cropped areas of subtropical and temperate belts in comparison to mandarin based agroforestry system due to high weedy biomass in former land-use. The number of estimates of C pools in above and belowground biomass of forested and non-forested land-uses lies within the range reported for mature eucalypt forest (Keith 1997). Carbon mass under belowground vegetation was very high in cardamom based agroforestry system. The higher carbon mass in belowground vegetation of cardamom based agroforestry system in the present study is mainly attributed to the management of this cash crop. Basilevich & Rodin (1968) suggested that belowground mass constituted 15-30% of total biomass in the world forest. Allocation of C in belowground stand was within the range review across global biomes by Raich & Nadelhoffer (1989).

The ratio of standing crop of carbon in short lived vegetation to long lived vegetation increased from forest to agroforestry system. Similar report was also made by Raghubanshi *et al.* (1991) for dry tropics of Savanna. Increase in the short-term : long-term C ratio implies a change in the sense that long-term storage of C declines relative to annual flux of C. Open cropped areas of subtropical and temperate belts had only short–term vegetation C, while agroforestry system had combination of short-term and long-term vegetation C with woody species in combination to crops.

Besides the living phytomass, the most important carbon reservoir of the biosphere is the litter which is also responsible for the large organic carbon pool in the soil. The carbon concentration of litter mass in all the land-uses were low compared to live biomass, since for some period before shedding, assimilate is withheld from abandoned biomass and thus the abandoned parts respire only their reserves. So, a substantial withdrawal of carbon takes place before shedding. Similar finding was reported by (Marshal 1986).

Since soil C is the largest C pool in all the land-use/covers, it is important to understand the effects of land-use/cover changes on C inputs and losses to the soil. Soil contains more carbon than vegetation. Soil organic matter (carbon) content is often related to soil fertility. Soil total and organic carbon level were highest in the dense forest. There was a decrease of total carbon and organic carbon content with consistent land-use/cover change. In conversion of forest to cropland, the organic layer is depleted, and soil carbon content and cation exchange capacities can decrease (Detwiler 1986; Man 1986; Schlesinger 1986; Davidson & Ackerman 1993). If cleared land is not cultivated or degraded, however, soil carbon amounts are mostly observed not to change over decades (Lugo & Brown 1996), although in some studies, soil carbon losses of upto 30% have also been reported (Garcia-Oliva *et al.* 1999). In tropical America, conversion from forest to cropland typically reduces soil C by 20-50% (Detwiler 1986; Man 1986).

Total carbon and organic carbon in soils of different land-uses ranged from 37 to 472 t C ha^{-1} and 19 to 292 t C ha^{-1} respectively. The levels of soil C are within the range reported for a variety of soils elsewhere (Raghubanshi *et al.* 1991; Brown & Lugo 1982; Houghton 1999). Clear-felling of forest trees and subsequent cropping caused an initial decrease in soil microbial biomass. Soil microbial biomass represents the active pool of organic matter and constitutes 2-4% of the total soil organic carbon (Singh *et al.* 1989). The rapid turnover of the soil microbial biomass makes it an important source of carbon and other nutrients. The levels of microbial C in soils are within the range reported for a variety of soils elsewhere (Srivastava & Singh 1988; Robertson *et al.* 1988; Brookes *et al.* 1984). In the present study, organic C in the microbial biomass varied from 1.69 to 4.33% much similar to values reported by Srivastava (1994) for dry tropics of Savana. Seasonality plays an important role in microbial C. Microbial C was highest in dry winter season and lowest in rainy season. Singh *et al.* (1989) have reported that there is a reciprocal relationship between the plant growth rates (which are highest during the wet period) and microbial biomass (which is highest in the dry period) in soil. Increase in soil water potential in the rainy season may induce microbial plasmoptysis. Reduced microbial biomass and increased microbial turnover in the wet period may result from feeding by expanded microvore population (Singh *et al.* 1989; Raghubanshi *et al.* 1990).

The cropped areas of both the belts occupied about 30% of the total watershed area, and the stand total C was only 48×10^3 t C of which 39×10^3 t C was contributed by soil. Most of the carbon stocks in croplands are in the soil because of frequent biomass removal during harvest. The net changes in soil C content varied according to the land-use type. The conversion from forest to agroforestry to cropland and wasteland typically leads to loss of soil C sequestration potential. The percentage decline in the soil C, microbial C, vegetation C, litter C and humus C are presented in Table 6.13. In the studied watershed, soil C loss was greater (92%) in open cropped areas than forests and agroforestry systems, indicating that agriculture practices without vegetation in such sloping land areas are highly vulnerable. The high decline of C sequestration potential of cropped areas owes to intensive cultivation, high erosion rate and oxidation of soils. Typically, crop production results in larger reduction in soil C even than wasteland due to increased soil disturbances and organic matter loss. This observation is consistent with other studies that reported greater C losses from croplands (Matson *et al.* 1997; Duiker & Lal 1999). The temperate natural forest open and subtropical natural forest open lost 50% and 73% carbon sequestration potential than dense forest due to high anthropogenic pressure in these forests. Agroforestry systems possess 80% more carbon sequestration potential than open cropped area and 59% more than wastelands. Therefore, strong agroforestry based agriculture is recommended in such a sloping land to enhance the C sequestration potential of this system. Managing agricultural soils to store more carbon is likely to have ancillary benefits by reducing soil erosion; the use of cover crops, crop rotations, nutrient management, crop residue management and organic amendments is likely to increase soil fertility and enhance food security for affected population. Hence, practices such as improved crop productivity and conservation tillage may be warranted to mitigate their carbon sequestration benefits. Improved productivity and conservation tillage typically allow increase in soil carbon at a rate of about 0.3 t C ha^{-1} yr^{-1} (Lal 1997). If these practices are adopted on 30% of the available arable land of the watershed, they might result in a capture of about 275 t C yr^{-1} over the next few decades.■

Table 6.1 Carbon concentration in plant materials of different land-use/cover

Land-use/cover	Components	Carbon concentration (%)
Temperate natural forest (dense + open)	**Tree**	
	Bole & Branch	42.53
	Leaf & Twig	47.33
	Root	45.01
	Herbs	
	Aboveground biomass	43.02
	Belowground biomass	41.15
	Litter	35.27
	Humus	21.25
Subtropical natural forest open	**Tree**	
	Bole & Branch	47.79
	Leaf & Twig	50.24
	Root	46.63
	Herbs	
	Aboveground biomass	44.62
	Belowground biomass	42.73
	Litter	39.97
	Humus	18.92
Cardamom based agroforstry system	***Alnus* + Mixed tree**	
	Bole & Branch	45.50
	Leaf & Twig	46.75
	Catkin	45.50
	Root	44.65
	Cardamom	
	Leaf	47.07
	Pseudostem	47.07
	Capsule	44.75
	Rhizome	45.56
	Litter	44.43
	Humus	18.91

Mandarin based agroforestry system	**Tree**	
	Bole & branch	45.95
	Leaf & Twig	44.93
	Orange fruit	43.00
	Root	44.98
	Crops	
	Aboveground residue	41.25
	Belowground residue	40.95
	Agronomic yield	45.00
	Litter	39.40
Open cropped area temperate	**Crops**	
	Aboveground residue	40.97
	Belowground residue	40.85
	Agronomic yield	45.50
	Weed	42.56
Open cropped area subtropical	**Crops**	
	Aboveground residue	41.25
	Belowground residue	40.95
	Agronomic yield	45.00
	Weed	43.10

Table 6.2 Plant carbon allocation (t C ha^{-1}) in different land-use/covers

Land-use/cover	Components	Aboveground C	Belowground C	Total C
Temperate natural forest dense	Tree	182.128	8.77	190.90
	Herb	0.296	0.071	0.37
	Total	182.424^{c}	8.84^{b}	191.27^{c}
Temperate natural forest open	Tree	80.94	4.52	85.46
	Herb	0.43	0.103	0.53
	Total	81.37^{b}	4.63^{a}	86.13^{b}
Subtropical natural forest open	Tree	88.447	1.327	89.77
	Herb	0.366	0.088	0.45
	Total	88.813^{b}	1.415^{a}	90.23^{b}
Cardamom based agroforestry system	Tree	25.03	5.70	30.73
	Cardamom	4.53	11.529	16.06
	Total	29.56^{a}	17.23^{c}	46.79^{a}
Mandarin based agroforestry system	Tree	2.85	0.70	3.55
	Crops	1.6	0.322	1.92
	Total	4.44^{a}	1.022^{a}	5.47^{a}
Open cropped area temperate	Crops	3.6	0.64	4.24
	Weed	4.032	1.008	5.04
	Total	7.632^{a}	1.648^{a}	9.28^{a}
Open cropped area subtropical	Crops	2.52	0.49	3.01
	Weed	4.152	1.038	5.19
	Total	6.672^{a}	1.528^{a}	8.20^{a}

ANOVA: Aboveground vegetation carbon, Land-use $F_{6,\ 14}$ =41.52, P<0.0001; Belowground vegetation carbon, Land-use $F_{6,\ 14}$ = 52.67, P<0.0001; Total carbon $F_{6,\ 14}$ = 40.68, P<0.0001. Values within columns not sharing the same letter in superscript differ significantly (P<0.05; n=3) (Tukey's honestly significant difference test).

Table 6.3 Carbon storage (t C ha^{-1}) in vegetation of different land-use/cover

Land-use/cover	Short-term C	Long-term C	Short-term C : Long-term C
Temperate natural forest dense	1.35^{a}	189.92^{c}	0.007
Temperate natural forest open	1.35^{a}	84.78^{b}	0.016
Subtropical natural forest open	0.76^{a}	89.47^{b}	0.008
Cardamom based agroforestry system	4.10^{c}	42.69^{a}	0.096
Mandarin based agroforestry system	2.41^{b}	3.06^{a}	0.79
Open cropped area temperate	9.28^{d}	-	-
Open cropped area subtropical	8.20^{d}	-	-

ANOVA: Short-term carbon, Land-use $F_{6,\,14} = 174.82$, $P<0.0001$; Long-term carbon, Land-use $F_{6,\,10} = 30.92$, $P<0.0001$. Values within columns not sharing the same letter in superscript differ significantly ($P<0.05$; n=3) (Tukey's honestly significant difference test).

Table 6.4 Carbon mass (t C ha^{-1}) in floor litter and humus of different forests and agroforestry systems

Land-use	Floor litter	Humus
Temperate natural forest dense	4.57^{b}	1.41^{b}
Temperate natural forest open	2.94^{a}	0.87^{a}
Subtropical natural forest open	3.03^{a}	0.63^{a}
Cardamom based agroforestry system	5.20^{c}	1.12^{a}
Mandarin based agroforestry system	1.5^{a}	-

ANOVA: Floor litter carbon, Land-use $F_{4,\ 10} = 14.98$, $P<0.0001$; Humus carbon content, and-use $F_{3,\ 8} = 8.01$, $P<0.01$. Values not sharing the same letter in superscript within columns differ significantly ($P<0.05$, n=3) (Tukey's honestly significant difference test).

Table 6.5 Per cent total carbon distribution in relation to (a) land-use/cover pattern and (b) depths. Values with different letters in superscript differ significantly (P<0.05, n=3). (Tukey's honestly significant difference test)

(a)

Land-use/cover	Total Carbon
Temperate natural forest dense	3.5062^{d}
Temperate natural forest open	1.8129^{c}
Subtropical natural forest open	1.6767^{c}
Cardamom based agroforestry system	2.7371^{d}
Mandarin based agroforestry system	1.7029^{c}
Open cropped area temperate	0.5136^{a}
Open cropped area subtropical	0.8100^{a}
Wasteland area temperate	1.5029^{b}
Wasteland area subtropical	1.5000^{b}

(b)

Depth (cm)	Total Carbon
0-15	3.0689^{d}
15-30	2.2004^{c}
30-45	1.8933^{b}
45-60	1.5852^{a}
60-75	1.3000^{a}
75-90	1.1889^{a}
90-100	1.0208^{a}

Table 6.6 Depth-wise total carbon and organic carbon (t C ha^{-1}) storage in soils of different land-use/covers

Land-use/covers	Depths (cm)													
	0-15		15-30		30-45		45-60		60-75		75-90		90-100	
	TC	OC	TC	OC	TC	OC	TC	OC	TC	OC	TC	OC	TC	OC
Temperate natural forest dense	121.04	82.90	82.41	52.40	76.81	49.10	59.32	36.00	58.43	32.40	48.51	24.90	25.01	14.20
Temperate natural forest open	69.32	40.40	43.61	24.40	32.19	14.60	26.64	14.40	19.97	11.30	16.03	11.10	11.7	7.30
Subtropical natural forest open	31.20	20.01	21.21	16.00	20.48	15.40	15.56	13.50	14.11	11.80	13.95	8.70	9.3	6.00
Cardamom based agroforestry systems	52.07	34.03	46.68	31.10	36.38	27.30	35.50	25.60	33.89	22.70	31.58	21.10	19.3	10.50
Mandarin based agroforestry system	23.94	13.70	23.59	13.50	22.11	12.50	22.96	13.00	21.36	12.50	21.39	12.30	14.65	8.20
Open cropped area temperate	18.29	8.81	8.07	4.30	5.94	3.20	2.31	1.20	1.24	0.90	0.67	0.50	0.36	0.30
Open cropped area subtropical	13.13	6.62	11.48	6.10	12.15	6.10	5.83	3.00	2.74	1.80	1.70	1.40	0.86	0.72
Wasteland area Temperate	22.13	14.23	14.43	7.60	13.95	7.70	13.42	7.30	10.89	6.60	8.64	6.10	6.00	4.60
Wasteland area subtropical	28.62	12.90	19.43	10.40	18.00	10.40	17.18	10.60	15.93	10.40	15.02	9.60	9.97	7.00

TC = Total Carbon; OC = Organic Carbon

Table 6.7 Per cent organic carbon distribution in relation to (a) land-use/cover pattern and (b) depths. Values with different letters in superscript differ significantly ($P<0.05$, n=3) (Tukey's honestly significant difference test)

(a)

Land-use/cover	Organic Carbon
Temperate natural forest dense	2.1667^{d}
Temperate natural forest open	1.0200^{c}
Subtropical natural forest open	1.2914^{c}
Cardamom based agroforestry system	1.8700^{d}
Mandarin based agroforestry system	0.9738^{c}
Open cropped area temperate	0.2903^{a}
Open cropped area subtropical	0.4424^{a}
Wasteland area temperate	0.8590^{b}
Wasteland area subtropical	0.8571^{b}

(b)

Depth (cm)	Organic Carbon
0-15	1.9144^{d}
15-30	1.3378^{c}
30-45	1.1637^{b}
45-60	1.000^{a}
60-75	0.8315^{a}
75-90	0.7289^{a}
90-100	0.6232^{a}

Table 6.8 Seasonal variation in soil organic carbon of different land-use/cover

Land-use/cover	Soil depth (cm)	Organic carbon (%)		
		Winter	Spring	Rainy
Temperate natural forest Dense	0-15	4.22±0.11	2.48±0.016	2.90±0.29
	15-30	2.55±0.03	2.31±0.17	2.17±0.25
Temperate natural forest open	0-15	2.31±0.15	2.64±0.01	2.86±0.34
	15-30	1.43±0.04	2.08±0.35	2.42±0.17
Subtropical natural forest open	0-15	1.03±0.03	1.51±0.06	1.86±0.18
	15-30	0.30±0.01	1.20±0.09	1.64±0.23
Cardamom based agroforestry system	0-15	2.55±0.05	2.19±0.26	1.90±0.17
	15-30	1.59±0.05	1.49±0.14	1.50±0.32
Mandarin based agroforestry system	0-15	1.08±0.01	1.94±0.29	1.27±0.08
	15-30	1.07±0.01	1.88±0.22	1.17±0.12
Open cropped area temperate	0-15	2.35±0.02	2.27±0.08	1.95±0.04
	15-30	2.28±0.16	1.63±0.29	1.44±0.27
Open cropped area subtropical	0-15	0.96±0.02	1.65±0.07	1.33±0.06
	15-30	0.79±0.01	1.24±0.01	1.15±0.13
Wasteland area temperate	0-15	0.93±0.02	2.26±0.01	1.96±0.06
	15-30	0.78±0.01	1.92±0.01	1.85±0.06
Wasteland area subtropical	0-15	1.20±0.02	1.21±0.01	1.07±0.21
	15-30	0.87±0.04	0.94±0.12	0.52±0.09

ANOVA: Land-use $F_{8,\ 161}$=57.60, P<0.0001; Depth $F_{1,\ 161}$=70.04, P<0.0001; Season $F_{2,\ 161}$=73.24, P<0.0001; Land-use x Depth $F_{8,\ 161}$=2.79, P<0.01; Land-use x Season $F_{16,\ 161}$=2.41, P<0.01: Depth x Season $F_{2,\ 161}$=0.42, NS; Land-use x Depth x Season $F_{16,\ 161}$=1.49, NS

Table 6.9 Microbial biomass carbon in (a) land-use/cover types and (b) seasons. Values with different letters in superscript differ significantly (*P*<0.05, n=3) (Tukey's honestly significant difference test)

(a)

Land-use/covers	Microbial Biomass Carbon
Temperate natural forest dense	863.6956^{e}
Temperate natural forest open	711.5561^{d}
Subtropical natural forest open	763.5972^{e}
Cardamom based agroforestry system	583.3678^{c}
Mandarin based agroforestry system	470.9939^{b}
Open cropped area temperate	389.6028^{a}
Open cropped area subtropical	291.3694^{a}
Wasteland area temperate	245.5556^{a}
Wasteland area subtropical	218.9622^{a}

(b)

Season	Microbial Biomass Carbon
Winter	650.3385^{c}
Spring	498.6998^{b}
Rainy	363.8619^{a}

Table 6.10 Carbon (kg ha^{-1}) in soils and microbial biomass of different land-use/covers

Land-use/covers	Organic C	Microbial C	% Organic C in microbial biomass	% change in organic C	% change in microbial C
Temperate natural forest dense	82900	1698	2.05	-	-
Temperate natural forest open	40400	1248	3.09	-51.27	-26.50
Subtropical natural forest open	20010	733	3.66	-75.86	-56.83
Cardamom based agroforestry system	34030	778	2.29	-58.95	-54.18
Mandarin based agroforestry system	13700	593	4.33	-83.47	-65.08
Open cropped area temperate	8810	333	3.78	-89.37	-80.39
Open cropped area subtropical	6620	201	3.04	-92.00	-88.16
Wasteland area temperate	14230	241	1.69	-82.83	-85.80
Wasteland area subtropical	12900	236	1.83	-84.44	-86.10

Table 6.11 Seasonal fluctuation in microbial biomass carbon (t C ha^{-1}) in different land-use/covers

Land-use/cover	Season		
	Winter	Spring	Rainy
Temperate natural forest dense	2.04	1.73	1.32
Temperate natural forest open	1.56	1.27	0.92
Subtropical natural forest open	0.85	0.73	0.62
Cardamom based agroforestry system	1.06	0.77	0.51
Mandarin based agroforestry system	0.80	0.59	0.40
Open cropped area temperate	0.45	0.32	0.23
Open cropped area subtropical	0.25	0.20	0.15
Wasteland area temperate	0.35	0.22	0.15
Wasteland area subtropical	0.38	0.18	0.14

Table 6.12 Area-weighted total stand carbon in the Mamlay watershed. Values are in (x 10^3 t C).

Land-use/cover	Vegetation	Litter	Humus	Soil	Total Stand
Temperate natural forest dense	30.6	0.73	0.22	75.52	107.07
Temperate natural forest open	84.6	2.89	0.86	215.11	303.46
Subtropical natural forest open	32.7	1.1	0.23	45.6	79.63
Cardamom based agroforestry system	4.91	0.60	0.13	29.3	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 6.13 Per cent decline of carbon in other land-use/covers compared to temperate natural forest dense

Land-use/cover	Vegetation	Litter	Humus	Soil	Stand Total
Temperate natural forest open	54.97	35.81	37.86	53.60	53.84
Subtropical natural forest open	52.83	33.84	55.71	73.31	67.15
Cardamom based agroforestry system	77.63	+ 12.11	20.00	45.97	54.56
Mandarin based agroforestry system	97.14	67.25	-	68.22	76.55
Open cropped area temperate	95.15	-	-	92.16	93.08
Open cropped area subtropical	95.71	-	-	89.83	91.60
Wasteland area temperate	-	-	-	81.14	87.88
Wasteland area subtropical	-	-	-	73.73	81.47

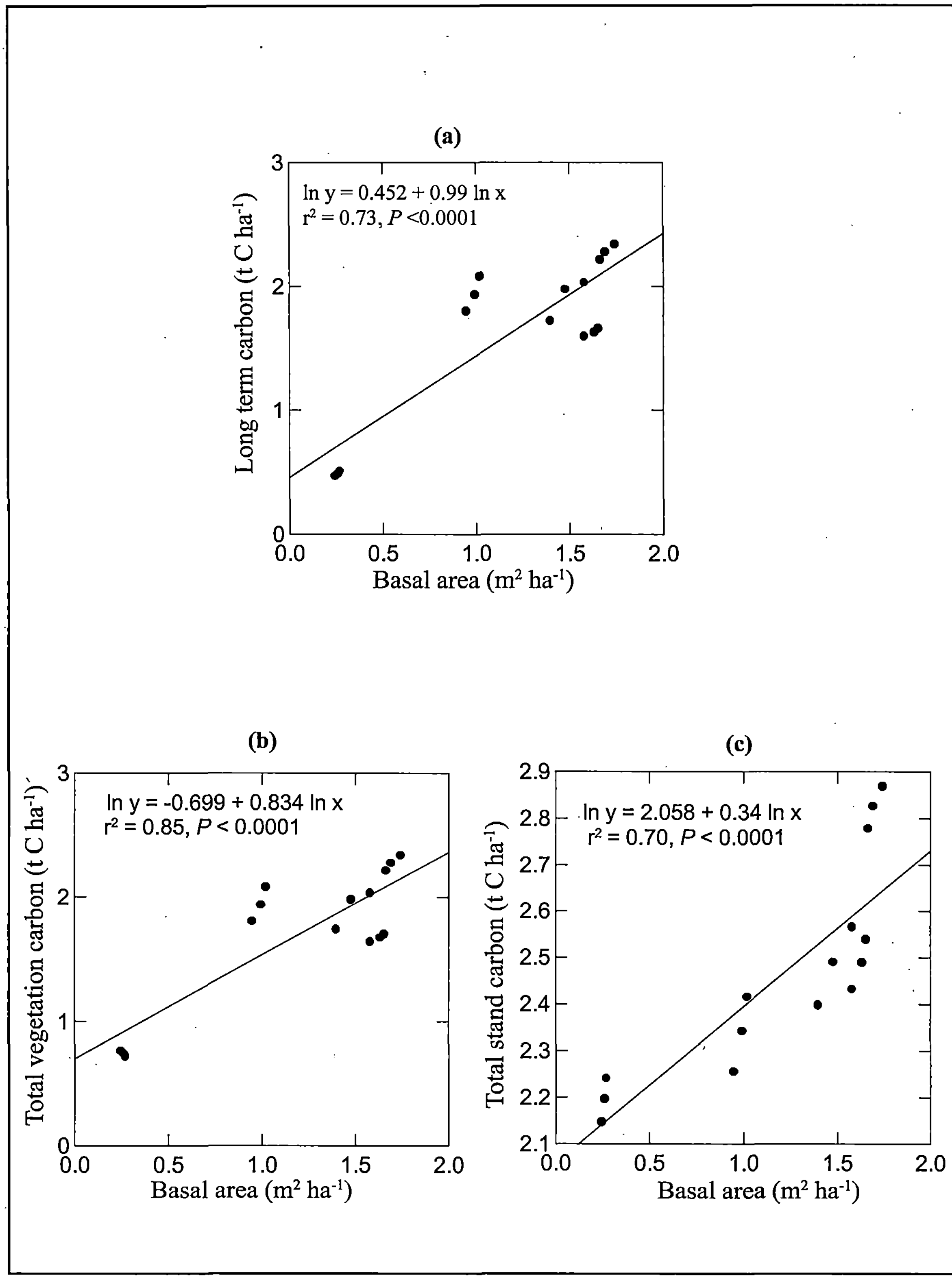

Fig. 6.1 Relationship between tree basal area (m^2 ha^{-1}) and **(a)** long term carbon, **(b)** total vegetation carbon and **(c)** total stand carbon.

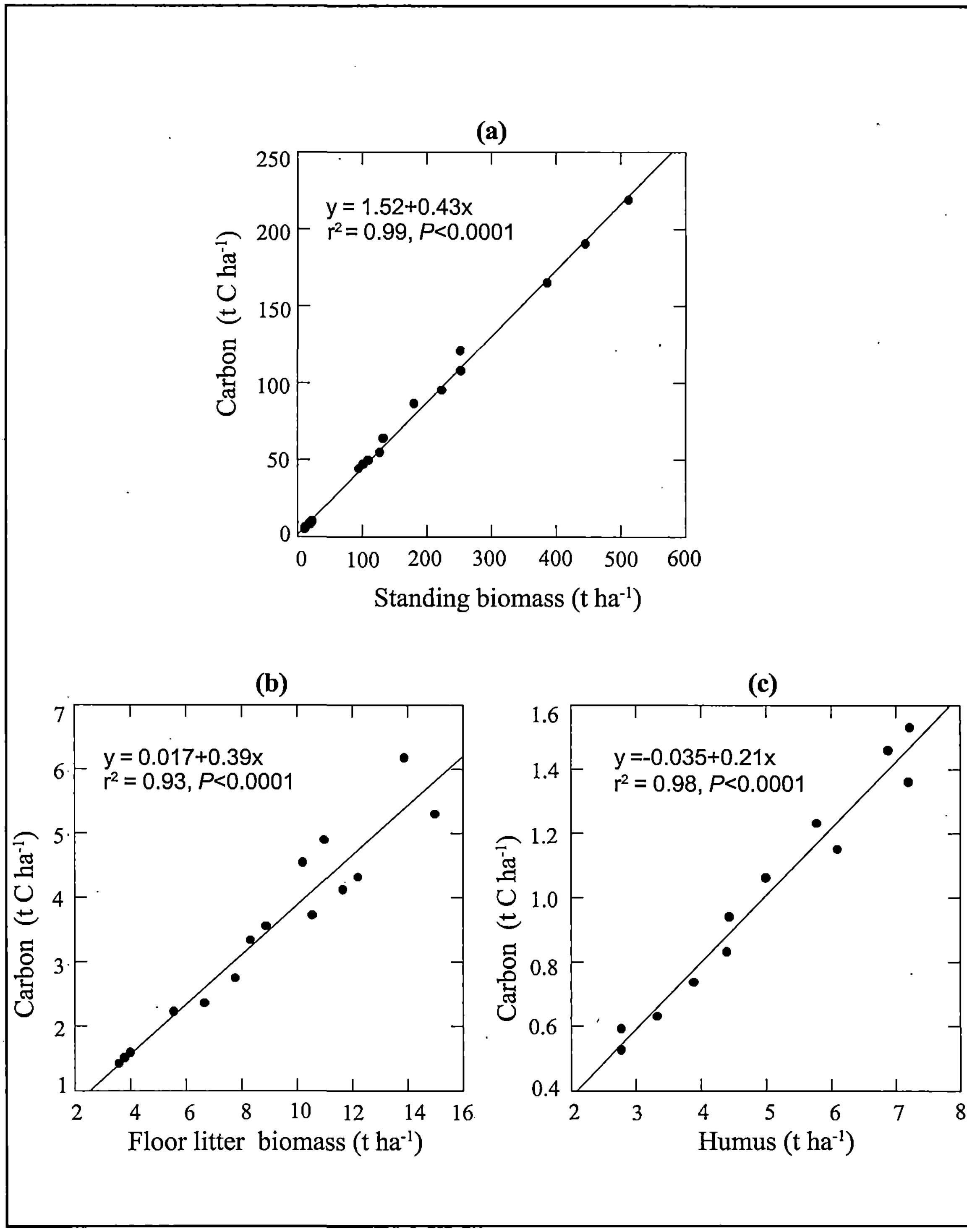

Fig. 6.2 Relationship between **(a)** standing biomass and carbon content in biomass, **(b)** floor litter biomass and carbon content in floor litter biomass and **(c)** humus and carbon content in humus in different forests and agroforestry systems.

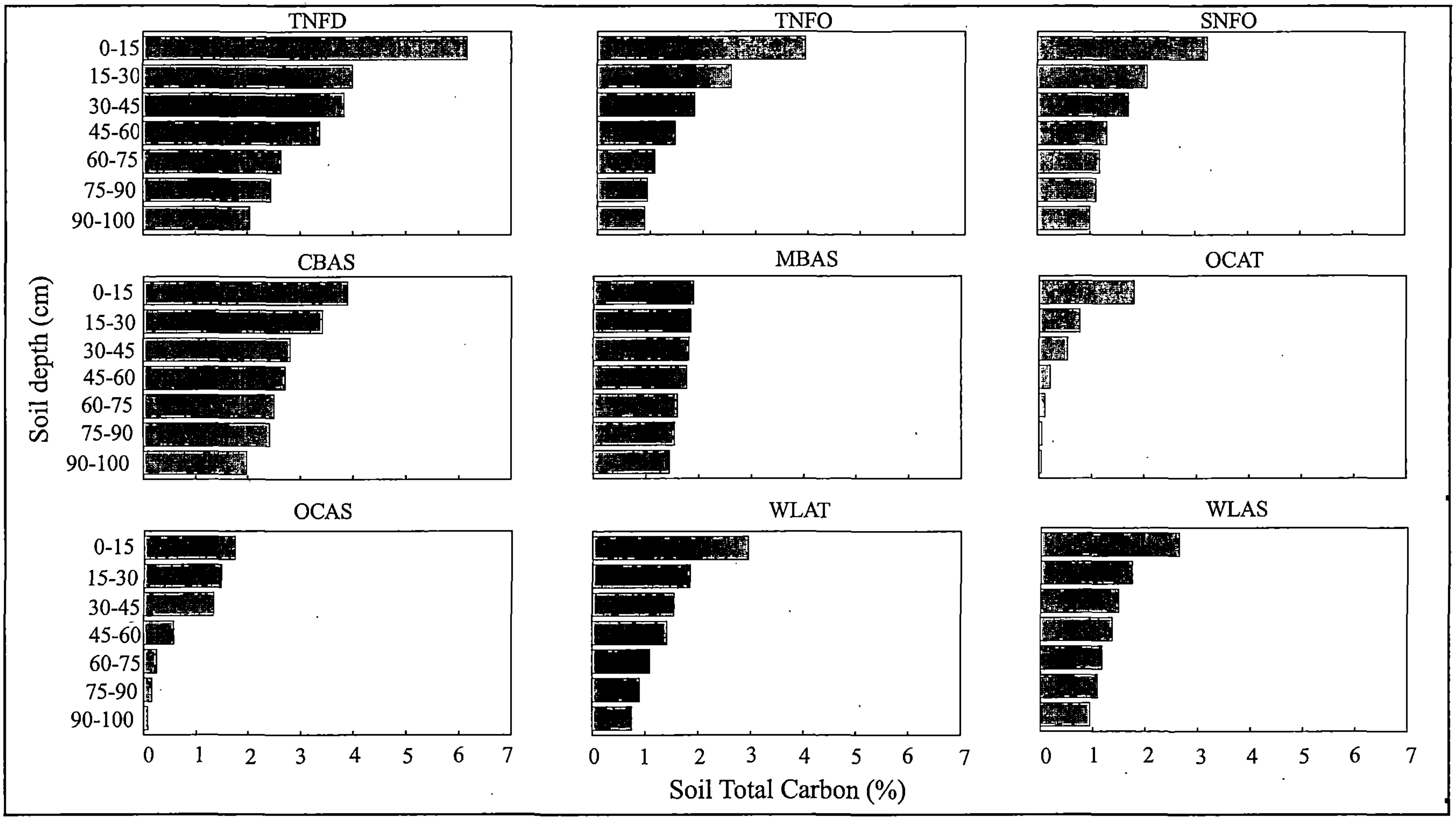

Fig. 6.3 Profile of soil total carbon distribution by land-use/covers; TNFD (Temperate Natural Forest Dense), TNFO (Temperate Natural Forest Open), SNFO (Subtropical Natural Forest Open), CBAS (Cardamom Based Agroforestry System), MBAS (Mandarin Based Agroforestry System) OCAT (Open Cropped Area Temperate), OCAS (Open Cropped Area Subtropical), WLAT (Wasteland Area Temperate) and WLAS (Wasteland Area Subtropical). ANOVA: Land-use $F_{8, 128} = 9936.82$, $P<0.0001$; Depth $F_{6, 126} = 5801$, $P<0.0001$; Land-use×Depth $F_{48, 126} = 451$, $P<0.0001$.

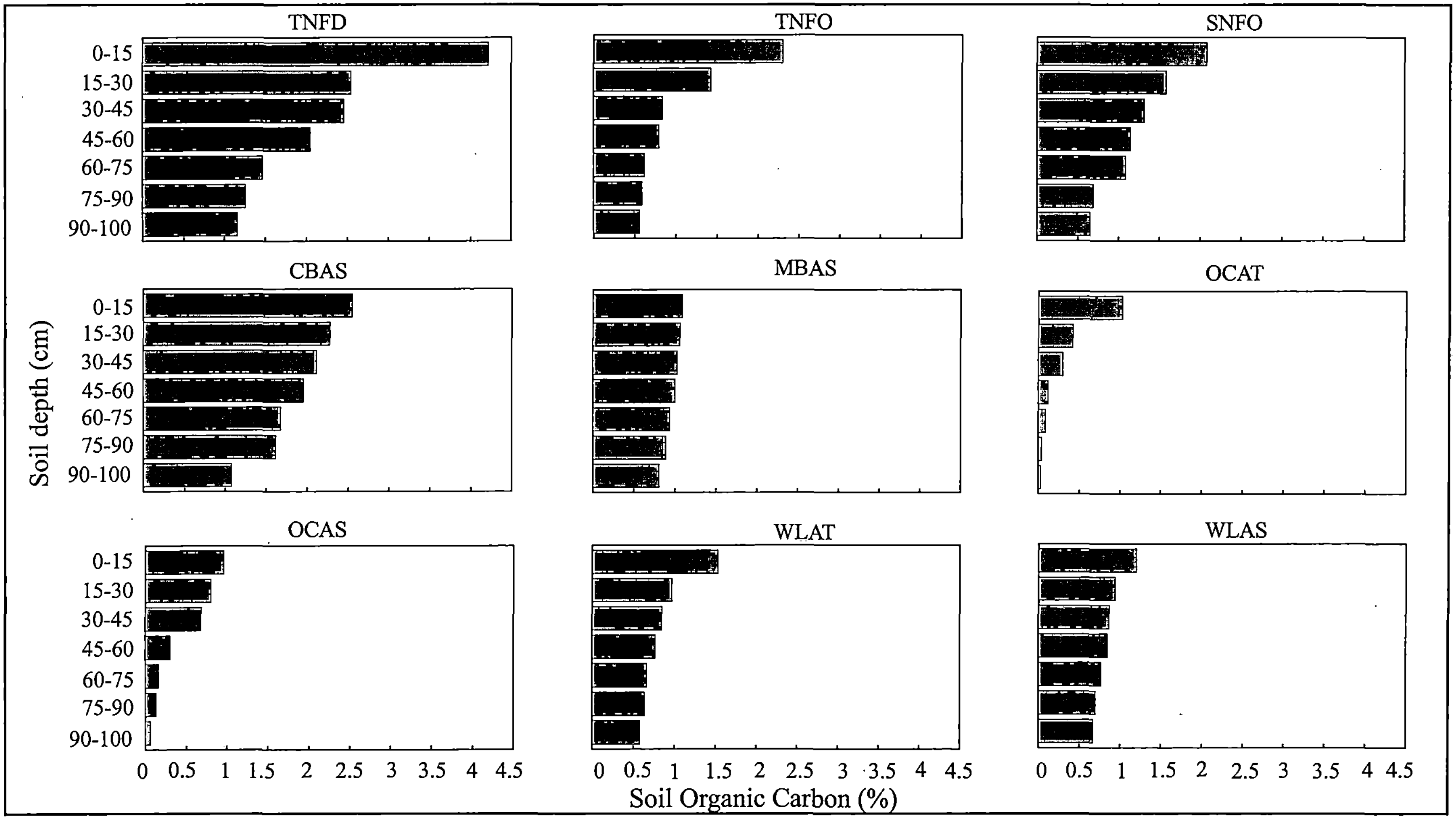

Fig 6.4 Profile of soil organic carbon distribution by land-use/covers; TNFD (Temperate Natural Forest Dense), TNFO (Temperate Natural Forest Open), SNFO (Subtropical Natural Forest open), CBAS (Cardamom Based Agroforestry System), MBAS (Mandarin Based Agroforestry System), OCAT (Open Cropped Area Temperate), OCAS (Open Cropped Area Subtropical), WLAT (Wasteland Area Temperate) and WLAS (Wasteland Area Subtropical).ANOVA: Land-use $F_{8, 126}=21801$, $P<0.0001$; Depth $F_{6, 126}=756$, $P<0.0001$; Land-use x Depth $F_{48, 126} = 756$, $P<0.0001$

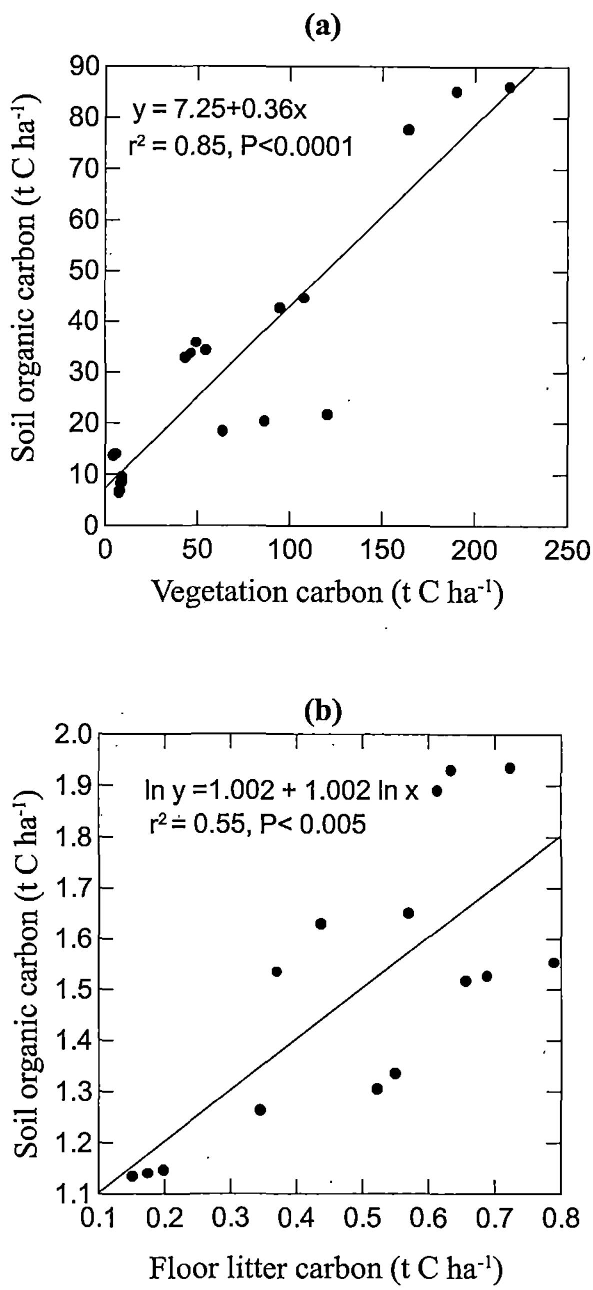

Fig. 6.5 Relationship between **(a)** vegetation carbon and soil organic carbon and **(b)** floor litter carbon to soil organic carbon.

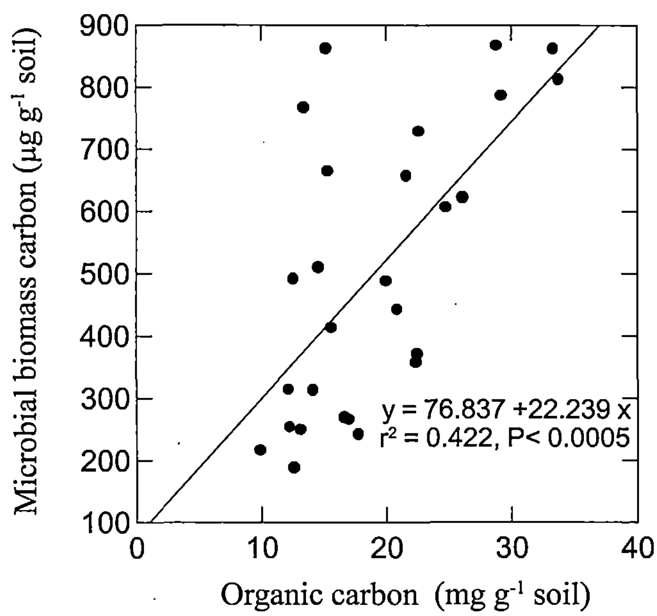

Fig. 6.6. Relationship between microbial biomass carbon and organic carbon.

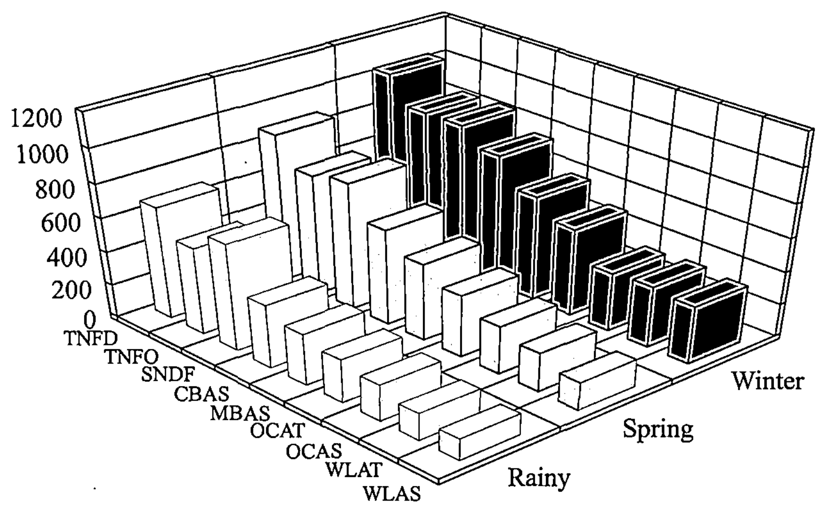

Fig 6.7 Seasonal variation in microbial biomass carbon in different land-use systems. TNFD = Temperate natural forest dense; TNFO = Temperate natural forest open; SNDF = Subtropical natural degraded forest; CBAS = Cardamom based agroforestry system; MBAS = Mandarin based agroforestry system; OCAT = Open cropped area temperate; OCAS = Open cropped area subtropical; WLAT = Wasteland area temperate; WLAS = Wasteland area subtropical. Microbial biomass carbon values are in mg g^{-1} soil (pooled for soil samples collected at three sites in two years, n=6).
ANOVA: Land-use $F_{8,135}$ =81.41, P <0.0001; season $F_{2,135}$ = 88.49, P <0.0001; land-use x season = Not Significant.

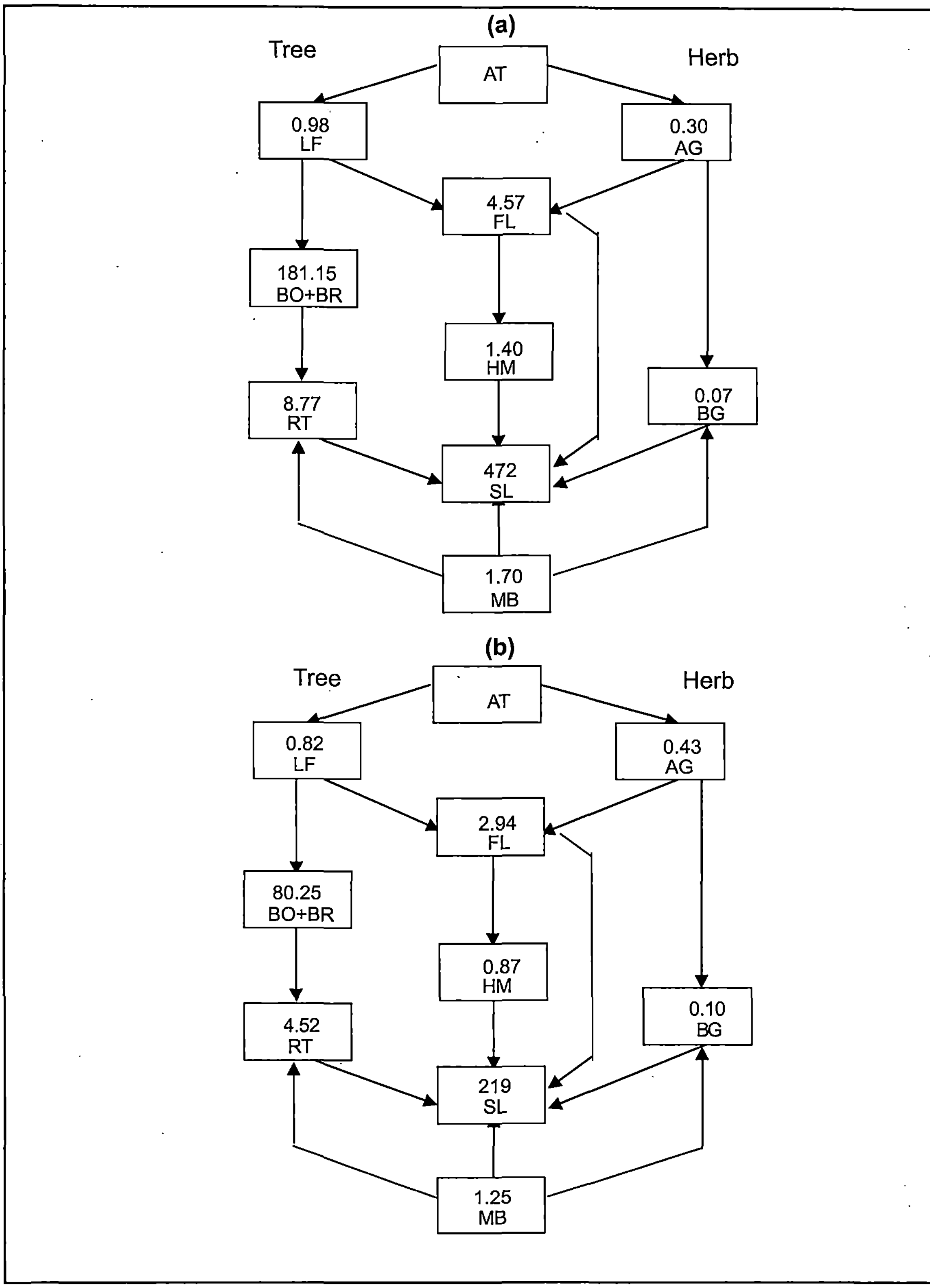

Fig. 6.8 Compartmental allocation of carbon in **(a)** temperate natural forest dense and **(b)** temperate natural forest open. Unit is t C ha^{-1} for compartments. AT = Atmosphere, LF = Leaf, BO = Bole, BR = Branch, RT = Root, AG = Aboveground herbaceous biomass, BG = Belowground herbaceous biomass, FL = Floor litter, HM = Humus, SL = Soil and MB = Microbial biomass.

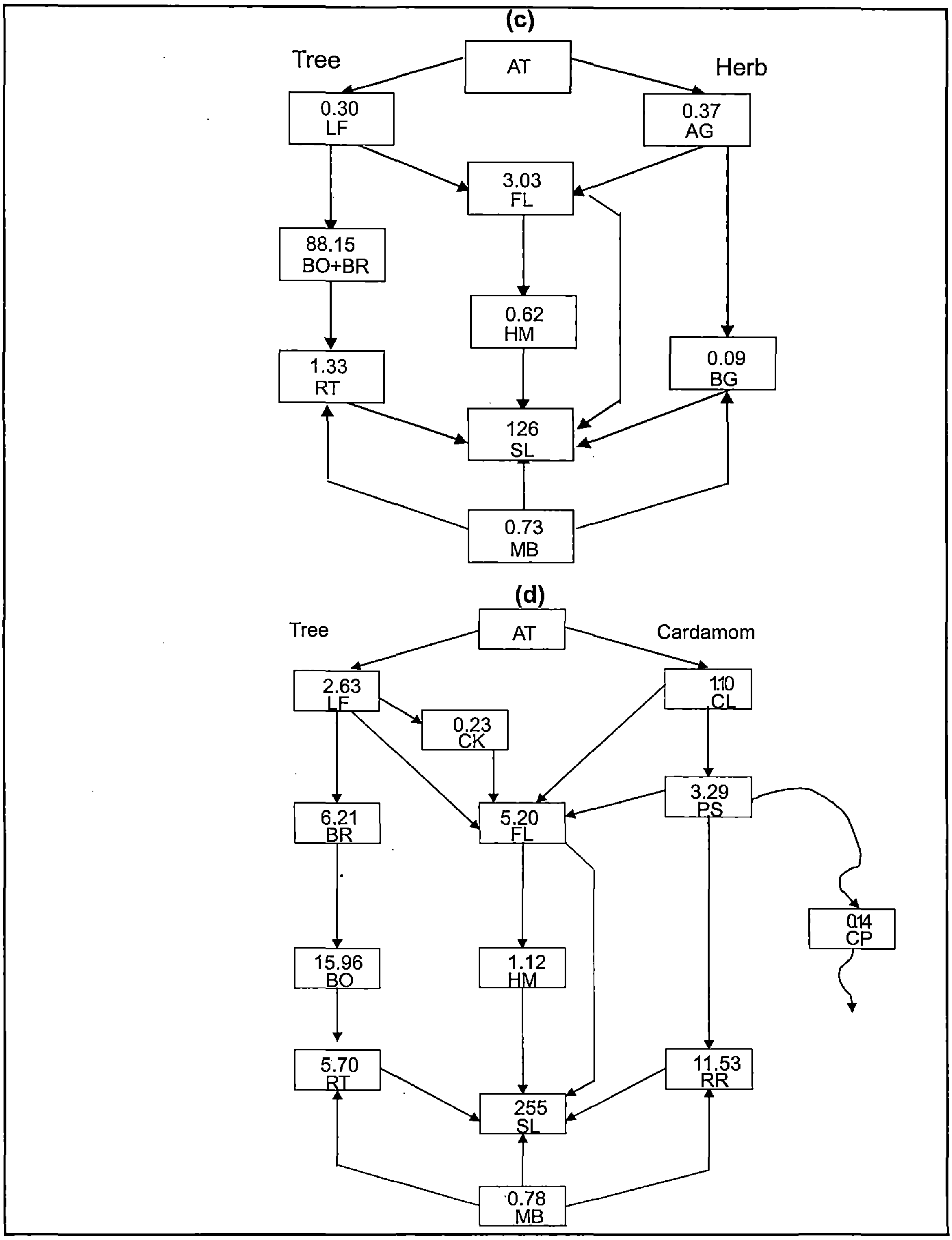

Fig. 6.8 Compartmental allocation of carbon in **(c)** subtropical natural forest open, **(d)** cardamom based agroforestry system. Unit is t C ha^{-1} for compartments. AT = Atmosphere, LF = Leaf, BO = Bole, BR = Branch, CK= Catkin, CL= Cardamom leaf, PS= Pseudostem, RR= Root/Rizome, CP= Cardamom Capsule, RT = Root, AG = Aboveground herbaceous biomass, BG = Belowground herbaceous biomass, FL = Floor litter, HM = Humus, SL = Soil and MB = Microbial biomass.

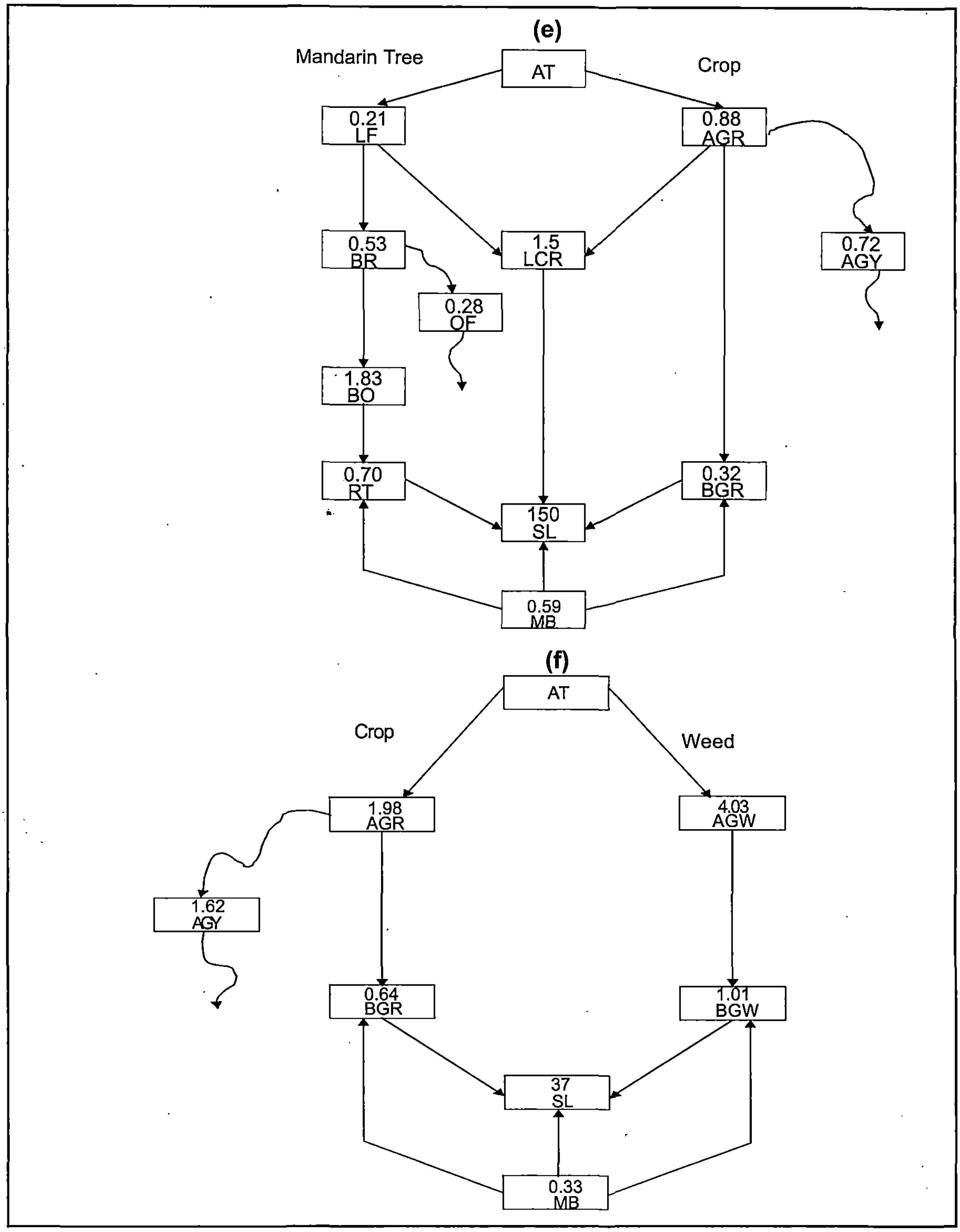

Fig 6.8 Compartmental allocation of carbon in **(e)** mandarin based agroforestry system and **(f)** open cropped area temperate. Unit is in t C ha-1. AT= Atmosphere, LF=Leaf, BR=Branch, BO= Bole, RT= Root, OF= Orange Fruit, AGR= Aboveground Residue, BGR= Belowground Residue, LCR= Litter and Crop Residue, AGY= Agronomic Yield, SL= Soil (upto 1m depth), MB= Microbial Biomass, AGW= Aboveground Weed, BGW= Belowground Weed.

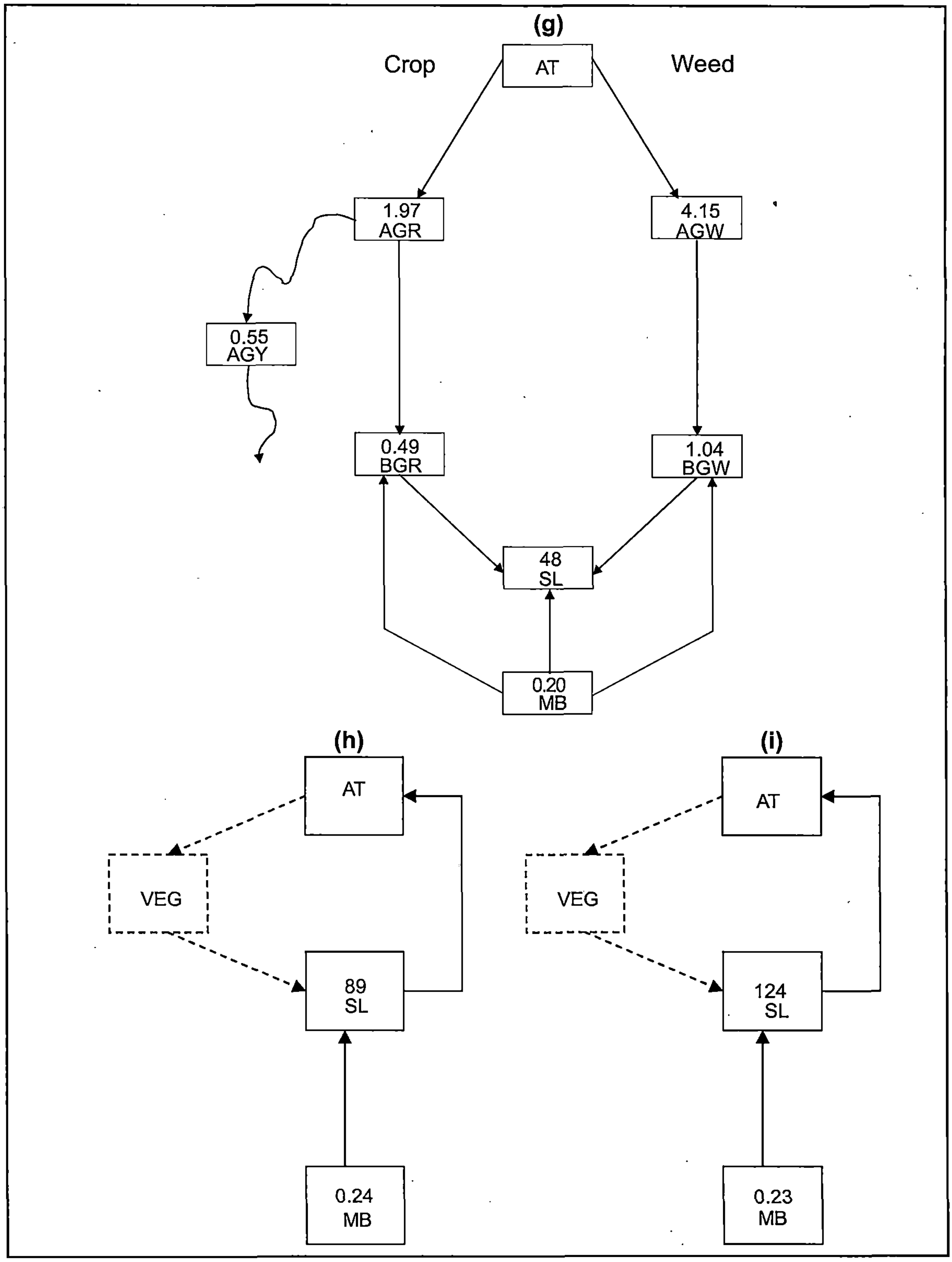

Fig 6.8 Compartmental allocation of carbon in **(g)** open cropped area subtropical, **(h)** wasteland area temperate and **(i)** wasteland area subtropical. Unit is in t C ha-1 for compartments. At=Atmosphere, AGR= Aboveground Residue, BGR=Belowground Residue, AGY= Agronomic Yield, AGW=Aboveground Weed, BGW=Belowground Weed, SL=Soil, MB=Microbial Biomass.

Chapter -VII

CARBON FLUX

7.1 INTRODUCTION

Carbon dioxide is the most abundant greenhouse gas and the release of CO_2 from terrestrial biota, including soil emission, contributes significantly to the present atmospheric CO_2 concentration (Bouwman 1990; Sitaula *et al.* 1992). Its atmospheric concentration (353 ppmv) is about 25% higher than the preindustrial value (280 ppmv) and is currently increasing by 0.5% per year accounting for about 60% of the current increase in the greenhouse effect (Erikson 1991; Keeling & Whorf 1994), largely due to global increase in fossil-fuel combustion and deforestation (Schlesinger 1997). The increasing concentration of carbon dioxide in the atmosphere since the industrial evolution is among the most significant of human influences on the global environment. The current release of carbon to the atmosphere from tropical deforestation could be 35-50% of current emissions from worldwide combustion of fossil fuels. According to the analysis of Houghton *et al.* (1999), changes in land-use over the past two centuries have caused a significant release of CO_2 to the atmosphere from the terrestrial biota and soils. Their estimates show a net release of 124 Pg C to the atmosphere between 1850-1990.

The deliberate conversion of natural forests to cultivated agroecosystems is responsible for a substantial increase in atmospheric CO_2 concentration (Houghton *et al.* 1983; Houghton 1995) but a few studies have directly examined the effect of land-use change on soil surface CO_2 flux. The evidence for this rise comes primarily from the continuous record started in 1958 at Mauna Loa, Hawaii (Pales &

Keeling 1965; Keeling *et al.* 1976b), and from a parallel record at the South Pole (Keeling *et al.* 1976a). The trend of the atmospheric record suggests that the rate of increase of the CO_2 content of air is accelerating and concentration will reach ~ 600 μL/L by 2030 (Keeling & Bacastow 1977). This concentration is approximately double the level of 1900 A.D. Increase of atmospheric CO_2 is expected to cause a global warming of 2-4 °C, with climatic warming greater at the poles than at the equator (Manabe & Stouffer 1979; Manabe & Wetherald 1980).

Certain analyses of the causes of the increase in atmospheric CO_2 (Bacastow & Keeling 1973; Keeling 1973a; Machta 1973; Oeschger *et al.* 1975) assumed that the only net source of CO_2 was from the combustion of fossil fuels. These assumptions may not be true, as few studies indicate that the land-use change also significantly contributed to the level of CO_2 rise in the atmosphere (Houghton & Hackler 1995). Land-use changes affect the amount of carbon stored in terrestrial ecosystems. The greatest changes in carbon storage per hectare result from the conversion of forests to cultivated land. Forests hold 20-50 times more carbon per hectare than cleared lands, and 100-200 tC ha^{-1} may be lost as a result of deforestation (Houghton & Hackler 1995). Deforestation not only transfers carbon stocks directly to the atmosphere by combustion, but it also destroys a valuable mechanism for controlling atmospheric CO_2. The 1995 Intergovernmental Panel on Climate Change (IPCC) estimated that agriculture was responsible for 20% of the annual increase in the total anthropogenic greenhouse gas radiative forcing potential. Therefore, great interest exists to quantify the carbon flux on land-use/cover basis.

Soil surface CO_2 flux, the sum of plant root and microbial respiration, is an important component of the carbon cycle of terrestrial ecosystems. Excluding gross canopy photosynthesis, soil surface CO_2

flux is commonly the largest flux in terrestrial ecosystem carbon budgets (Raich & Schlesinger 1992). Almost 10% of the atmosphere's CO_2 passes through soils each year (Raich & Potter 1995); this is more than 10 times the CO_2 released from fossil fuel combustion. Terrestrial ecosystems are an important component of the global C budget, but a better understanding of the effect of land-use practices on the C budget, especially soil surface CO_2 flux, is needed (Johnson 1992). Rates of soil respiration are largely dependent upon soil temperature and moisture conditions (Singh & Gupta 1977; Schlentner & Van Cleve 1985; Carlyle & Than 1988). Soil respiration rates also vary significantly with vegetation and among major biome types (Schlesinger 1977; Raich & Schlesinger 1992). Hence, changes in vegetation structure resulting from human activities can modify the soil-to-atmosphere CO_2 flux. Despite its importance in the ecosystem carbon cycle, no systematic research, however, has been made for the emission estimate of CO_2 on land-use/cover basis. The objective here, then was to quantify the net C flux on an annual basis for the land surface associated with the change. This chapter, will focus the carbon flux attributable to changes in land-use/cover. An attempt has also been made to study the respiration loss (litter, humus and soil), harvest flux, and land-use change emissions on land-use/cover basis.

7.2 MATERIALS AND METHODS

7.2.1 Approach

The C flux associated with the land-use/cover change is the product of C uptake via photosynthesis and C release via autotrophic and heterotrophic respiration. The method used to calculate emissions (and accumulations) of carbon from land, as a result of land-use/cover change is based on field measurements. The accounting procedure is based on the fact that most uses of land affect the amount of carbon held in vegetation and soil. The human activities that reduce the area of forest release carbon to the atmosphere as a result of burning and decay. More subtle changes within forests also affect the storage of carbon in biomass.

The approach used here to calculate change was based on two types of data. First, the land-use/cover change detection data generated through remote sensing technique was used to determine the spatial extent affected by different land-use/covers. Second, the per hectare changes in carbon associated with these changes in land-use/cover formed the basis to calculate annual changes in C ha^{-1}. The approach accounts for all of the carbon on an affected unit of land: live vegetation, soil, litter, humus and wood products. The losses and accumulations of carbon following an initial change in land-use occur over years to decade, dead materials decays and as forests regrow following harvest. Thus the calculated flux of carbon includes only those changes in carbon that were associated with land-use/covers change, however, the analysis did not include all anthropogenic effects.

The land-use/cover C flux was partitioned into four categories, (i) net primary production, which incorporates all the biologically-driven C transfers between the biosphere and atmosphere; (ii) respiratory loss that accounts for C release via litter, humus and soils; (iii) harvest flux, which accounts for removals associated with tree harvest; and (iv) land-cover change emissions.

7.2.2 Vegetation Carbon Accretion Analyses

The net primary production flux is the product of the area within each inventory type. The carbon flux was measured on an annual basis for the different compartments viz., above and belowground vegetation, litter and humus from each of the land-use/cover. The specific importance of each of these components varies widely among land-use/covers. Total plant production (i.e., above and belowground biomass) and litter and humus production was multiplied by the C concentration of the each of the component to express NPP on a mass-of-C basis. In cropped area of both the belts weed productivity were not measured.

Monthly tree litterfall estimations were carried out in different land-uses using five litter traps of 1 m^2 collecting area in each sample plots and pooled to annual values. Results were converted in terms of carbon by multiplying with per cent carbon. Decomposition was estimated by taking the ratio of litter production and its biomass on the ground.

Turnover time of carbon in the standing vegetation was computed by getting the ratio of standing state and the annual uptake (Chaturvedi & Singh 1987; Sharma 1993). The turn over time for carbon on stand floor was calculated following Olson (1963).

7.2.3 CO_2 Flux Measurements

7.2.3.1 Litter and humus CO_2 flux

The litter and humus CO_2 flux were measured monthly and data were pooled on seasonal and annual basis. To measure the litter CO_2-flux, a thick plastic plate was placed in between litter and humus layer in order to restrict humus and soil CO_2 flux and similarly to measure humus CO_2 flux the plastic plate was placed in between soil and humus layer to avoid the soil CO_2 flux at random locations in each plot of the replicated treatments of all the land-use/covers using the CO_2 Infrared Gas Analyzer. CO_2 flux was translated in terms of C flux on annual basis.

7.2.3.2 Soil surface CO_2 flux

Soil surface CO_2 flux was measured monthly in all the land-use/covers between January to December of 2000 and data were pooled on seasonal and annual basis. The C-flux in soil respiration defines the rate of C-cycling through soils. Soil CO_2 flux was measured with a CO_2 Infrared Gas Analyzer (CI-301 PS Model, USA) equipped with a soil respiration chamber that fit on top of the soil and were generally conducted in the morning between 0800 and 1200 hrs. This method provides a rapid, reliable estimate that is comparable to other approaches. Furthermore, the method is well suited to quantify the influence of environmental factors on *in situ* soil surface CO_2 flux measurements. The thick-walled ring was inserted 2 cm into the soil at random locations in each of the three replicated treatments of the nine land-use/cover types. The collars were relocated three times during the measurement period to minimize surface disturbance and over estimation of CO_2 flux.

Soil respiration rates can be used to calculate the mean residence or turnover time of the soil carbon pool, provided as assumption is made regarding the contribution that live root respiration makes to total soil respiration. The remaining respiration is presumably derived from the decomposition of soil organic matter, representing the true turnover of this pool. Most studies indicate that live root respiration contributes 30 to 70% of the total soil respiration (Schlesinger 1977). Turnover time is estimated based on the assumption that 30% of soil respiration is derived from root respiration (Schlesinger 1984). CO_2 flux was translated in terms of C flux on annual basis.

7.2.4 The Harvest Flux

To quantify the effects of harvest removals adopted in this study are based on field measurements. The principle budget terms associated with logging were (i) mortality or reduction of tree C from the phytomass pool, and (ii) the partitioning of that tree C between logs removed from the forest and residue which is left to decompose.

Total tree C mortality was a function of reported growing stock removals and the ratio of total tree C to growing stock C. Timber harvest from forests was taken from the field measurement. Fuelwood removal, some of which do not show up in the growing stock harvest, may be greater than commercial logging removals but it is very difficult to isolate this flux. Small scale fuelwood gathering tends to be a dispersed activity and may be balanced to some degree by unquantified tree growth.

The C in logs removed from the land base is assumed to be returned to the atmosphere. However, some forest products have lifetime on the order of hundreds of years and may thus represent a significant C sink. The pool of wood products still in use and in landfills is a function of inputs and outputs, and an accounting system which tracks current and historical inputs, turnover times of the different product types, and the return of C to the atmosphere is desirable.

7.2.5 Land-cover Change Emissions

Deforestation is the most significant land-cover change in terms of C flux. Direct emissions associated with deforestation are a function of several factors including the area converted during the base period, the initial C pools or standing crop and the burning efficiency. Estimates for rates of land-cover change were based on satellite data and ground surveys. Approaches to estimate the standing crop biomass in forests and agroforestry systems has already been described in Chapter IV. Burning efficiencies is quite low in the watershed.

7.2.6 Statistical Analyses

The plots were considered the experimental unit and were in replicate and completely random experimental design was used to test the effects of land-use/cover changes in the carbon flux dynamics of the watershed. An analysis of variance (ANOVA) was used to determine the effect of land-use type and its interaction with season. All statistical analyses were conducted using SYSTAT version 6.0 and SPSS version 6.0. Statistical differences among the nine land-use/covers were determined using Tukey's honestly significant difference test at 5% level. Soil surface CO_2 flux was correlated to soil temperature and moisture and organic C and microbial C using single and multiple-variable regression models.

7.3 RESULTS

7.3.1 Productivity and Carbon Accretion

The net carbon input in different land-use/covers ranged between 3 and 7.43 tC ha^{-1} yr^{-1} (mean= 4.88) (Table 7.1). Analysis of variance showed significant variation between the land-use ($P<0.0001$). Total vegetation accretion was significantly greater in the temperate natural forest dense ($P<0.05$) than other land-uses. Mean difference between cardamom based agroforestry systems was also significantly higher than the other stands. Pairwise mean difference showed no significant differences between mandarin based agroforestry systems and open cropped areas ($P>0.05$). However, total net carbon input was significantly greater in the temperate natural forest open and subtropical natural forest than mandarin based agroforestry system and open cropped areas of both the belts.

Aboveground net C input varied significantly between the land-use ($P<0.0001$). Aboveground net C accretion was three-fold greater ($P<0.05$) for the temperate natural forest dense than the open cropped area subtropical (Table 7.1). Mean aboveground net C input for the temperate natural forest open and subtropical natural forest were significantly greater ($P<0.05$) than agroforestry systems and open cropped areas, while mean difference between mandarin based agroforestry and open cropped areas of both the belts were not significant ($P>0.05$). However, mean difference was significantly higher in the cardamom based agroforestry system than mandarin based agroforestry and open cropped areas.

Belowground net C input varied significantly between the land-use ($P<0.0001$). Belowground net C input was significantly higher ($P<0.05$) in cardamom based agroforestry system than other stands. Although the mean differences were not significant among temperate natural forest dense, mandarin based agroforestry and open cropped area subtropical ($P>0.05$), temperate natural forest dense had significantly higher belowground C input than temperate natural forest open and subtropical natural forest open. Mean difference was significantly greater ($P<0.05$) in the open cropped area temperate than other land-uses except cardamom based agroforestry system (Table 7.1).

The values of turnover time and turnover rate for carbon in standing vegetation of the different land-uses are given in Table 7.2. The turnover time of carbon ranged from 1.82 years in mandarin based agroforestry system to 25.74 years in temperate natural forest dense.

Turnover rate of C ranged from 0.039 in temperate natural forest dense to 0.548 in mandarin based agroforestry system.

7.3.2 Carbon Input into Litter and Humus

The annual litter C input in different land-use/covers varied from 1.13 tC ha^{-1} yr^{-1} to 1.83 tC ha^{-1} yr^{-1}. Analysis of variance showed significant variation between the land-uses ($P<0.0001$). Mean variation between litter C input was significantly greater ($P<0.05$) in cardamom based agroforestry systems than other land-uses. Mean difference between temperate natural forest dense was also significantly higher than other forests and mandarin based agroforestry systems. Pairwise mean difference showed no significant differences between similar open forest stands ($P>0.05$) while net carbon input was significantly higher in the mandarin based agroforestry systems than both the forests (Table 7.3).

Carbon entry into humus through litter decomposition varied significantly between the land-use ($P<0.0001$). Pairwise mean difference was significantly higher ($P<0.05$) in cardamom based agroforestry system than other land-uses. Mean difference between temperate natural forest dense with other forest types was also significantly higher ($P<0.05$) but open forests of both the belts were not significantly different to each other (Table 7.3).

The values of turnover time and turnover rate for carbon on the stand floor litter are given in Table 7.4. The turnover time of carbon ranged from 1.19 years in mandarin based agroforestry system to 2.85 in cardamom based agroforestry system while turnover rate ranged from 0.351 in cardamom based to 0.841 in mandarin based agroforestry systems.

7.3.3 Respiration Loss

7.3.3.1 Litter CO_2 flux

Analysis of variance showed significant variation between the land-use and season ($P<0.0001$). Interactions between land-use and season were not significant (Fig. 7.1a). Litter CO_2 flux decreased significantly ($P<0.05$) in mandarin based agroforestry system than other stands. Mean difference showed no significant differences between forests and cardamom based agroforestry systems ($P>0.05$) (Fig 7.2a). Mean difference within seasons was not significantly different. A strong positive relationship was observed in between litter CO_2 flux and moisture content of the litters ($y= -0.775 + 0.119x$, $r^2= 0.828$, $P<0.0001$).

The total annual mean C flux from litter was 0.05 tC ha^{-1} yr^{-1} and 3.78 tC ha^{-1} yr^{-1} for mandarin based agroforestry system and temperate natural forest dense, respectively (Table 7.3).

7.3.3.2 Humus CO_2 flux

Humus CO_2 flux varied significantly between land-use and seasons. Interactions between land-use and seasons were not significant (Fig 7.1b). Mean humus CO_2 flux was significantly higher ($P<0.05$) in temperate natural forest dense than other stands, but the increase in humus CO_2 flux in open forest stands of both the belts were not significantly different ($P>0.05$). However, mean difference was significantly higher in the cardamom based agroforestry systems ($P<0.05$) than the temperate natural forest open and subtropical natural forest (Fig 7.2b). Mean difference between the seasons were significant for rainy with spring and winter, but spring and winter were not significantly different ($P>0.05$).

7.3.3.3 Soil surface CO_2 flux

Soil surface CO_2 flux differed significantly among land-use and season ($P<0.0001$). The interaction effect (significant at $P<0.0001$) can be seen by comparing seasonal soil surface CO_2 flux patterns for each of the nine land-use/covers (Fig 7.1c). Mean annual soil surface CO_2 flux was significantly greater ($P<0.05$) in croplands than other land-uses. In between temperate natural forest open and both the agroforestry systems, soil CO_2 flux did not differ significantly. However, soil surface CO_2 flux was significantly higher ($P<0.05$) in the subtropical natural forest than other land-uses (Fig 7.2c). Soil respiration rates were consistently greater in temperate natural forest dense than wastelands of temperate and subtropical belts. Between the seasons, differences were significant for rainy with spring and winter.

A strong seasonality in the soil surface CO_2 flux was observed. ANOVA indicated that differences in the soil CO_2 flux due to season were significant as was land-use x season ($P<0.0001$) (Fig 7.1c). The minimum values for the rate of flux occurred during the winter and maximum in the rainy season (Fig 7.1c). Seasonal variations in the soil respiration rates closely followed those of temperature variations in both the belts. Considering all the land-use/covers of both the belts, mean annual soil respiration positively correlated with surface soil temperature but feeble ($y = 2.721 + 0.103x$, $r^2 = 0.246$, $P<0.01$) where as no relation was found with moisture ($y = 4.527 - 0.008x$, $r^2 = 0.008$, NS). Combining soil temperature and moisture to estimate soil CO_2 flux improved the regression equation (multiple linear regression, $y = 2.982 + 0.108\ T - 0.014\ M$, $r^2 = 0.273$, $P<0.05$, where y is soil CO_2 flux, T is soil temperature and M is soil moisture) explained significantly more variation than a regression equation with soil temperature alone (Fig.

7.3a). Other factors that influence soil surface CO_2 flux are soil organic carbon and microbial communities.

Annual estimates of soil surface CO_2 flux in different land-use are 12.11 tC ha^{-1} yr^{-1} (lowest) and 21.67 tC ha^{-1} yr^{-1} (highest) for the wasteland area temperate and open cropped area subtropical, respectively. Annual soil surface CO_2 flux estimates were also greater (18 tC ha^{-1} yr^{-1}) for subtropical natural forest than the other forests and agroforestry systems.

Estimated turnover time of soil carbon based on mean carbon pool and mean soil respiration are presented in Table 7.5. The values ranged from about 47 years in the temperate natural forest dense to 3 years in open cropped area temperate. The watershed pool of soil organic carbon has a mean residence time of about 14 years (Table 7.5).

7.3.3.4 Carbon flux through the soil microbial biomass

Annual flux of carbon through microbial biomass ranged from 96 kg C ha^{-1} yr^{-1} to 679 kg C ha^{-1} yr^{-1} (mean= 347 kg C ha^{-1} yr^{-1}) in wasteland temperate and temperate natural forest dense, respectively (Table 7.6). The land-use change increased the rate of carbon flux and made the microbial biomass an important source of carbon. A multiple regression was developed to see the role of soil organic C and microbial biomass C in soil surface CO_2 flux. Combining soil organic C and microbial biomass C to estimate soil CO_2 fluxes improved the regression equation ($y= 4.392-0.745OC + 27.195\ MBC$, $r^2= 0.391$, $P<0.005$, where, y= soil surface CO_2 flux, OC= Soil Organic Carbon and MBC= Soil Microbial Biomass Carbon) (Fig 7.3b).

7.3.4 The Harvest Flux

The harvest flux is relatively higher (2.08 tC ha^{-1} yr^{-1}) in subtropical natural forest than temperate natural forest dense (1.34 tC ha^{-1} yr^{-1}) and temperate natural forest open (1.17 tC ha^{-1} yr^{-1}) (Table 7.7). It was clear from the field visits that even the remotest part of the forest was being used for timber and fuelwood collection. Species use varied in their utilization for house construction, fuelwood and agricultural tools. The direct emissions associated with commercial harvest are greater from subtropical natural forest because of the high level of logging.

7.3.5 Land-cover Change Emission

The release of carbon or its accumulation depends on the standing stock of carbon in vegetation and soils and on the rates of deforestation. The vegetation stock changes as (dense forest converted into open forest to open cropped area to wastelands) and consequently in the standing crop of carbon. Thus land conversion during the past 13 years (1988-2001) resulted into a net release of 119×10^3 t vegetation C and 183×10^3 t soil C (Table 7.8). This translates into release of 7.78 tC ha^{-1} yr^{-1} from the entire watershed due to land-cover change.

7.3.6 Carbon Flux Variation Between Land-use/covers

Distribution of biomass C and flow rates in different components of each land-use/cover are presented in Fig 7.4a, b, c, d, e, f, g, h & i. Values in the compartments are carbon stocks and arrows show net flow rate. The differences of the value on the arrows of either side of a compartment give the component net production. A comparative account of the different land-uses showed high biomass C build-up in temperate natural forest dense, especially of perennial parts like bole, branch and belowground parts. Annual carbon uptake from the atmosphere was highest in temperate natural forest dense (7.43 tC ha^{-1} yr^{-1}) that was more than 2 times greater than the mandarin based agroforestry systems and open cropped areas. In both the agroforestry systems, allocation of C from the annual uptake remained between 30% and 64% in cardamom and crops respectively. Amongst forest, allocation of C from the annual uptake varied from 7-10% in herbaceous biomass.

C exit from the system in the form of harvest was highest in the subtropical natural forest (2.08 tC ha^{-1} yr^{-1}), which was 1.6 to 1.8 times greater than temperate natural forest dense and open, respectively. C exit from the system in the form of agronomic yield was highest in open cropped area temperate (1.62 tC ha^{-1} yr^{-1}) that was about 12 times higher than cardamom based agroforestry system and about 2 times higher than mandarin based agroforestry systems.

Mean C flux from soil to the atmosphere was greater in open cropped areas (21.28 tC ha^{-1} yr^{-1}) that were 48% higher than temperate natural forest dense and 68% than wasteland areas. C flux from litter to the atmosphere was highest in temperate natural forest dense, which was 75 times higher than mandarin based agroforestry systems. The impacts of erosion were not included in the C flux estimates because it is not clear to what degree erosional losses end up in the atmosphere.

7.4 DISCUSSION

Total C input through primary productivity was higher in temperate natural forest dense than other stands. This is attributed to high rates of biomass production. The carbon storage in agroforestry systems (mean B/P= 4.87) was about five times lower than that in forests (mean B/P= 19.72), carbon flux was higher in agroforestry stands, resulting in mean P/B ratio 0.34 for agroforestry systems and 0.05 for forests. The contribution of ground vegetation plus fine roots to total net productivity averaged 42% for agroforestry based systems and only 9% for forests. Low standing crop of C in the agroforestry and open cropped areas where functional importance shift from woody canopy to herbaceous ground stratum with short-term vegetation predominance, was associated with high C flux. A similar observation was reported by Singh *et al.* (1991) in dry tropics of savanna.

Annual input of C to the forests and agroforestry stands floor through litter and slashed pseudo-stems of cardamom ranged from 1.13 to 1.83 tC ha^{-1} yr^{-1} to be highest in the cardamom based agroforestry system and lowest in subtropical natural forest. The litterfall of cardamom based agroforestry system and temperate natural forest dense were higher because these are closed canopy systems with a greater tree density. The greater rate of litter and residue production in the cardamom based agroforestry system than in the temperate natural forest dense was matched by a proportional increase in the litter biomass of the ground. But the carbon release through respiration was slightly higher in temperate natural forest dense than cardamom based agroforestry system. Carbon loss through litter decomposition was higher in cardamom based agroforestry system than other stands. Release of carbon through respiration and decomposition is more than annual litter production in most of the systems because the accumulated litter of the previous years also decompose and also because of microbial biomass buildup and activity, respiration and release. Microbial growth is exponential and turnover rate is fast that led to this higher contribution. The turnover time of C on the floor litter was slightly higher for cardamom based agroforestry system than temperate natural forest dense. This suggests that C cycling in cardamom was much quicker than other stands.

Land-use type influenced soil surface CO_2 flux (Alvarez *et al.* 1998; Wagai *et al.* 1998). Mean rates of soil respiration varied widely within and among land-use types. The highest rate of soil respiration occurred in the open cropped area subtropical where soil temperature was high year-round. Published measurements of annual soil respiration rates in tropical and subtropical moist forests ranged from 8.90-14.50 tC ha^{-1} yr^{-1} (Raich & Schlesinger 1992), but these data were biased towards lowland forests only. The relatively high rates observed in this study (12 to 21 tC ha^{-1} yr^{-1}) may reflect the diverse land-use/covers in the study site. Although soil respiration rates are known to vary seasonally, a significant relationship between rates of soil respiration and soil temperature was found. Wildung *et al.* (1975) measured soil surface CO_2 flux in an arid grassland in eastern Washington and observed a strong positive correlation between soil CO_2 flux and soil temperature. It was argued that the multiple regression equation using the temperature-moisture interaction provide the best estimate of annual CO_2 flux in this environment that has periodic moisture limitation. de Jong (1974) also reported that the addition of soil moisture in a regression equation improved the fit for native grasslands.

Seasonality plays an important role in soil surface CO_2 flux. Maximum soil surface CO_2 flux rates occur during rainy season in all the land-use/covers at both the belts. Other researchers have also reported that maximum soil surface CO_2 flux occur between June and August for forests and agroecosystems (Kucera & Kirkham 1971; de Jong 1974; Buyanovsky *et al.* 1987; Grahammer *et al.* 1991; Norman *et al.* 1992). Results of this and other studies suggest that soil temperature has a greater effect on soil surface CO_2 flux than soil moisture. Soil surface CO_2 flux does not correlate well to soil moisture for all the land-use/cover types. However, soil surface CO_2 flux may not correlate to soil moisture for several reasons. Soil moisture varied mostly between 17 to 34% in all the land-uses making it difficult to detect a significant pattern. Soil water contents may not have reached the extreme range necessary to affect microbial activity. Kucera & Kirkham (1971) noted that soil CO_2 fluxes were reduced only when soil moisture reached permanent wilting point or exceeded field capacity.

Humans have altered the land-cover of the earth and further changes in land-cover are expected as human impacts on earth continue. The obvious changes in land-use that have already occurred, and further changes in land-cover that is likely to occur, have the potential to alter the carbon flux. The release of carbon or its accumulation depends on the standing stock of carbon in vegetation, litter, humus and soil which further depends on land-use/cover change. 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 305×10^3 tC over 13 year's period (1988-2001). Reduction in the biomass of the forests as a result of conversion were responsible for a net loss of 119×10^3 t vegetation C and 183×10^3 t soil C (Table 7.8). This translates into release of 7.78 tC ha^{-1} yr^{-1} due to land-use change. The uptake and release ratios of carbon varied between land-uses. The release: uptake ratio was highest (7.20) in open cropped area subtropical and lowest (2.60) in temperate natural forest dense. In addition to changes in the area of forests are changes of biomass within forests. Lanly (1982) reported that degradation, as well as deforestation, are occurring throughout the tropics. The degradation ratio was defined here as the ratio of carbon lost to area lost, relative to the initial carbon (in biomass) per unit area. The total loss of biomass was 96032 tC and 47242 tC from temperate natural forest dense and subtropical natural forest, and the total loss of forest area was 446.81 and 319.29 ha, respectively (Table 7.9). Thus, the ratio of biomass lost to area lost in 13 years period was 214.93 and 147.96 tC ha^{-1}, respectively in temperate natural forest dense and subtropical natural forest open. The average biomass of these forests in 1988 was 208.69 and 117.28 tC ha^{-1}. For the forests in the watershed, the degradation ratio was 1.03 and 1.26 i.e., the average carbon lost was 1.09 and 1.29 times larger per unit area than average biomass of the initial forests (Table 7.9). One interpretation of this ratio is that for every ton of carbon released to the atmosphere through deforestation, an additional 0.09 and 0.29 of carbon is released from degradation of the remaining forests. These indicate that the relative importance of degradation increased over time. Similar observation was also reported by Flint & Richards (1991). The degradation ratio is affected by at least three factors: (i) the biomass and areas of forest in the watershed, (ii) the amount of degradation taking place within an interval of time and (iii) the biomass of forests cleared in that interval. The first of these factor is the simplest to discuss, and sheds light on the amount of degradation likely to have occurred before 1988. When little degradation was assumed to have occurred before 1988, the resulting degradation ratios of the experiments were all less than 1.0. They were low because the initial carbon per unit area (denominator in the ratio) was high. To yield degradation ratios above 1.0, many of the forests in 1988 must have already been degraded. The second factor affecting the degradation ratio is the factor of interest here; the rate of reduction of biomass within forests (degradation). Higher rates of degradation will yield higher degradation ratios. The third factor is the biomass of the forest cleared. If high biomass forests are cleared, the degradation ratio will be greater than 1.0. The degradation ratio was more than 1.0 in the present study. The fact that empirical studies (Flint & Richards 1991; Brown *et al.* 1991) found degradation ratios greater than 1.0 means that the flux of carbon was greater than would be calculated on the basis of deforestation alone. This statement is true whether the ratios resulted from degradation *per se* or from deforestation of high-biomass forests.

Based on the results obtained for Mamlay watershed and assuming the same conditions, the total release of carbon from the entire Sikkim state and Indian Himalayan region can be assessed. Sikkim state occupy 284779 ha forest land (about 40% of the total geographical area of Sikkim), land-use change (harvest and forest clearings) release 22.16×10^5 tC annually. If the same results is applied to the entire Indian Himalayan forests area (6.692 million ha); the total release of carbon would be 520.6×10^5 tC annually. Singh *et al.* (1985) reported 46×10^5 tC yr^{-1} for the Indian Central Himalayan region alone. The estimate of net release is conservative, because soils may loose 20-30% of their stored organic carbon following disturbances (Chan 1982). Similar conditions have been reported by Kawosa (1984) for Kashmir and other Himalayan states. It is clear that, because of overexploitation and continuous land conversion, the land-use/cover change have become a net source of C to the atmosphere. It is equally clear, however, that most of these lands when unchanged can constitute an effective net sink of C. Obviously, further land-use/cover change in the Sikkim as well as in the Himalayan region must be prevented, the existing open forests should be allowed to attain dense condition and wastelands should be put back under forest to sequester excess atmospheric carbon as wood.

In conclusion, efforts should be made to allow carbon sequestration under the Kyoto protocol. Irrespective of scale and geographic location, a key objective should be to identify and implement best available management practices to improve soil quality, there by ensuring food productivity and sustainability, while simultaneously reducing CO_2 concentrations in the atmosphere. Before implementing the "best practices" due attention must be paid also to any possible adverse environmental and socio-economic effects they may have.■

Table 7.1 Carbon input through net primary production (tC ha^{-1} yr^{-1}) in different land-use/covers. Different superscript letters in each column represent significant difference ($P<0.05$) (Tukey's honestly significant difference test)

Land-use/cover	Components	Above-ground vegetation	Below-ground vegetation	Total
Temperate natural forest dense	Tree	6.57	0.33	6.90
	Herb	0.43	0.10	0.53
	Total	7.0^{d}	0.43^{b}	7.43^{d}
Temperate natural forest open	Tree	4.71	0.19	4.9
	Herb	0.46	0.11	0.57
	Total	5.17^{c}	0.30^{a}	5.47^{b}
Subtropical natural forest open	Tree	4.59	0.02	4.61
	Herb	0.40	0.10	0.50
	Total	4.99^{c}	0.12^{a}	5.11^{b}
Cardamom based agroforestry system	Tree	3.49	0.63	4.12
	Cardamom	0.87	0.92	1.79
	Total	4.36^{b}	1.55^{d}	5.91^{c}
Mandarin based agroforestry system	Tree	1.00	0.08	1.08
	Crops	1.6	0.32	1.92
	Total	2.60^{a}	0.40^{b}	3.00^{a}
Open cropped area temperate	Crops	3.60^{a}	0.64^{c}	4.24^{a}
Open cropped area subtropical	Crops	2.52^{a}	0.49^{b}	3.01^{a}

Table 7.2 Turnover time (years) and turnover rate of carbon in the standing vegetation of different land-use/cover. Values are pooled for three sites replicate.

Land-use/cover	Turnover time	Turnover rate
Temperate natural forest dense	25.74	0.039
Temperate natural forest open	15.75	0.064
Subtropical natural forest open	17.66	0.057
Cardamom based agroforestry system	7.92	0.126
Mandarin based agroforestry system	1.82	0.548

Table 7.3 Carbon entry into litter through annual litter production and release through respiration and decomposition. Different superscript letters represent significant difference ($P<0.05$) (Tukey's honestly significant difference test).

Land-use/cover	Annual litter production ($tC\ ha^{-1}\ yr^{-1}$)	Release through respiration ($tC\ ha^{-1}\ yr^{-1}$)	Release through decomposition ($tC\ ha^{-1}\ yr^{-1}$)
Temperate natural forest dense	1.61^{c}	3.78	2.18
Temperate natural forest open	1.17^{a}	2.42	1.64
Subtropical natural forest open	1.13^{a}	2.88	1.55
Cardamom based agroforestry system	1.83^{d}	3.07	2.47
Mandarin based agroforestry system	1.26^{b}	0.05	2.32

Table 7.4 Turnover time (years) and turnover rate of carbon on different land-use floor litter in the different land-use/covers

Land-use/cover	Turnover time	Turnover rate
Temperate natural forest dense	0.352	2.84
Temperate natural forest open	0.397	2.52
Subtropical natural forest open	0.372	2.69
Cardamom based agroforestry system	0.351	2.85
Mandarin based agroforestry system	0.841	1.19

Table 7.5 Estimated turnover time of soil carbon based on mean carbon pool top 1 m of soil and mean soil respiration rates

Land-use/covers	Soil C ($tC\ ha^{-1}$)	Soil respiration ($tC\ ha^{-1}\ yr^{-1}$)	Turnover time (yr)
Temperate natural forest dense	472	14.37	46.92
Temperate natural forest open	219	15.80	19.80
Subtropical natural forest open	126	18.11	9.94
Cardamom based agroforestry system	255	16.00	22.77
Mandarin based agroforestry system	150	16.074	13.33
Open cropped area temperate	37	20.89	2.53
Open cropped area subtropical	48	21.67	3.16
Wasteland area temperate	89	12.11	10.50
Wasteland area subtropical	124	13.23	13.39

Table 7.6 Flux of carbon through the microbial biomass in different land-use/covers

Land-use/covers	Carbon in microbial biomass (kg ha^{-1})	Annual flux (kg ha^{-1} yr^{-1})
Temperate natural forest dense	1698	679
Temperate natural forest open	1248	499
Subtropical natural forest open	733	586
Cardamom based agroforestry system	778	311
Mandarin based agroforestry system	593	474
Open cropped area temperate	333	133
Open cropped area subtropical	201	160
Wasteland area temperate	241	96
Wasteland area subtropical	236	189
Mean	673	347

Table 7.7 Carbon removal out of the system through harvest flux

Land-use/covers	Components	C removal ($tC\ ha^{-1}\ yr^{-1}$)
Temperate natural forest dense	Tree	1.34
Temperate natural forest open	Tree	1.17
Subtropical natural forest open	Tree	2.08
Cardamom based agroforestry system	Cardamom capsule	0.14
Mandarin based agroforestry system	Orange fruit	0.28
	Crop agronomic yield	0.72
Open cropped area temperate	Crop agronomic yield	1.62
Open cropped area subtropical	Crop agronomic yield	0.55

Table 7.8 Vegetation C, soil C, litter C, humus C, and total C injected into the atmosphere due to land-use/cover change during 1988-2001.

From	To	Changed area (ha)	Release of vegetation C ($\times 10^3$ t)	Release of litter C ($\times 10^3$ t)	Release of humus C ($\times 10^3$ t)	Release of soil C ($\times 10^3$ t)	Total release ($\times 10^3$ t)
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

No changed in area observed in cardamom and mandarin based agroforestry systems

Table 7.9 Area, total carbon and average carbon per hectare in forests of the Mamlay watershed.

Parameters	Temperate Natural Forest Dense			Subtropical Natural Forest Open		
	1988	13-year change	2001	1988	13-year change	2001
Area (ha)	606.81		160.00	681.54		362.25
Loss of area (ha)		446.81			319.29	
Total carbon in biomass (tC)	126635		30603	79931		32689
Loss of biomass (tC)		96032			47242	
Average biomass (tC ha^{-1})	208.69		191.27	117.28		90.24
Ratio of biomass lost to area lost (tC ha^{-1})		214.93			147.96	
Degradation ratio in 13 years		1.03			1.26	

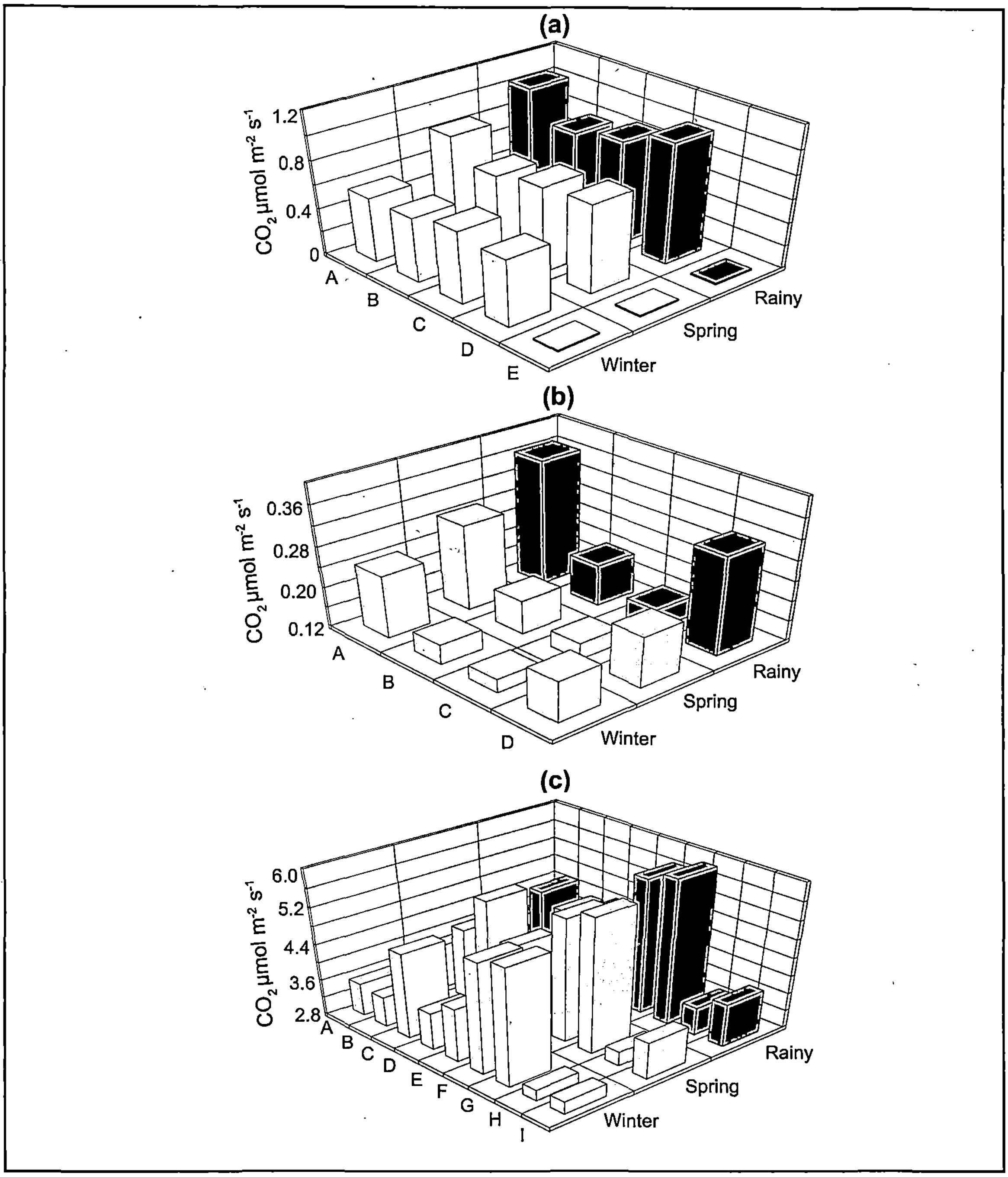

Fig. 7.1 CO_2 flux from **(a)** litter, **(b)** humus and **(c)** soil of different land-uses; A= Temperate natural forest dense, B= Temperate natural forest open, C= Subtropical natural forest, D= Cardamom based agroforestry system, E= Mandarin based agroforestry system, F= Open cropped area temperate, G= Open cropped area sub-tropical, H= Wasteland area temperate and I= Wasteland area subtropical.

ANOVA: Litter CO_2 flux; Land-use $F_{4, 30}$= 62.257, P<0.0001; Season $F_{2, 30}$= 19.402, P<0.0001; Land-use x Season $F_{8, 30}$= 1.801, NS.

Humus CO_2 flux; Land-use $F_{3, 24}$= 23.256, P<0.0001; Season $F_{2, 24}$= 10.369, P<0.001, Land-use x Season $F_{6, 24}$= 1.542, NS.

Soil CO_2 flux; Land-use $F_{8, 54}$= 277.828, P<0.0001; Season $F_{2, 54}$= 127.002, P<0.0001; Land-use x Season $F_{16, 54}$= 3.659, P<0.0001.

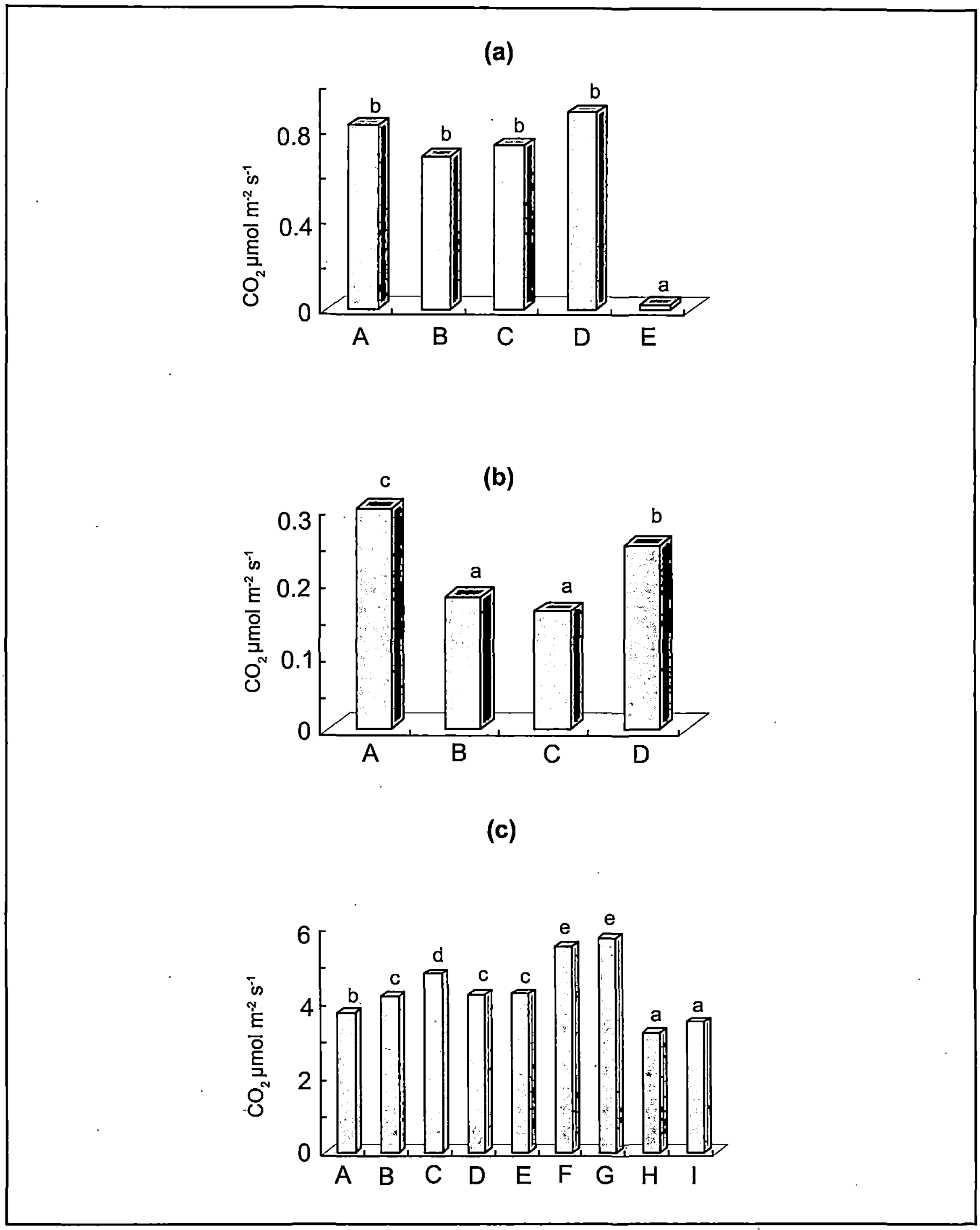

Fig. 7.2 Mean annual CO_2 flux from **(a)** litter, **(b)** humus and **(c)** soil of different land-uses; A= Temperate natural forest dense, B= Temperate natural forest open, C= Sub-tropical natural forest, D= Cardamom based agroforestry system, E= Mandarin based agroforestry system, F= Open cropped area temperate, G= Open cropped area sub-tropical, H= Wasteland area temperate and I= Wasteland area subtropical. Different letters above each bar denotes significant difference ($P<0.05$) among land-use/covers (Tukey's honestly significant difference test).

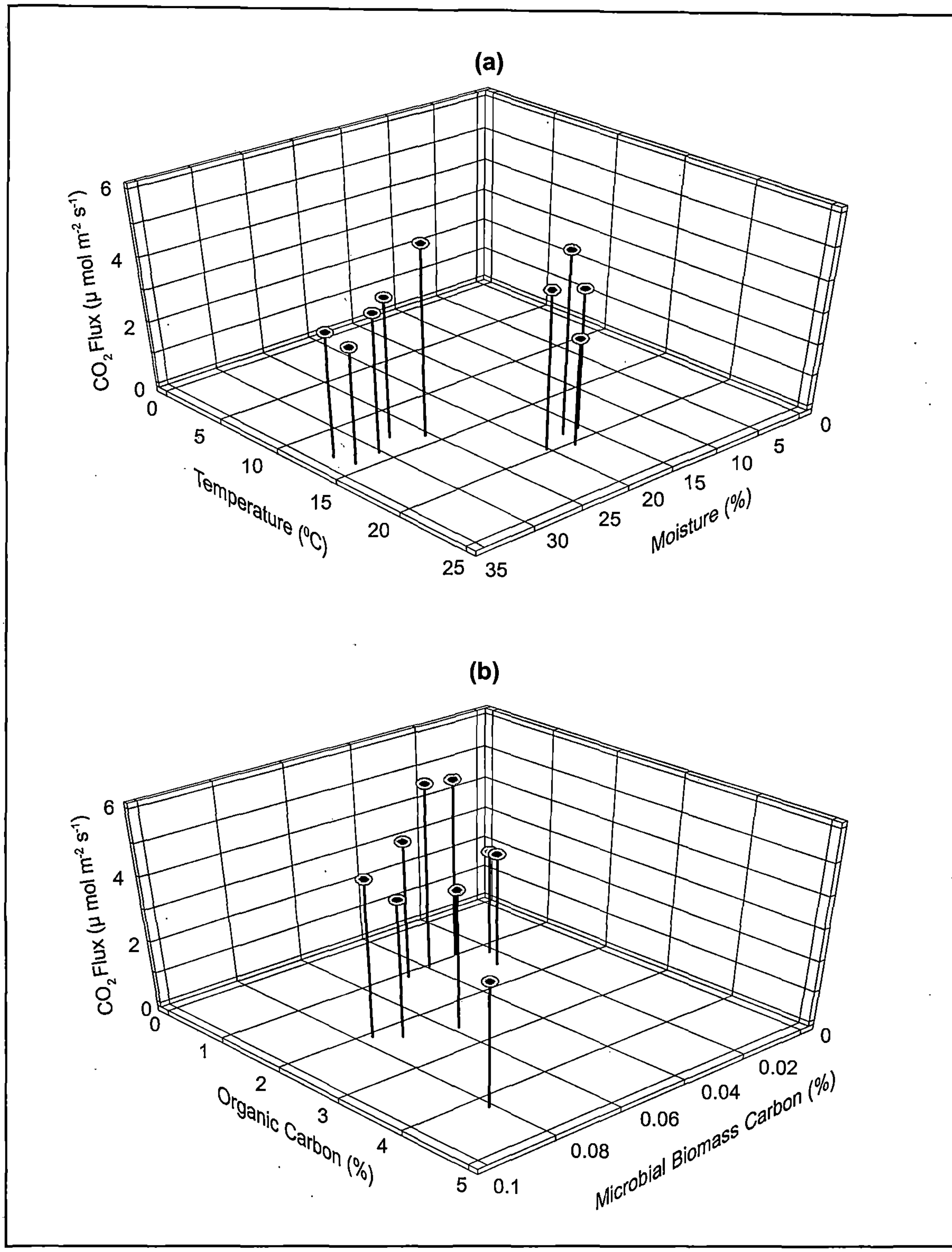

Fig. 7.3 Distribution of mean CO_2 flux rates along gradients of **(a)** soil temperature and soil moisture (0-15 cm). The multiple regression equation was: CO_2 flux= 2.982 + 0.108T - 0.014 M, where T is soil temperature and M is soil moisture, (r^2= 0.273, P<0.05), **(b)** soil organic carbon and microbial biomass carbon. The multiple regression equation was: CO_2 flux= 4.392- 0.745 OC + 27.195 MBC, where OC is soil organic carbon and MBC is soil microbial biomass carbon (r^2= 0.391, P<0.005).

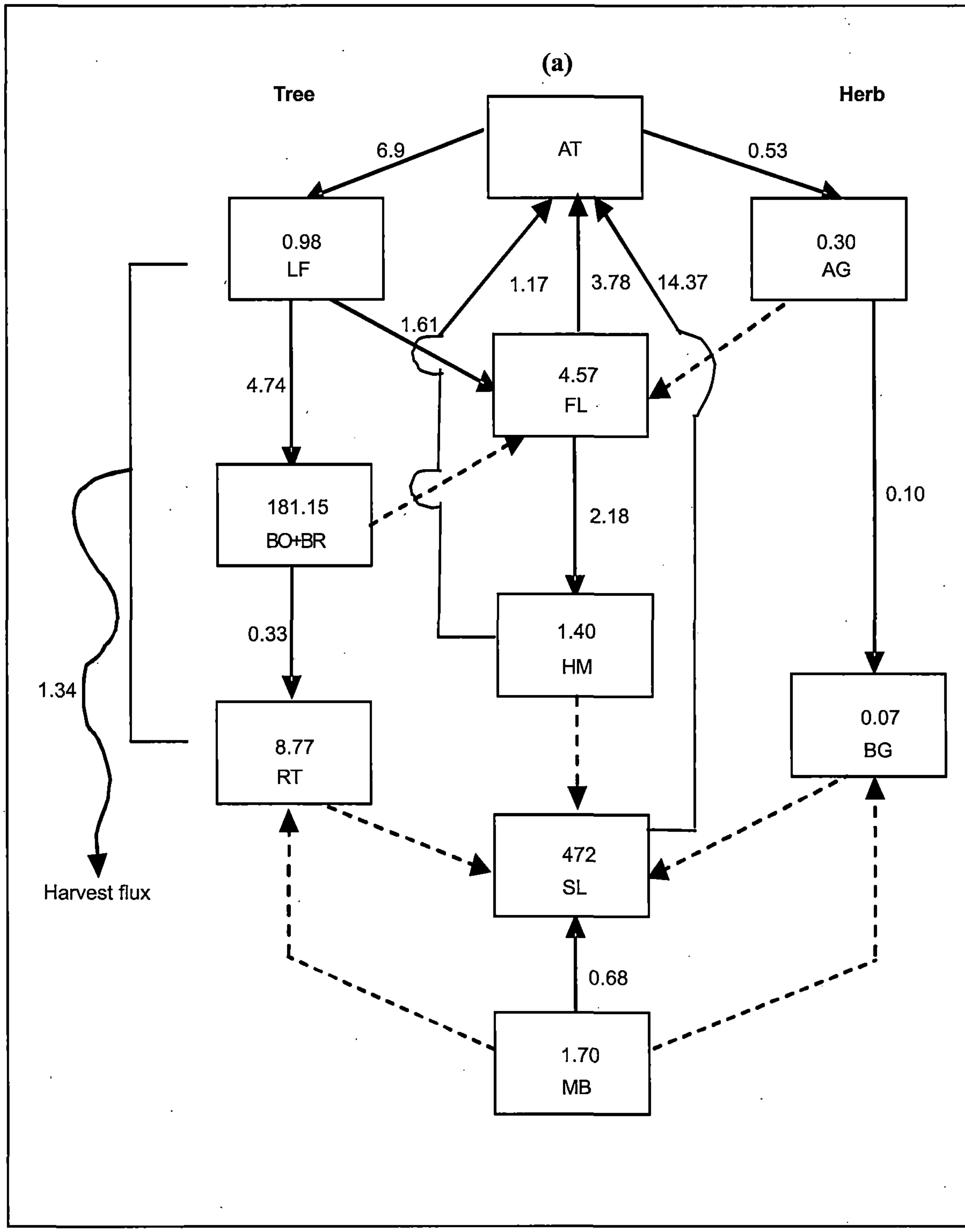

Fig. 7.4a Compartmental flow of carbon in temperate natural forest dense. Unit is tC ha^{-1} for compartments and tC ha^{-1} yr^{-1} for flows. Broken lines indicate the values are not measured. Curved lines indicate the loss of carbon out of the system. AT= Atmosphere, LF= Leaf, BO= Bole, BR= Branch, RT=Root, AG= Aboveground herbaceous biomass, BG= Belowground herbaceous biomass, FL= Floor litter, HM= Humus, SL= Soil and MB= Microbial biomass.

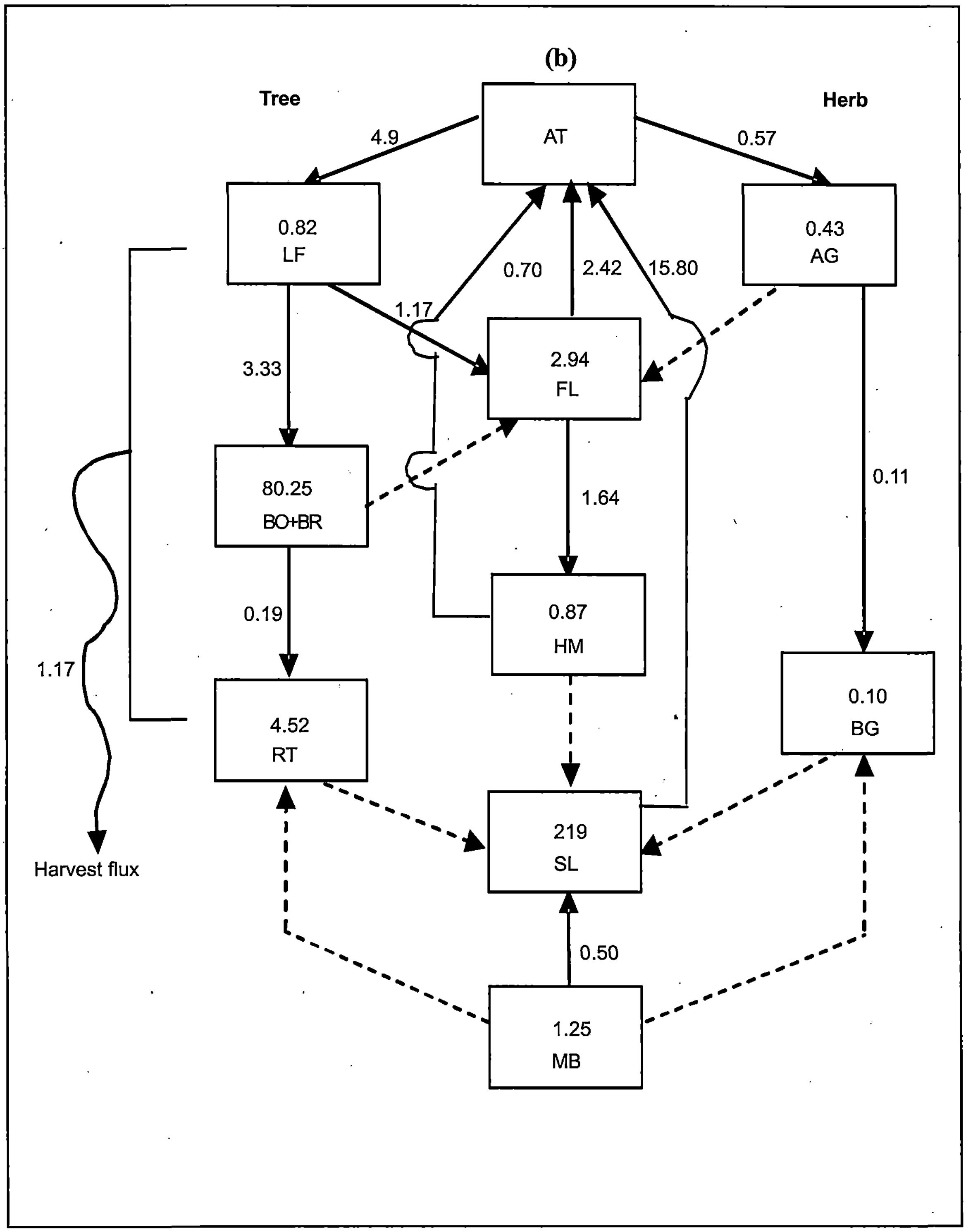

Fig. 7.4b Compartmental flow of carbon in temperate natural forest open. Unit is tC ha^{-1} for compartments and tC ha^{-1} yr^{-1} for flows. Broken lines indicate the values are not measured. Curved lines indicate the loss of carbon out of the system. AT= Atmosphere, LF= Leaf, BO= Bole, BR= Branch, RT=Root, AG= Aboveground herbaceous biomass, BG= Belowground herbaceous biomass, FL= Floor litter, HM= Humus, SL= Soil and MB= Microbial biomass.

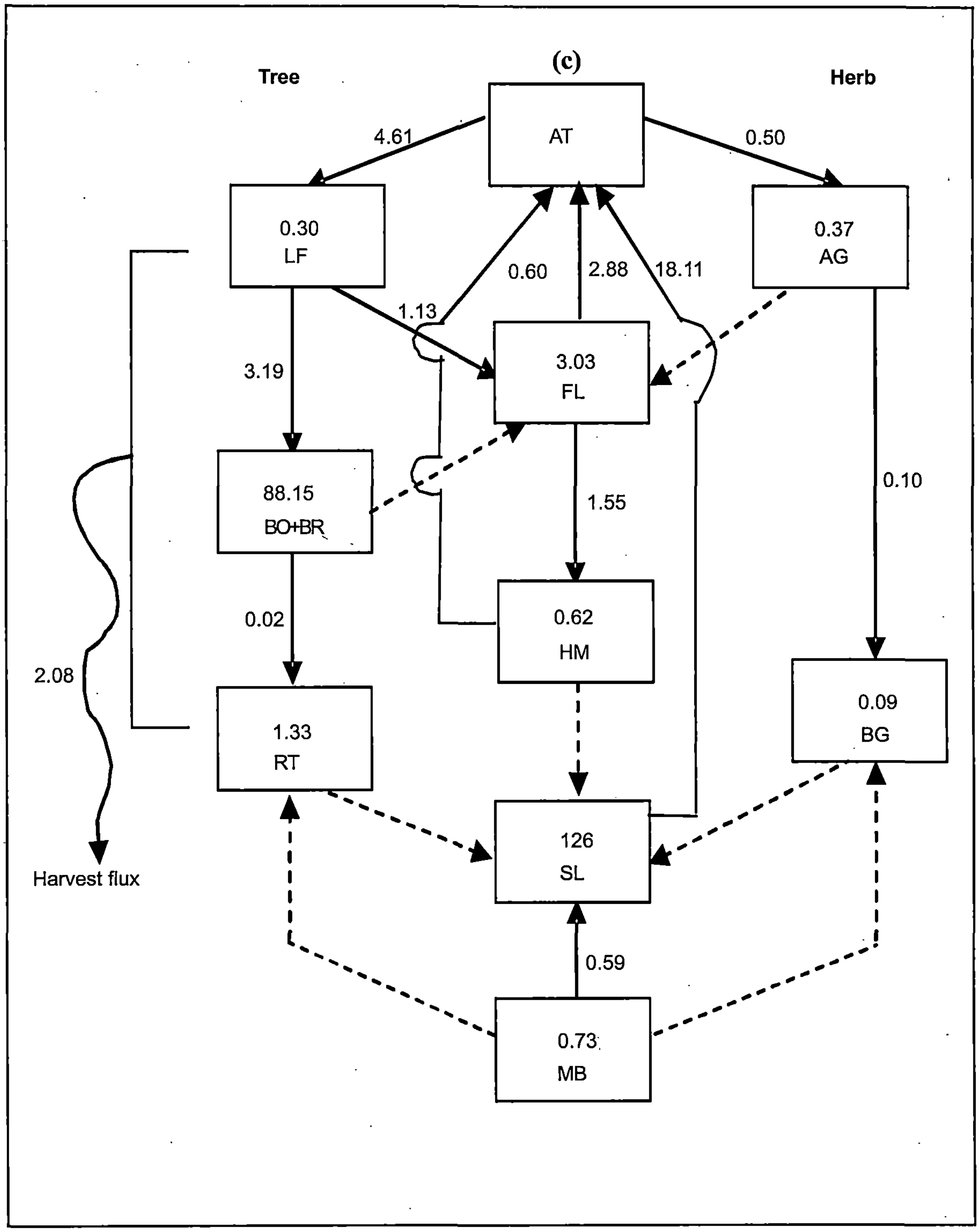

Fig. 7.4c Compartmental flow of carbon in subtropical natural forest open. Unit is tC ha^{-1} for compartments and tC ha^{-1} yr^{-1} for flows. Broken lines indicate the values are not measured. Curved lines indicate the loss of carbon out of the system. AT= Atmosphere, LF= Leaf, BO= Bole, BR= Branch, RT=Root, AG= Aboveground herbaceous biomass, BG= Belowground herbaceous biomass, FL= Floor litter, HM= Humus, SL= Soil and MB= Microbial biomass.

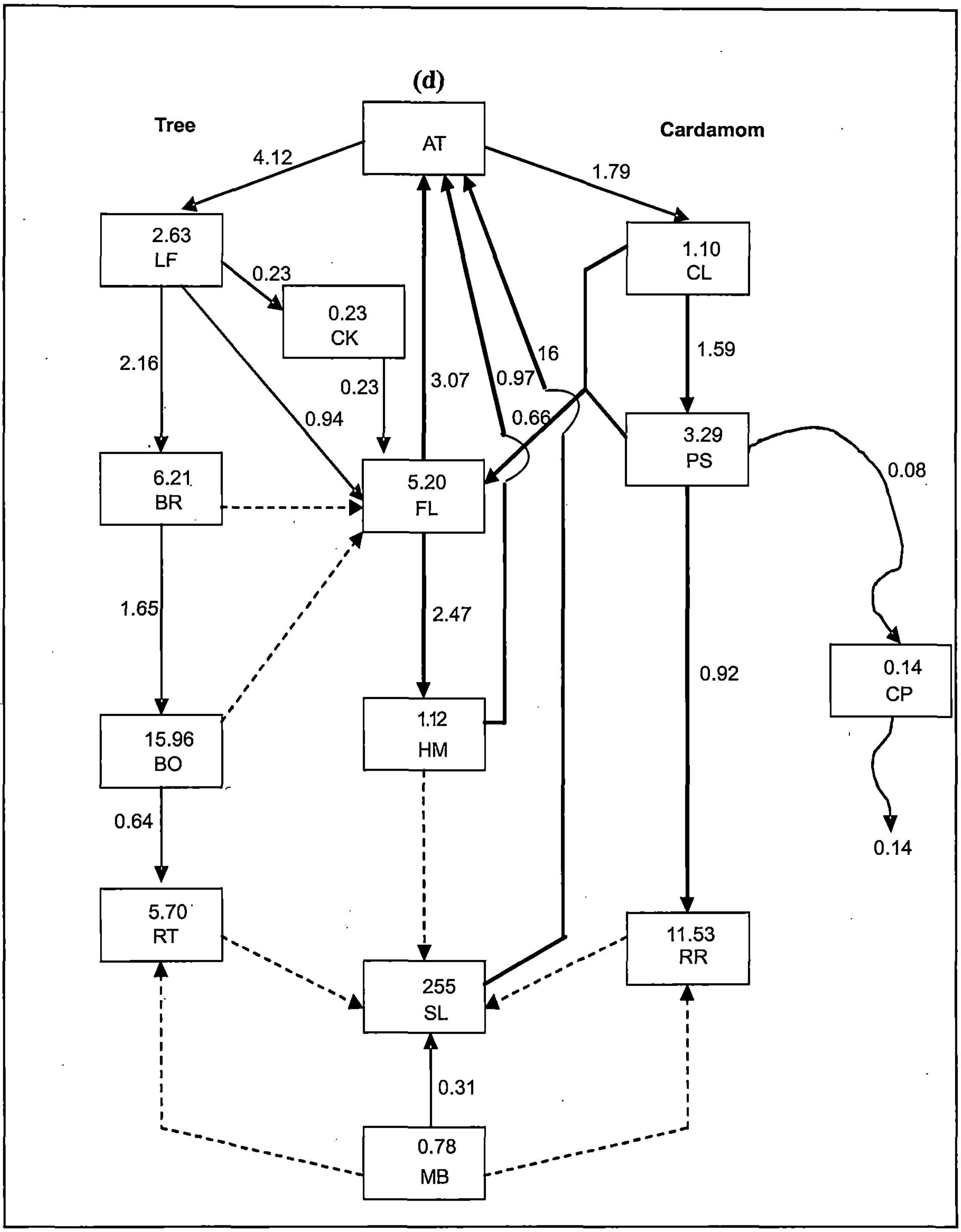

Fig. 7.4d Compartmental flow of carbon in cardamom based agroforestry system. Unit is tC ha^{-1} for compartments and tC ha^{-1} yr^{-1} for flows. Broken lines indicate the values are not measured. Curved lines indicate the loss of carbon out of the system. AT= Atmosphere, LF= Leaf, BO= Bole, BR= Branch, RT=Root, CK= Catkin, CL= Cardamom leaf, PS= Pseudostem, RR= Root/Rhizome, CP= Cardamom capsule, FL= Floor litter, HM= Humus, SL= Soil and MB= Microbial biomass.

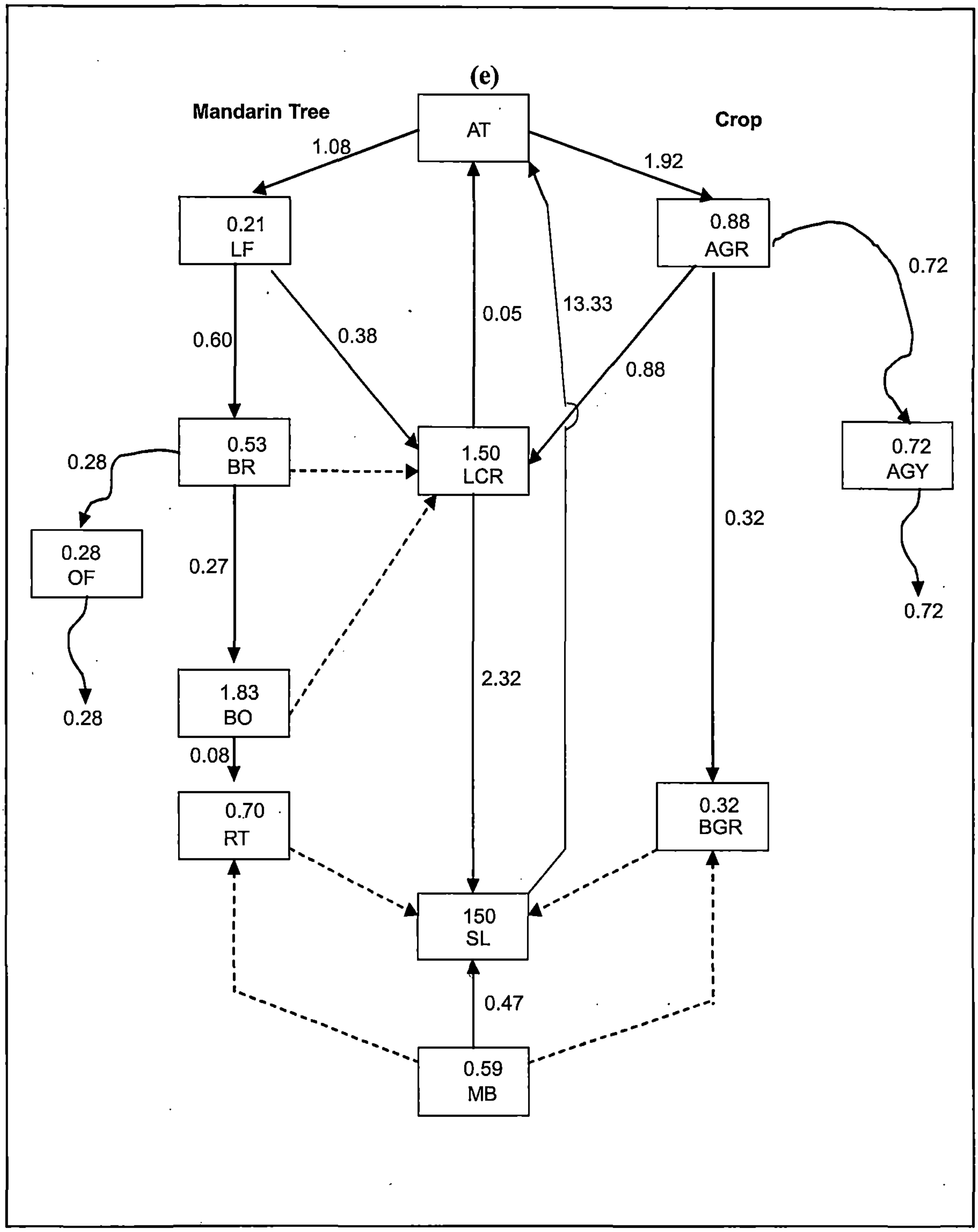

Fig. 7.4e Compartmental flow of carbon in mandarin based agroforestry system. Unit is tC ha^{-1} for compartments and tC ha^{-1} yr^{-1} for flows. Broken lines indicate the values are not measured. Curved lines indicate the loss of carbon out of the system. AT= Atmosphere, LF= Leaf, BO= Bole, BR= Branch, RT=Root, OF= Orange fruit, AGR= Aboveground residue, BGR=Belowground residue, LCR= Litter and crop residue, AGY= Agronomic yield, SL= Soil and MB= Microbial biomass.

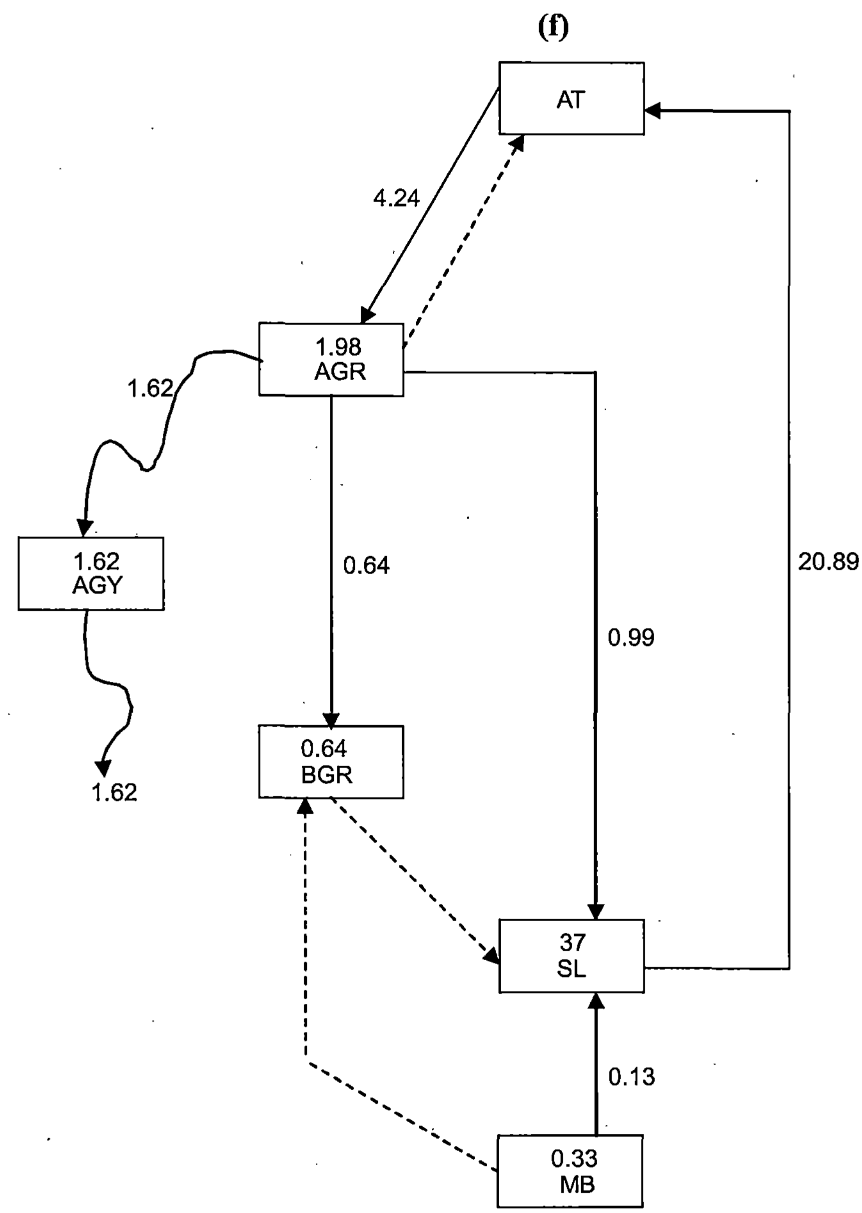

Fig. 7.4f Compartmental flow of carbon in open cropped area temperate. Unit is tC ha^{-1} for compartments and tC ha^{-1} yr^{-1} for flows. Broken lines indicate the values are not measured. Curved lines indicate the loss of carbon out of the system. AT= Atmosphere, AGR= Aboveground residue, BGR= Belowground residue, AGY= Agronomic yield, SL= Soil and MB= Microbial biomass.

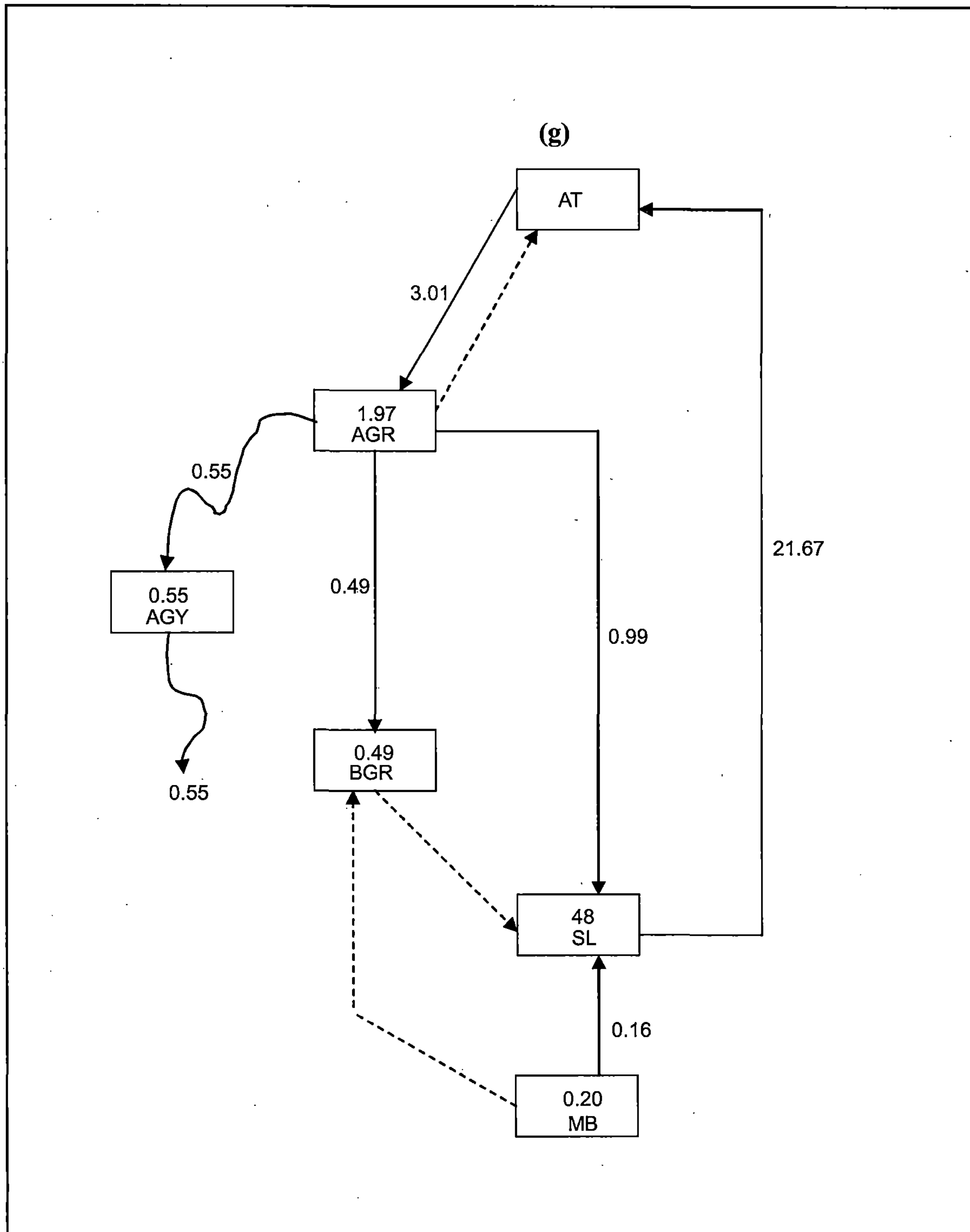

Fig. 7.4g Compartmental flow of carbon in open cropped area subtropical. Unit is tC ha^{-1} for compartments and tC ha^{-1} yr^{-1} for flows. Broken lines indicate the values are not measured. Curved lines indicate the loss of carbon out of the system. AT= Atmosphere, AGR= Aboveground residue, BGR= Belowground residue, AGY= Agronomic yield, SL= Soil and MB= Microbial biomass.

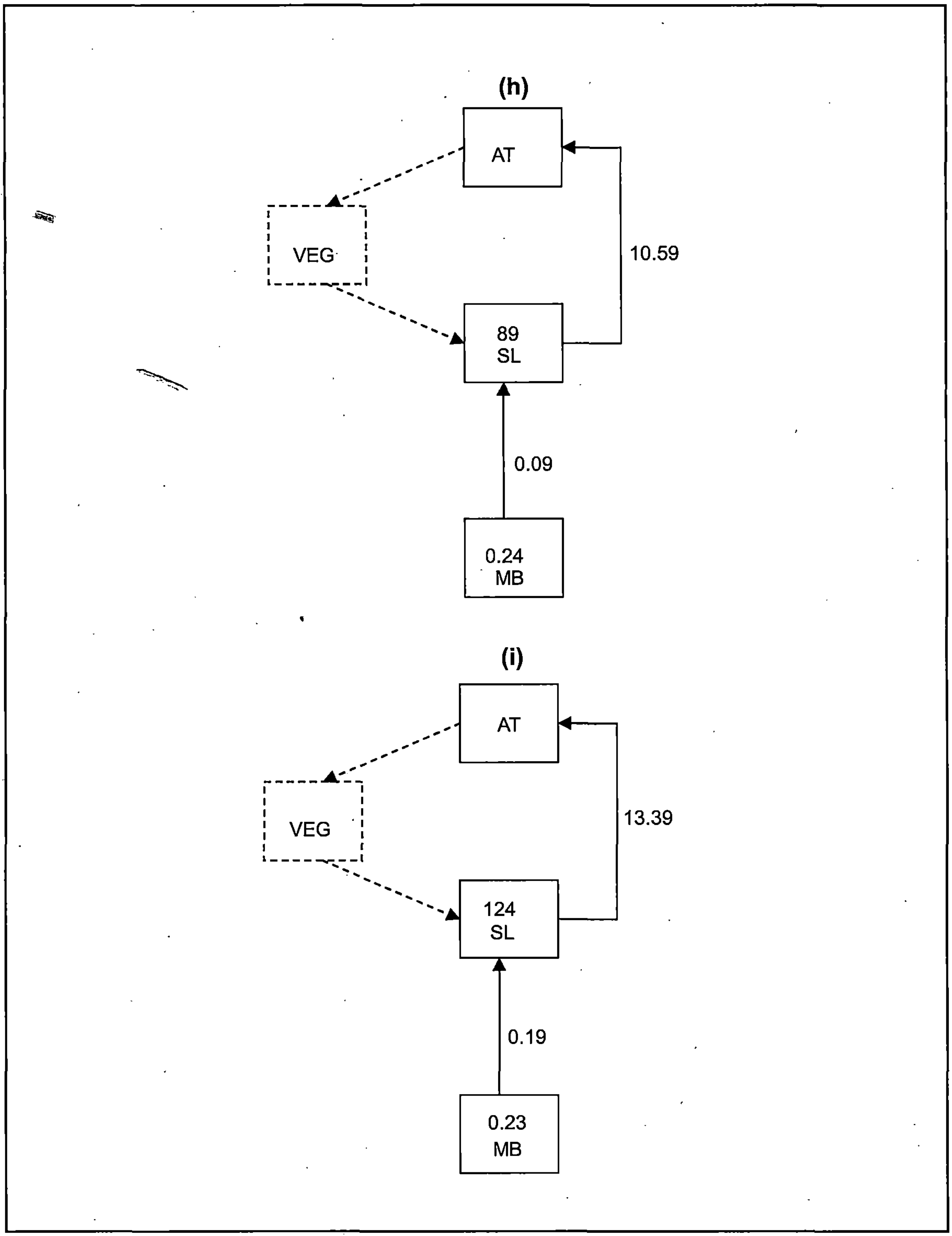

Fig. 7.4 Compartmental flow of carbon in **(h)** wasteland area temperate and **(i)** wasteland area subtropical. Unit is tC ha^{-1} for compartments and tC ha^{-1} yr^{-1} for flows. Broken lines indicate the values are not measured. AT= Atmosphere,SL= Soil, MB= Microbial biomass and VEG= Vegetation.The box in doted line indicates values were not measured.

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) $$\frac{dN_5}{dt} = 2.24\times10^{-3} N_2 + 0.430 N_3 + 0.2075 N_4 - 0.072 N_5$$

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) $$\frac{dN_5}{dt} = 2.235\times10^{-4} N_2 + 0.425 N_3 + 0.217 N_4 - 0.1437 N_5$$

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

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

(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

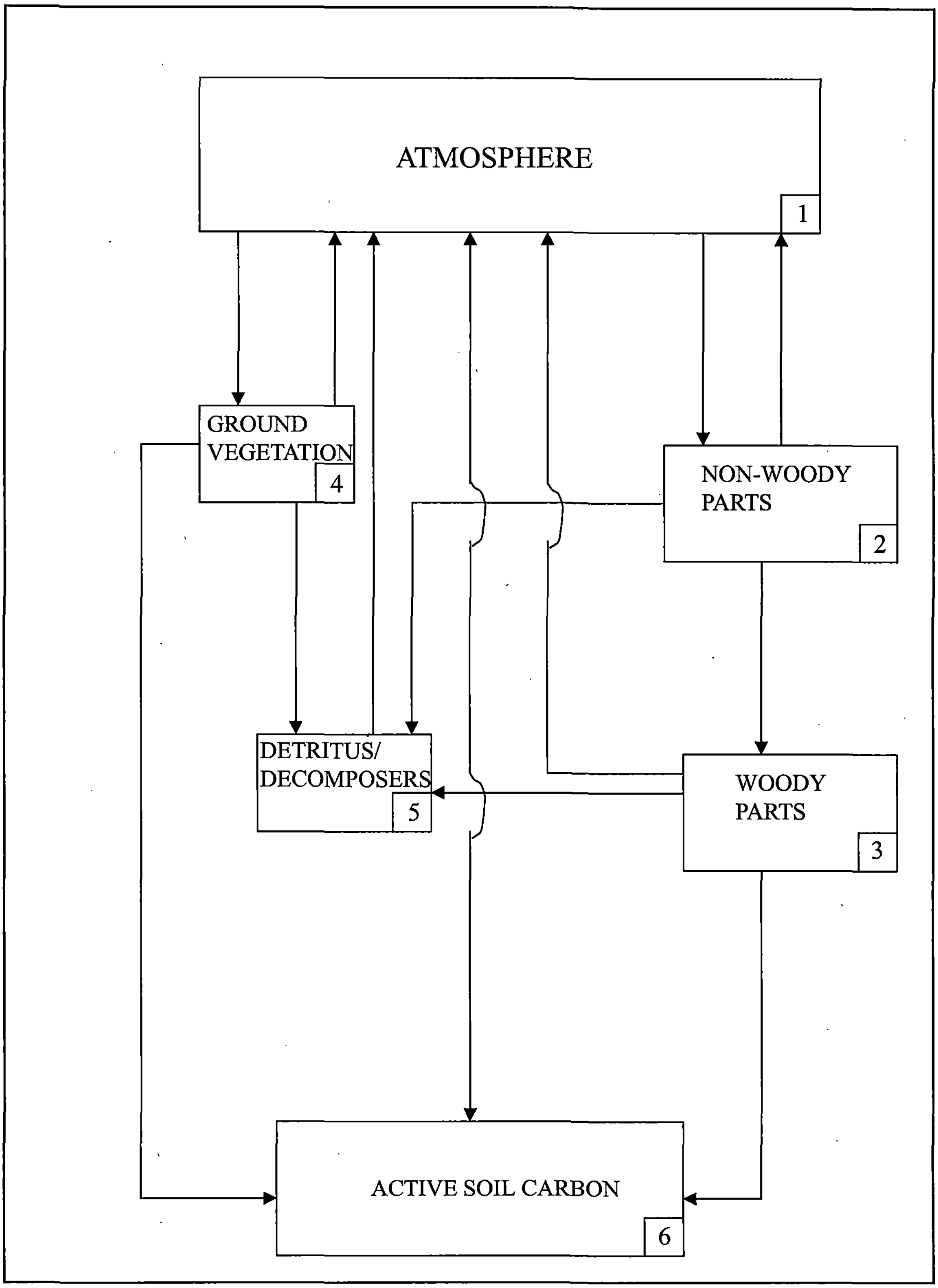

Fig. 8.1 Compartment diagram for the circulation of carbon in the Mamlay watershed. The number of each compartment, corresponding to its variable assignment in the model equations is boxed in each compartment.

SUMMARY

There has been a large scale conversion of forests to other land-uses in the past few decades from the Himalayan region. This has disrupted the hydrological cycle and a great loss of carbon is envisaged. The pressure in the forest has been tremendous due to increase in population and limitation of natural resources in subsistence hill farming systems. The land-use change from forest to agriculture has been conspicuous over the last 50 years in the state of Sikkim. The land-use transformation have observed to cause tremendous loss of carbon to atmosphere and to streams, which has both regional and global concern in terms of climate change. These carbon loss and carbon dynamics in relation to hydro-ecological linkages is a major gap area in understanding a watershed functioning. It is expected that land-use change cause enormous loss of valuable nutrients from the system. It is also envisaged that the ecological linkages are distorted in the process of land-use transformation. Such changes in the Himalayan watersheds draw attention towards understanding the mechanisms of change in the ecosystem processes. Carbon is the most appropriate indicator for studying the mechanisms of change in the ecosystem functioning in a series of land-use transformation from natural forest to plantation forest to different types of agroforestry systems and to open agriculture. Therefore, the present study on "Ecological linkages of carbon dynamics in relation to land-use/cover change in a Himalayan watershed" was undertaken in the Sikkim Himalaya with the following main objectives: (i) Dynamic monitoring and systematic analysis of land-use/land-cover change; (ii) Investigate the hydrological parameters such as overland

flow, soil erosion, carbon loss through soil erosion and sediment concentration in stream water and discharge on land-use/cover basis; (iii) Study the biogeochemical cycling of carbon i.e. carbon flux between compartments along with carbon fixation, loss through respiration, harvest flux, land cover change loss and agricultural loss and sequestration; (iv) Study the land-use sustenance taking the soil carbon level as an indicator; (v) Quantify the carbon budget in various ecological compartments and also in humus and litter components in different land-uses and (vi) Correlate the hydrological processes with ecological dimensions and ultimately develop a mathematical model to quantify ecological linkages especially in relation to carbon dynamics.

SALIENT FINDINGS:

1. Sikkim is a small state with an area of 7096 km^2 (0.22% of India's total geographical area) and a population of 540493 (0.05% of India's population), with an average density of 76 persons per km^2 in 2001. The study area (Mamlay watershed) is located in the southern part of the state which is the most populated zone (27° 10′ 8″ to 27° 14′ 16″ N and 88° 19′ 53″ to 88° 24′ 43″ E). It has an elevational range of 300-2650 m a.s.l. with a total area of 3014 ha encompassing nine revenue blocks (34 settlements) and five micro-watersheds. The population of the watershed was 4522 in 1991 with an average density of two person's ha^{-1}. There are five perennial streams (Tirikhola, Rangrangkhola, Sombareykhola, Pockcheykhola, and Chemcheykhola) which finally merge into Rinjikhola, the outlet of the watershed. The micro-watershed for each perennial stream has a mosaic distribution of land-use practices.

2. Structurally, the watershed area 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 evidences of two persistent thrusts, namely, the Sikkip and the Tendong. The major rock formations in the watershed are Damuda and Daling.

3. The climate of the area is typically monsoonic having the three main seasons: winter (November-February), spring (March-May) and rainy (June-October). Mean monthly rainfall was much higher at the temperate site 2992 mm, while it was 1295 mm at the subtropical site, mean monthly maximum temperature ranged from 18-30 °C and mean monthly minimum temperature from 11-15 °C at the study sites. Mean monthly evaporation ranged from 2-12 mm and relative humidity varied between 66-88% in both temperate and subtropical belts.

4. Soil texture of different forest and agroforestry types are either sandy loam, silty loam, or clay loam varying at different physiographic divisions and land-use/cover types of the watershed. The bulk density of the soil horizon (0-100 cm) varied distinctly within land-use/cover and soil depths. Most of the soils were acidic (pH ranged from 5.02 to 6.43) across the study sites. Average soil moisture level ranged from 17% in wasteland area subtropical to 34% in temperate natural forest dense. All nutrients were higher in temperate natural forest dense and lower in subtropical wasteland.

5. The land-use/cover pattern in the watershed as a whole showed about 69% and 49% of the total area under forest cover in 1988 and 2001, respectively. Micro-watershed wise, Pockcheykhola and Sombareykhola were dominated by temperate natural forest dense and open, whereas Tirikhola by subtropical natural forest open in both the assessment years. Spatial distribution pattern reveals that the Pockcheykhola, Sombareykhola and Chemcheykhola micro-watersheds were dominated by forest at the ridge tops, agroforestry in

the middle and agriculture in the valley areas. The agroforestry practices in the watershed are traditional and promising for higher economic returns. About 4% area in 1988 and 2001 came under agroforestry practices. Sombareykhola micro-watershed is dominated (3%) by large cardamom based agroforestry system, whereas Tirikhola and Rangrangkhola by mandarin based agroforestry system. About 14.39% and 30.53% area was under intensive agricultural practices in 1988 and 2001, respectively. Micro-watershed wise, the highest agricultural coverage was recorded in Chemcheykhola (4.17%), followed by Tirikhola (3.96%) and Pockcheykhola (3.11%) of the total watershed in 1988, while in 2001, the highest coverage was observed in Tirikhola (13.11%), followed by Chemcheykhola (8.58%) and Rangrangkhola (3.69%). The wasteland covers about 11 and 15% of the total area of the watershed in 1988 and 2001, respectively. About 9 ha area was under landslides in 2001, whereas no landslides were observed in 1988. Micro-watershed wise, Chemcheykhola, Pockcheykhola and Sombareykhola were dominated by wasteland area temperate, while Tirikhola by wasteland area subtropical in both the assessment years.

6. The land-use/cover change detections were generated by the multi-date satellite data. Monitoring of land-use/cover reflected that changes were greater in extent over the span of 13 years in the land under different categories. A positive change was recorded in agricultural usage at the cost of other land-use practices. The open cropped area subtropical increased by more than 166% for the thirteen years period, while wasteland increased by about 117%. The total forest covers comprising dense mixed, open mixed of both the belts decreased by 28% during 1988-2001. Micro-watershed wise, major land-use/cover

changes were observed in Tirikhola, Chemcheykhola and Pockcheykhola. Ground truth verification supports the finding that the depletion of closed forest or its conversion into other categories is the result of maximum anthropogenic pressure on the limited forest resources.

7. Mean basal tree-trunk cover among different forest and agroforestry types ranged from 2 m^2 ha^{-1} in mandarin based agroforestry to 50 m^2 ha^{-1} in temperate natural forest dense. The total biomass (aboveground + belowground) for different types of forests and agroforestry systems were similar to that of basal cover. The total biomass varied from 12 t ha^{-1} in mandarin based agroforestry system to 448 t ha^{-1} in temperate natural forest dense. The total biomass of large cardamom based agroforestry was 103 t ha^{-1}. The total biomass was 22 times higher in temperate natural forest dense than open cropped area. Of the total biomass, over 95% is contributed by aboveground component in forest ecosystems, upto 98% in mandarin based agroforestry and 52% in cardamom based agroforestry systems. The highest (16.93 t ha^{-1} yr^{-1}) net primary productivity was estimated in temperate natural forest dense and lowest (6.93 t ha^{-1} yr^{-1}) in mandarin based agroforestry system.

8. The floor litter biomass was measured in different forests and agroforestry systems to quantify the total carbon pool. The floor litter biomass was recorded maximum (13 t ha^{-1}) in temperate natural forest dense and the mandarin based agroforestry system had the minimum (3.8 t ha^{-1}). The annual litter production was recorded highest in temperate natural forest dense (4.57 t ha^{-1} yr^{-1}) and lowest in subtropical natural forest open (2.82 t ha^{-1} yr^{-1}). The humus content followed the similar trend as floor litter biomass with highest value

recorded in temperate natural forest dense (6.7 t ha^{-1}) and the lowest in subtropical natural forest open (3.3 t ha^{-1}).

9. The study watershed is a part of the Rangit River, the second largest river of the Sikkim Himalaya. The drainage network of the watershed is dendritic type and the texture is fine in the upper part of the watershed. Outlet of the watershed is the Rinjikhola that feeds the river Rangit, a main tributary of Tista River. The total length of first order stream is 60.60 km, second order stream 12.15 km and third order 9.85 km. The watershed has a total area of 30.14 km^2 and the total stream length is 82.6 km. The drainage density of the watershed is very high having a value of 2.74. Total numbers of channels are 80, 18 and 7 in the first order, second order and third order streams, respectively. The bifurcation ratio (ratio between the number of streams of a particular order and that of the streams of the next higher order) of the first order stream was 4.44 and the second order stream 1.14.

10. All the streams attain significant sizes during the rainy season. The highest discharge of 4143 ls^{-1} was recorded in the rainy season in 1999 followed by 4137 ls^{-1} in 2000 and lowest of 850 ls^{-1} and 840 ls^{-1} in summer season, in the respective years in the Rinjikhola, the outlet of the watershed. For the different streams, the discharge was in the order Pockcheykhola> Sombareykhola> Chemcheykhola> Tirikhola> Rangrangkhola and the significant variation was observed only in rainy season. The discharge in various streams showed high seasonality and direct relationship with precipitation.

11. Sediment concentration varied distinctly with seasons in different streams and the outlet of the watershed. The sediment concentration during 1999 and 2000 ranged from 9-61 mg l^{-1} in winter, 8-59 mg l^{-1}

in summer and 14-399 mg l^{-1} in the rainy season. The highest sediment concentration in the rainy season was mainly because of high precipitation and extensive agriculture practices followed in this season. Seasonal and yearly soil loss value was recorded in stream waters of the micro-watersheds and total watershed for the two year period 1999-2000 and it ranged from 0.001 to 7.48 t ha^{-1} in 1999 and from 0.001 to 6.62 t ha^{-1} in 2000. The soil loss rate from the total watershed ranged from 6 to 7 t ha^{-1} yr^{-1} during the two years of study. The total soil loss from the watershed with an area of 30.14 km^2 is significant, ranging from 18295 t yr^{-1} in 1999 to 21953 t yr^{-1} in 2000.

12. Organic carbon loss from soil sediment in the stream water of the micro-watersheds and total watershed were analyzed. Organic carbon loss ranged from 0.014 to 136 t yr^{-1} in the micro-watersheds, while the annual loss from the outlet of the watershed was 833 t yr^{-1}. Soil erosion, organic carbon and soluble carbon loss as estimated from stream water show high values. The soluble carbon loss ranged between 0.96 and 814 t yr^{-1} for the micro-watersheds and was about 2025 t yr^{-1} at the watershed outlet.

13. Overland flow (percentage of rainfall during rainy season) was estimated to be maximum in open cropped area subtropical (10.86% of precipitation) and minimum in temperate natural forest dense (2.80%). Soil loss was greatest in open cropped area subtropical (525 kg ha^{-1}), followed by open cropped area temperate (480 kg ha^{-1}), mandarin based agroforestry (31 kg ha^{-1}), sub-tropical natural forest open (27 kg ha^{-1}), wasteland area subtropical (25 kg ha^{-1}), wasteland area temperate (24 kg ha^{-1}), large cardamom based agroforestry (18 kg ha^{-1}) and lowest in temperate natural forest dense (16 kg ha^{-1}).

14. Organic carbon concentration in parent soil and eroded soil was estimated during the rainy season in different sub-divided land-uses. Concentration of total organic carbon was higher in eroded soil than the parent soil. Total organic carbon content in the parent soil upto 30 cm depth was highest in temperate natural forest dense and very little variation was recorded in other land-use/covers. Largest loss of total organic carbon through soil erosion was recorded in wasteland area of the temperate belt and smallest from temperate natural forest dense.

15. Partitioning of incident precipitation into various pathways in temperate natural forest dense, temperate natural forest open, sub-tropical natural forest open, large cardamom based agroforestry and mandarin based agroforestry systems of the watershed were analyzed. In temperate natural forest dense, precipitation partitioned into 77.86% throughfall, 11.20% stemflow and 9.20% intercepted by canopy. About 42% of the water was collected as leachate and the floor interception was 44.60%. In the case of temperate natural forest open, 48.66% canopy interception was recorded. In the large cardamom based agroforestry system, throughfall was recorded 53.40% of total precipitation, canopy interception was 38% and stemflow was just 5%. In the sub-tropical natural forest open, throughfall was about 45%, canopy interception was 44% and the stemflow was negligible that amounted 3%. The floor leachate was 69% and the remaining 31% was recorded to be the floor interception. Stemflow in the mandarin agroforestry system was higher (5%) than that recorded from sub-tropical natural forest open. The total amount of water on the floor partitioned as 72% as leachate and remaining as floor interception in the mandarin based agroforestry system. Higher throughfall in the temperate natural forest dense than the temperate natural forest open

was because of broad leaf nature and more canopy coverage of natural forest species than the coniferous species. Our data on canopy interception corroborate that broad-leaved forest intercepts less rainfall than do the coniferous species.

16. Soluble carbon concentration in throughfall, stemflow, and floor leachate were estimated in different forest and agroforestry system stands in sub-tropical and temperate belts of the watershed. The soluble carbon concentration in throughfall was highest in large cardamom based agroforestry system. In stemflow water also, soluble carbon was recorded highest in cardamom based agroforestry system, while soluble carbon in floor leachate was highest in sub-tropical natural forest open.

17. Per cent carbon in woody biomass of temperate natural forest dense and open, subtropical natural forest open, cardamom based agroforestry system and mandarin based agroforestry system were 42.53, 47.79, 45.50 and 45.95, respectively. Similarly in leaf, it was 47.33, 50.24, 47.07 and 44.93 and in root, 45.01, 46.63, 45.50 and 44.90, respectively. In crop residue the total carbon was 40.97%. The total vegetation C varied significantly with land-use ($P<0.0001$). Per cent carbon in floor litter ranged from 35 to 44 and in humus 18.91 to 21.25%. Total carbon storage in vegetation ranged from 5.47 to 191 tC ha^{-1}.

18. In the forested and agroforestry stands, tree basal cover was linearly related ($r^2=0.73$, $P<0.0001$) with long term carbon and total vegetation carbon ($r^2=0.85$, $P<0.0001$), while short-term C did not show any relationship with basal area. Standing biomass was also linearly related ($r^2=0.99$, $P<0.0001$) with stand total carbon. The total carbon content in floor litter ranged from 1.50 to 5.20 tC ha^{-1}. Floor litter

biomass and floor litter carbon was linearly related (r^2=0.93, P<0.0001). The carbon content in humus ranged from 0.63 to 1.41 tC ha^{-1}. In forested and agroforestry area, humus biomass was linearly related (r^2=0.98, P<0.0001) with humus C storage.

19. Effect of change in land-use/covers on soil total carbon (TC) was studied upto 1m depth. The TC values for the soils ranged from 1.75 to 6.16% in the surface layer (0-15cm), slightly decreased to 0.22-4.01% in 15-60cm and then drastically decreased to 0.08-2.05% at 1 m depth. The highest value was recorded in temperate natural forest dense and lowest in wasteland area sub-tropical. Total carbon in soil varied significantly with land use and depth (P<0.0001). Total carbon content upto 100 cm depth in different land-use/covers ranged from 37 t ha^{-1} in open cropped area temperate to 472 t ha^{-1} in temperate natural forest dense. Along the different land-uses the storage of total C in the surface layer (0-15 cm) ranged between 13 tC ha^{-1} and 121 tC ha^{-1}. The vertical distribution of TC was deepest in temperate natural forest dense and shallowest in open cropped area sub-tropical.

20. Organic carbon distribution was also higher (0.96 to 4.22%) in surface layer (0-15 cm), slightly decreased (0.30 to 2.55%) in 15-60 cm and drastically decreased (0.067 to 1.16%) at 90-100 cm depth in all the land-use/covers. Soil organic carbon storage upto 1m depth ranged from 19 t ha^{-1} in open cropped area temperate to 292 t ha^{-1} in temperate natural forest dense.

21. Across the land-use/covers, mean annual microbial C ranged from 219 to 864 μg g^{-1}. The highest value of microbial biomass carbon was found in the temperate natural forest dense soil and lowest in the wasteland area subtropical soil. The microbial biomass C and organic C were positively related. The seasonal pattern of soil microbial C was

similar in all land-use/covers, the values being highest in the winter and lowest in the rainy season. Seasonality plays an important role in microbial C turnover because there is a reciprocal relationship between the plant growth rates and microbial biomass. Microbial biomass is directly related to the plant biomass and is very sensitive to land-use/cover changes as it is found to decrease remarkably after transformation.

22. Area-weighted standing carbon values for vegetation, litter, humus and soil are calculated on land-use/cover basis. Total vegetation C in forested land-use ranged between 30.60 to 84.60×10^3 tC. In agroforestry, this value ranged from 0.01 to 4.91×10^3 tC. The overall range of soil C was 45.60 to 215×10^3 tC in forested land area, between 2.61 to 29×10^3 tC in agroforestry systems, between 8.5 to 40×10^3 tC in wastelands and between 15 to 24×10^3 tC in open cropped areas of subtropical and temperate belts. Total stand carbon in the studied watershed area (3014 ha) was 624×10^3 tC, total carbon stored in the soil to a depth of 1 m was 456×10^3 tC. Total vegetation C was 161×10^3 tC, litter C 5.33×10^3 tC and humus C 1.44×10^3 tC in the whole watershed.

23. The net carbon input in different land-use/covers ranged between 3 to 7.43 tC ha^{-1} yr^{-1}. Total vegetation carbon accretion was significantly greater in the temperate natural forest dense than other land-uses. Above-ground net C input varied significantly between the land-use. Above-ground net C accretion was three-fold greater for the temperate natural forest dense than the open cropped area. Below-ground net C input also varied significantly between the land-use. It was significantly higher in cardamom based agroforestry system than other stands. The annual litter C input in different land-use/covers varied

from 1.13 $tC\ ha^{-1}\ yr^{-1}$ to 1.83 $tC\ ha^{-1}\ yr^{-1}$. Carbon entry into humus through litter decomposition varied significantly between the land-use.

24. The turnover time of carbon ranged from 1.82 years in mandarin based agroforestry system to 25.74 years in temperate natural forest dense. Turnover rate of C ranged from 0.039 in temperate natural forest dense to 0.548 in mandarin based agroforestry system. The turnover time of carbon on the stand floor litter ranged from 1.19 years in mandarin based agroforstry system to 2.85 years in cardamom based agroforestry system, while turnover rate ranged from 0.351 in cardamom based to 0.841 in mandarin based agroforestry system.

25. The total annual mean C flux from litter respiration ranged between 0.05 $tC\ ha^{-1}\ yr^{-1}$ to 3.78 $tC\ ha^{-1}\ yr^{-1}$ in different land-use/covers. Annual estimates of soil surface C flux in different land-uses were 12.11 $tC\ ha^{-1}\ yr^{-1}$ (lowest) and 21.67 $t\ C\ ha^{-1}\ yr^{-1}$ (highest) for the wasteland area temperate and open cropped area subtropical, respectively. Estimated turnover time of soil carbon based on mean carbon pool and mean soil respiration ranged from about 47 years in the temperate natural forest dense to 3 years in open cropped area temperate. The watershed pool of soil carbon has a mean residence time of about 14 years. Annual flux of carbon through microbial biomass ranged from 96 $kg\ C\ ha^{-1}\ yr^{-1}$ to 679 $kg\ C\ ha^{-1}\ yr^{-1}$ in wasteland temperate and temperate natural forest dense respectively.

26. The harvest flux of carbon is relatively higher (2.08 $tC\ ha^{-1}\ yr^{-1}$) in subtropical natural forest open than temperate natural forest dense (1.34 $tC\ ha^{-1}\ yr^{-1}$) and temperate natural forest open (1.17 $tC\ ha^{-1}\ yr^{-1}$). The direct emissions associated with commercial harvest are greater from subtropical natural forest open because of high level of logging.

27. The land conversion during the past 13 years (1988-2001) resulted into a net release of 305×10^3 t carbon to the atmosphere from the watershed. Reduction in the biomass of the forest as a result of conversion was responsible for a net loss of 119×10^3 t vegetation carbon and 183×10^3 t soil carbon. This translates into release of 7.78 tC ha^{-1} yr^{-1} from the entire watershed 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 state can be assessed. Sikkim state occupy 284779 ha forest land, land-use change (harvest and forest clearing) release 22.16×10^5 tC annually. If the same result is applicable to the entire Indian Himalayan forest area (6692000 ha), the total release of carbon would be 520.6×10^5 tC yr^{-1}.

28. A mathematical model for the circulation of carbon in the watershed is proposed. A five-compartment representation is developed which corresponds to the functional components studied. The model is analyzed in terms of response to a unit impulse, thereby displaying a transient time distribution. The simulated values showed that there is reasonably good agreement between observed and predicted values except for few land-use/covers due to unaccounted factors.

29. Top soil management, soil water conservation and management, soil fertility regulation and erosion control are all important aspects of carbon sequestration in soil. Basically, land management systems should be aimed to reduce the carbon emissions. Carbon sequestration in the biomass and soils of terrestrial ecosystems vary with the land-use/cover types. On forest lands, the focus should be on below-ground carbon (in stable pools) and on long term management and utilization of standing stocks, under story, ground cover and litter. For

agricultural lands, that are mainly cropland, the focus should be on increasing organic carbon in the stable SOC pools. In the case of degraded lands, restoration can offer significant benefits in terms of carbon sequestration potential, both in the soil and above-ground.

30. In conclusion, efforts should be made to allow carbon sequestration under the Kyoto protocol. Irrespective of scale and geographic location, a key objective should be to identify and implement best available management practices to improve soil quality, thereby ensuring food productivity and sustainability, while simultaneously reducing carbon dioxide concentration in the atmosphere. Before implementing the "best practices" due attention must be paid to any possible adverse environmental and socio-economic effect they may have.■

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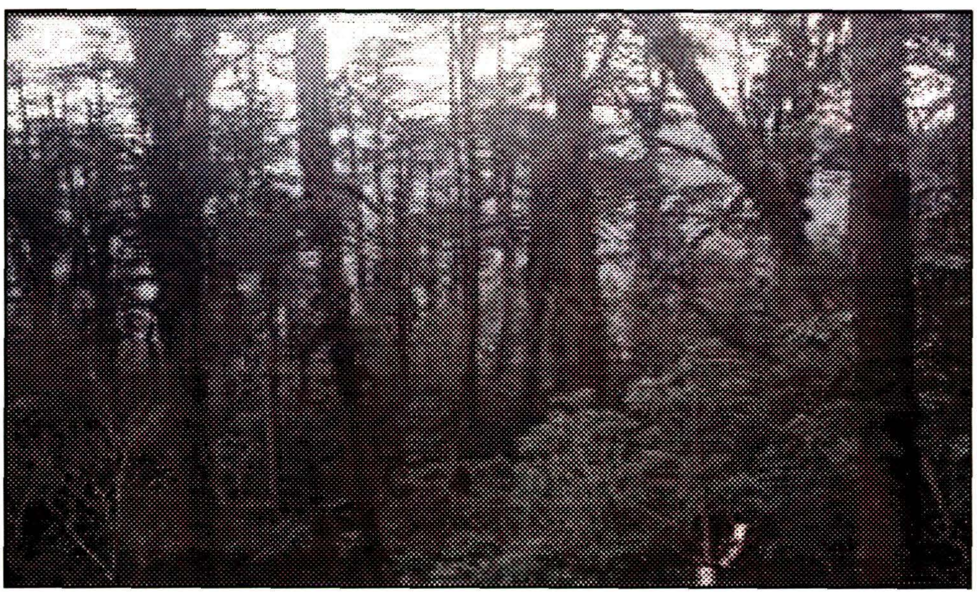
PHOTOPLATES

Plate - I

(a) A panoramic view of the Temperate Natural Forest (close canopy)



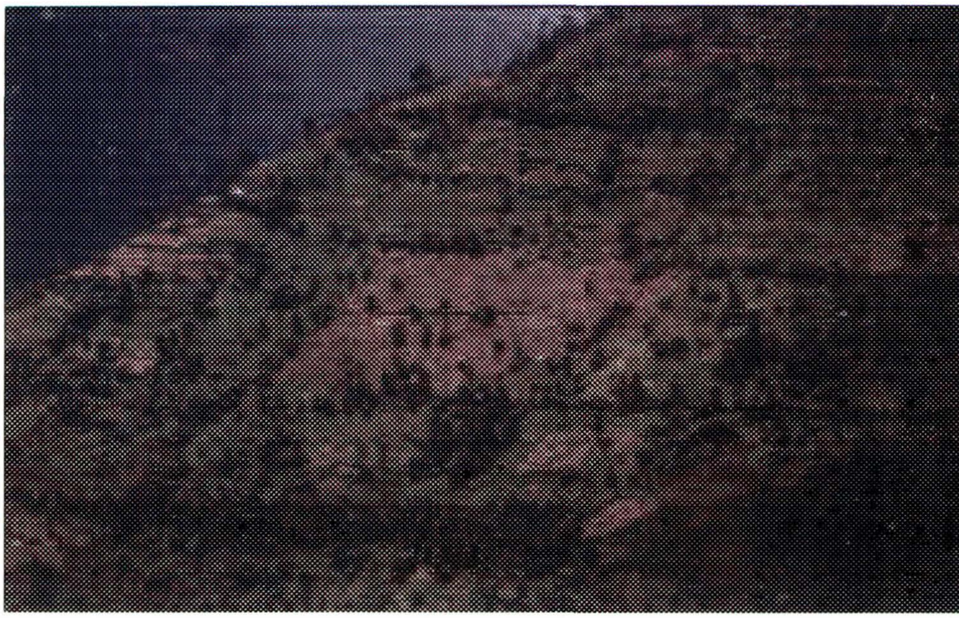
(b) An inside view of Temperate Natural Forest (open canopy)

Plate - II

(a) Large cardamom: an age old cash crop based agroforestry system

(b) Mandarin agroforestry system with maize intercropping

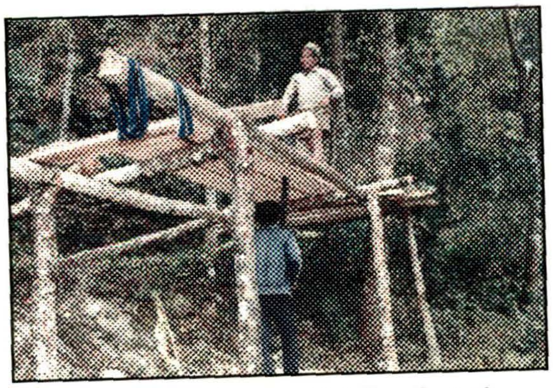
Plate - III



(a) A view of the rainfed agriculture system in the watershed

(b) Maize cultivation: the major cereal of the watershed

Plate - IV



(a) Timber sawing amidst the forest

(b) New house construction using timber

(c) Fuelwood collection from the forest

(d) Fodder collection from the forest

(a) Erosion plot in maize field

(a) Throughfall and stem flow measurements

(a) Soil surface CO_2 flux measurement by CO_2 infrared gas analyzer