ECOLOGICAL EVALUATION OF TRADITIONAL AGROECOSYSTEMS IN THE CENTRAL HIMALAYA

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CERTIFICATE

The research work embodied in this dissertation entitled **"Ecological evaluation of traditional agroecosystems in the central Himalaya"** has been carried out at the **School of Environmental Sciences, Jawaharlal Nehru University, New Delhi-110067**. This work is original and has not been submitted in part or in full for any other degree or diploma of any University.

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INTRODUCTION

Atmospheric CO_2 levels

It is now well established that atmospheric CO_2 levels have been rising. The most obvious method to monitor CO_2 level is to directly measure the atmospheric CO_2 concentration over the time period of interest. Keeling and his associates have been measuring CO_2 concentration in dry air samples using a nondispersive infrared gas analyzer at Mauna Loa in Hawaii from 1959 onwards. Their dataset indicates that CO_2 levels have risen from 315.98 parts per million by volume (ppmv) in 1959 to 373.1 ppm in 2002 (Keeling and Whorf, 2004; Keeling *et al.,* 1995). This indicates a rise of 18% in the CO_2 concentration. However, for ascertaining precisely the climate- atmospheric chemistry relationship data is needed over longer time periods.

This long term data is available from ice cores. One of the most famous ice core data is from Vostok, Antarctica (Petit *et al.*, 1999). This data gives values for CO_2 concentration over the past 420000 years. The CO_2 is detected from the air bubbles which get trapped when snow fall occurs. The disadvantage with Vostok Ice Core is that temporal resolution is relatively low.

On the other hand high resolution ice core date is available from Law Dome, Antarctica (Etheridge *et al.*, 1996) and Taylor Dome, Antarctica (Indermuhle *et al.*, 1999). These datasets suffer from the time periods which they cover. While the Law Dome covers 1000 years, the Taylor Dome ice core is for 11000 years.

The importance of the Vostok ice core data is that it puts the present CO_2 rise in perspective with the earth's past climatic changes. It shows that the present CO_2 rise is anomalous and does not have a counterpart in the last four glaciation- delglaciation cycles. The finer picture provided by the Taylor Dome ice core shows the point in time of the beginning of this anomalous rise in CO_2 concentration. Surprisingly, this data set shows that anomalous rise in CO_2 level began before 8000 years and not 1800 A.D., the year most often quoted in climate change studies (Ruddiman, 2003).

Carbon dioxide and climate

The CO_2 concentration in atmosphere is important because it is a radiative gas. CO_2 captures the long wave radiation and traps energy which would otherwise leave earth. Effect of CO_2 can be estimated by comparing projected temperature of earth with and without CO_2 and water vapour (the main greenhouse gasses). In the absence of CO_2, earth's temperature would be around - 18°C instead of the present 15°C.

It follows that if carbon dioxide levels rise, then earth's temperature should rise as well. It has been found that there has been a rise of 0.3 to 0.6°C in earth's temperature during the past 100 years. Carbon dioxide is estimated to account for 61% of this rise, methane for 17%, nitrous oxide for 4% and chlorofluorocarbons for 12%. Further, it is predicted that if the present trends continue, earth's temperature would increase by about 4.5°C by 2100 (Cubasch and Meehl, 2001).

Climate models

Climate models simulate the climate system comprising the atmosphere, the hydrosphere, the cryosphere, the biosphere and the lithosphere. Due to unequal distribution of heat energy, water and air currents are set into motion which tend to equalize temperature. Changes in energy input or output (forcing) can cause change in the climate. The climate does not achieve instantaneous stability. It will achieve a new equilibrium after a transitionary phase. In most of the models which have been used in climate change predictions, the lithosphere has not been included as it responds over a timescale of a million years.

Analogue climate models use precipitation and temperature data derived from geological sources to give the scenario of the past climate. These models are then used to predict the outcomes of man-made changes on the climate system. These models have been criticized as the forcings of the past may not operate in the future, data from small area is being used to predict climates over continental scales, and the dating of the geological data is not precise.

Atmospheric general circulation models (AGCMs) have been widely used to predict the changes in temperature. These models need the following variables at one point of time: atmospheric pressure, wind velocity, temperature, and humidity over a three dimensional grid laid onto the earth's surface. It has been criticized that it tends to overestimate the sensitivity of the climate to carbon dioxide change and a poor database of these variables, more so in the tropics (Houghton, 2001).

Climate change and its impacts

Temperature

As already stated, in the past 100 years the temperature has risen by 0.6°C. This rise has been more in the minimum temperatures than in the maximums, resulting in a smaller diurnal temperature range (Easterling *et al.*, 1997). Over the same time span, annual precipitation has risen in the mid and high latitude regions but has decreased in the tropics and subtropics (India being an exception) (Cubasch and Meehl, 2001). The number of frost free days have also risen which can be explained from the trend of increasing minimum temperatures (Easterling *et. al,* 1997).

Precipitation

The General Circulation Models predict that warming will increase the speed of the hydrological cycle. Consistent with this, the number of days with heavy precipitation has risen over the 20th century (Zhai *et al.*, 1999). Also the change in precipitation is centred more towards the days of heavy or extreme precipitation (Groisman *et al.*, 1999).

Droughts and floods

The spatial extent of regions experiencing droughts or excessive wetness has increased (Dai *et al.*, 1998). It has also been seen that the interannual variability in the Indian monsoons has increased such that the probability of droughts or floods has also increased (Kitoh *et al.*, 1997). Models have predicted future climate for the Pacific region which is more akin to those of the El Nino years (Meehl *et al.*, 2000). This translates into lesser precipitation in

Australasia. Mirza (1997) reported that the inflow to the river Ganga will be in the rage of 27-116% of present inflow in $2XCO_2$ scenario.

Snow and glaciers

Martin and Durand (1998) worked out a snow model according to which in the Southern parts of French Alps both the amount of snow and the duration of its stay will be significantly reduced. Broadly, with every 1°C rise in temperature, the snowline will rise by about 150 m in the mountains.

It has been found that glaciers in European Alps have lost about 30 – 40% of their areal extent and 50% of their volume since 1850 (Haeberli and Beniston, 1998). Similar reports of glacial retreats are also available from Central Asia (Fitzharris, 1996), Mt Kenya and Kilimanjaro (Hastenrath and Greischar, 1997).

Sea level rise

A large number of studies have shown that there has been a rise in the mean sea level at the rate of 1 mm per year over the past 100 years (Peltier and Tushingham, 1990; Trupin and Whar, 1990). This has been attributed to: thermal expansion of oceans, and melting of glaciers and small ice caps on land and of the Greenland ice sheet and the Antarctic ice sheet. However, the Antarctic ice sheet has been found to be expanding since last few years (Warrick and

Oerlemans, 1990). Studies indicate that by 2030 sea level may rise by 10-30 cm (Oerlemans, 1989; Raper *et al.*, 1990) and this would lead to a doubling of the population at risk due to storm surges (i.e., from 45 million to 90 million).

Diseases

As the climatic conditions will become more suitable for the vectors, diseases are expected to spread in some of the present non-disease areas in northern latitudes and higher altitudes. For example, both in tropical Africa and Asia malaria is unknown at altitudes above 1300-1500 m where Anopheles mosquitoes are not able to survive (Craig *et al.*, 1999). A 1°C elevation in temperatures would result in a higher incidence of malaria at elevation 1300 m and above (IPCC, 1998; Loevinsohn, 1994). During the El Nino years, characterised by a higher temperature and lower precipitation a rise in malarial incidence has been noted in Colombia (Poveda *et al.*, 2001).

Ecosystem

A change in climate is bound to have implications for the living systems. An elevation in atmospheric CO_2 is likely to increase photosynthesis, reduce photorespiration (Gifford *et al.*, 1985), increase in biomass accumulation (more response being shown by C_3 plants), increase in root to shoot ratios (Curtis *et al.*, 1990), reduction in nutrient quality of the plant (Curtis *et al.*, 1990), reduced effect of environmental stress (Warrick *et al.*, 1986), increased growing season due to delayed senescence (Mooney *et al.*, 1990), competitive edge for C_3 plants over C_4 plants (Bazzaz and Carlson, 1984), increased herhivory (Fajer *et al.*, 1989), increased symbiotic association with nitrogen fixing microorganisms and mycorrhizae (Hardy and Havelka, 1975; O'Neill *et al.*, 1987) and reduction in decomposition rates of litter.

Also a shift or migration of species to higher latitudes and altitudes has been predicted with rising temperatures. For instance, *Picea sitchensis* initiates bud burst only after it has been exposed to temperature less then 5°C for a period of at least 140 days (Cannell and Smith, 1986). In a warmer climate this species may need to migrate to higher altitudes. However, it must be remembered that mountain tops are smaller than the bases and thus the population size is reduced making it more prone to genetic and environmental stresses (Bortenschlager, 1993).

Carbon cycle – sources and sinks

Increase in the CO_2 concentration of the atmosphere may be explained on basis of the carbon cycle which consists of stocks (pools) and fluxes (movement/change). The largest amount of carbon on earth is stored in the oceans: ~ 39000 Gt ($1Gt=10^{15}g$).

The second largest pool of C is fossil C with just 6000 Gt. The C stocks in all the vegetation and soils on earth is only 2500 Gt (2.4 times smaller than the fossil carbon stock). The smallest stock is the atmosphere with only 760 Gt of carbon (Ciais *et al.*, 2000).

During 1990's, 6.3 ± 0.4 Gt C was emitted annually due to fossil fuel combustion and cement manufacture. Of this emission, 1.7 ± 0.5 Gt was being absorbed by oceans and 1.4 ± 0.7 by terrestrial vegetation. Thus, an amount of 3.2 ± 0.1 Gt C was added to the atmosphere annually, leading to the rise in atmospheric CO_2 levels (Schimel *et al.*, 2001). This may be presented in the form of a equation:

Atmosphere increase	=	fossil fuel source	–	oceamic sink	–	terrestrial sink
3.2 (± 0.1)	=	6.3 (± 0.4)	-	1.7 (± 0.5)	-	1.4 (± 0.7)

(adapted from Houghton, 2001)

This equation shows that the terrestrial ecosystems acted as a net sink of 1.4 Gt C yr-^{1}. If one adds up the emission estimates from terrestrial system (due to land use change: 0.6 to 2.54 Gt C yr^{-1}), the gross sink capacity of the terrestrial ecosystem is likely in the range of 2 to 4 Gt C yr^{-1}. This is the residual terrestrial sink (Schimel *et al.*, 2001).

Atmospheric = fossil fuel + net source – oceanic – residual

increase source from land use change sink terrestrial

$$[3.2 \pm 0.1] = [6.3 \pm 0.4] + [0.6 - 2.5] - [1.7 \pm 0.5] - [2\text{-}4]$$

Spatial distribution of sinks and sources in tropics

Schimel *et al.* (2001) used inverse model calculation to ascertain the broad location of the terrestrial sinks. Inverse models use the spatial variation in CO_2 concentration in order to identify sources and sinks. Based on these models, Northern extratropical regions (broadly N. America and Europe) are sinks of around 2.4 Gt C yr^{-1}. This outcome is also supported by other studies where atmospheric CO_2 concentrations have been monitored (Bousquet *et al.*, 2000), and C stocks in ecosystems have been estimated (Brown and Schroeder, 1999; Pacala *et al.*, 2001). However, the inverse model calculations have not been able to show the large sources of C expected from the tropics due to deforestation. On the contrary, the models indicate net emission to be around zero (i.e., C emitted = C sequestered) or – 0.4 Gt C yr^{-1} (i.e., C emitted < sequestered). Thus it is not only the loss of 1.6 Gt C yr^{-1} due to deforestation that is sequestered , an additional amount of 0.4 Gt C yr^{-1} is sequestered in the tropics . In order to explain this sink, Schimel *et al.* (2001) referred the study by Phillips *et al.* 1998 where increased uptake of carbon has been shown in mature forest. It has, however, not been resolved whether the increased carbon input is due to physiological change in mature trees (due to a fertilization effect of elevated CO_2, N_2 deposition) or due to forest regrowth on abandoned lands.

Caspersen *et al.* (2000) compared the growth rate of trees in the 1980s to those of the past. If there is a fertilization effect, growth rate in the 1980s should have been higher. However, the authors were able to detect any such fertilization effect and concluded that carbon accumulation was dependent more on forest regrowth and land use change than on growth enhancement. However, these forest regrowth studies have been carried out in South America (Phillips *et al.*, 1998) and Eastern United States (Carpersen *et al.*, 2000) and hence cannot be generalised for the tropics. Further, Schimel *et al.* (2001) stated that both atmospheric as well as ecological data for the tropics is sparse and thus reported C flux values are highly uncertain and that the major obstacle to equate the C cycle is the lack of data on land use change and ecosystem processes in the tropics.

Kyoto protocol

Alarmed by the rising carbon dioxide concentration and its likely impacts, the international community adopted the Framework Convention on Climate Change (FCCC) in 1992. Its aim was to stabilise the CO_2 levels and reduce human influence on the climatic system. In 1997, 39 developed nations (called the Annexe I Parties) committed to reduce their CO_2 by 5% of that in 1990 by 2012 (FAO, 2001).

These targets can be met in two ways: (i) directly reducing CO_2 emissions and/or (ii) sequestering C in the biospheric sinks (Albrecht and Kandji, 2003). The sequestration may be achieved by the Annexe I parties by themselves (known as Joint Implementation) or with non-Annexe I parties (mostly developing nations and known as Clean Development Mechanism) (FAO, 2001).

The amount of carbon that can be sequestered over a period of about 50 years will, however, be only 12-15% of the amount of CO_2 emitted by fossil fuel combustion over the same period (Brown, 1999). Brown (1999) states that the largest potential to conserve and sequester carbon is in the tropics followed by the temperate and then the boreal zone.

It is clear that sequestration is not the permanent solution to enhanced CO_2 levels. For reducing CO_2 levels emissions need to be reduced. However, sequestration in the biosphere can provide some time in order to make a change from fossil fuel based energy to other sources of energy.

Not much is known about the carbon stock in the different land use systems in the tropical settings (De Jong *et al.*, 1999; Smith *et al.*, 2002; Albrecht & Kandji, 2003). Thus there is a need to assess the carbon pools in various land use types to assess the potential present for C sequestration.

Carbon is fixed by autotrophs during the process of photosynthesis. Some amount of C fixed is utilized by the autotrophs themselves and released back into the atmosphere as carbon dioxide. The remaining fixed C is allocated to the various tissues in the plant. Litter from the autotrophs (from aboveground and belowground parts) is transferred to the soils. In the soils, litter is decomposed with CO_2 released into the atmosphere and the remaining part being retained as soil organic matter. There are a number of factors which govern each of the above mentioned processes. All the factors act simultaneously and influence each other in a number of ways. Thus, isolation of any factor, pool or process is artificial and arbitrary.

Soil organic carbon

However, soil organic carbon accounts for half of the total terrestrial carbon pool (De Jong *et. al*, 1999; Lal, 2004) and may therefore serve as a good starting point. The amount of organic carbon present in soils depends on a number of factors. Soil texture was shown to be an important factor by Ingram and Fernandes (2001). They are of the opinion that higher amount of clay and silt lead to storage of soil organic carbon. This is brought about by stabilization of soil organic carbon due to adsorption on clay and silt particles. Clay and silt particle scan also participate in the formation of micro- and macro aggregates. However, Silver *et al.* (2000) found that in Amazonia, soil texture was not related to soil organic carbon. They hypothesized that in sandy soils allocation to roots may be higher and also the decomposition may be slower. In sandy soils, the C:N and C:P ratios are higher and therefore the plant litter which is available (both aboveground and belowground) will be of poor quality and will thus result in a high soil organic carbon. Recalcitrant litter has been shown to increase soil organic carbon (Lehman *et al.*, 2001; Schroth *et al.*, 2002).

Carbon allocation

Allocation of carbon to roots will lead to higher soil organic carbon. The allocation of C to roots by tree was shown not to be dependant on latitude, soil moisture, soil texture, soil nutrient status, tree species or the age of the tree or stand (Cairns *et al.*, 1997; Enquist and Niklas, 2002). Rather, 84% of the variation in allocation to roots is explained by the aboveground biomass. This is to say that places with high aboveground biomass will have high belowground biomass, provided huge quantities of aboveground biomass is not removed from the site.

Climate and carbon partitioning

A high belowground biomass may not necessarily translate into high soil organic carbon content. The climate (predominantly the temperature and precipitation) of a region plays an important role (Post *et al.*, 1982). In temperate climates, soils store most of the carbon while lesser amounts are present in the biomass, while in the tropics the situation is reverse. Tropics provide a favorable climate for decomposers for a longer time period as compared to the temperate regions. Therefore, even though production is higher in tropics, the soil C content is higher in temperate regions.

Carbon in pastures

Studies by Cairns *et al.* (1997) and Enquist and Niklas (2002) relate to trees and forests and do not concern herbs/shrubs and grasses. These plant forms have a low aboveground biomass allocation but a very high belowground allocation (Houghton and Hackler, 2000). Thus pastures in many cases have been shown to have much higher amounts of C in the soils compared to the forests (Garcia-Olivia *et al.*, 1994; Fiegl *et al.*, 1995; Moraes *et al.*, 1996; Osher *et al.*, 2003). Although pastures may have higher soil organic carbon than forests, forest may have total carbon density higher than that of pastures. Although Sharrow and Ismail (2004) have shown values of total carbon in pastures to be higher than in plantations, one needs to understand that as the plantation ages, biomass will keep rising. However, storage of carbon in above ground components is less desirable from sequestration point of view as it is exposed to a greater degree to disturbance such as forest fires.

Carbon at the ecosystem level

The higher values of soil organic carbon in pastures than in forests indicates that establishment of trees leads to loss of soil organic carbon. Support to this may be lend by stdies by Sharrow and Ismail (2004) and Jackson *et al* (2002) which show that as compared to pastures, forests soils have lower soil organic carbon. While the study by Sharrow and Ismail (2004) is of a designed setting in which pastures, agroforests and plantations are compared, the study by Jackson *et al.* (2002) is that of natural grasslands which are being invaded by woody species. The latter research indicated that while in low precipitation areas, loss of soil organic carbon is more than compensated by increase in aboveground accumulation of carbon, in high precipitation areas, loss of carbon from soils is more than the amount of carbon sequestered in aboveground biomass. Sharrow and Ismail (2004) found that while pastures have very high soil carbon content and low biomass carbon, and plantations have high carbon content in biomass and low carbon content in soils, agroforests because of the presence of both grasses and trees have the highest total carbon stocks. Looking at both the studies, it appears that highest carbon content conditions are achieved at a specific (intermediate) density of trees. If the tree density rises above this, the loss of soil organic carbon can not be compensated by the sequestration of carbon in the biomass while below this density, the amount of carbon stored in soil by grasses will not match the deficiency in aboveground carbon content due to absence of trees. In the study by Sharrow and Ismail (2004), the agroforests have intermediate tree density compared to pastures (low tree density) and plantation (high tree density). Jackson *et al.* (2002) did not report tree density but it can be safely assumed that with higher precipitation the tree density might have risen so that at high precipitation the loss of carbon from soil is more than the carbon sequestered in the tree biomass. Thus, identification of the tree density at which soil carbon loss is less than the gain in tree biomass carbon is of importance. Not only will it help in using land to maximize the sequestration of carbon but at the same time will allow the land to be used for agricultural purposes.

In abandoned fields, in the initial stages grasses are present which lead to higher values of soil organic carbon when compared to primary forests (Koto-Same *et al.*, 1997). But as trees establish and the density increases, a decrease in soil organic carbon might be expected.

Agroecosystems

Human managed ecosystems differ from natural ones in that the inputs and outputs are regulated either directly or indirectly by human agency. Conversion of forest to agricultural lands have been extensively quoted to result in loss of soil carbon (Vitorello *et al.*, 1989; Johnson, 1992;

Davidson and Ackerman, 1993; Bashkin and Binkley, 1998; Osher *et al.*, 2003; Lal, 2004). However, if recommended management practices are followed, soil organic carbon increases. Recommended management practices include mulch farming, conservation tillage, agroforestry and diverse cropping systems, cover crops and integrated nutrient management including use of manure, compost, biosolids, improved grazing and forest management (Lal, 2004). These RMPs have their own costs and constraints. For example, mulching of fields will not allow residues of crops to be used for fodder or fuel (Lal *et al.*, 2004). Similarly, application of large quantities of manure depends on extraction of litter and leaf biomass from forests. Thus very large forest areas are needed to maintain this manure requirement. Studies have estimated that 5 to 17 units of forest land are needed for each unit of agricultural land (Rao and Pant, 2001).

Cost of carbon sequestration

In order to sequester great amount of carbon one needs to look not only at the technical feasibility and social acceptability but also at the economic viability of a given intervention. Shively *et al* (2004) have shown that the price for sequestering carbon ranges from $ 3.30 per tonne on fallow land to $ 62.50 per tonne on land planted with high value crops is replaced by forests, and $ 3.30 per tonne to $ 48 per tonne if replaced by agroforest in a watershed in the Philippines. Thus, establishment of forest or agroforest on fallow/abandoned land is the cheapest option available.

Land use- land cover change and albedo

Land use- land cover changes not only lead to flux of carbon but can also involve change in the albedo (reflectance of sun's rays from earth's surface). While considering land use- land cover change it should also be considered as how it will lead to changes in the earth surface energy budget (Marland *et al.*, 2003). In Florida wetlands had been cleared for cultivation of winter vegetables, sugarcane and citrus. This area was selected because of the lower risk of frosts in the given region. However, due to land use- land cover change the winter temperatures have lowered and the incidence of frosts has increased (Marshall *et al.*, 2003).

Objective

The Himalayas is a vast mountain system covering partly or fully eight countries of Asia including Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan. Although Himalayas cover only 18% of India's geographical area, it accounts for more than 50% of India's forest cover and 40% species endemic to the Indian subcontinent. Agriculture is a minor land use (with only 10% in Indian Himalaya being sown) and is distributed as patches in a matrix of forest. Traditional crop – livestock mixed farming is the basis of livelihood of local communities and backbone of rural economy (Rao and Saxena, 1996).

Efforts have been made to analyse changes in land use- land cover types in the Himalaya (Rao and Pant, 2001; Semwal *et al.*, 2004) but knowledge on the amount of carbon stored in the various land use – land cover types is limited. Though soil organic matter has been regularly analysed (Semwal *et al.*, 2002) but complete profile data is not available.

The objective of the present study was to estimate the carbon stock in aboveground tree component, litter, herbs/shrubs, soils and roots in major land use- land cover types *viz*, oak forest, pine forest, abandoned agricultural land, irrigated agriculture and rainfed agriculture, in a mid-altitude village landscape.

MATERIALS AND METHODS

Study Area

The study was carried out in and around the villages of Uttron, Langasu, Niwari, Chamoli and Bansoli (800-1400 m above sea level) in the District of Chamoli, Garhwal (30° 27'N and 79° 5'E), in the state of Uttaranchal. The area experiences a typical monsoon climate. Upto 80% of the precipitation in obtained during the monsoons (July to September) amounting to approximately 1200 mm. The parent material of the soils are feldspathic quartz schists, quartz muscovite schists and quartz chlorite schists, and can be classified as Dystric Cambisol according to FAO system.

The landscape is differentiated into five land use-land cover types: (a) settled irrigated agriculture, (b) settled rainfed agriculture (c) abandoned agricultural land, (d) oak (*Quercus leucotrichophora*) forest and (e) pine (*Pinus roxburghii*) forest. In irrigated fields two crops are grown (summer and winter) in each year. The summer season crops are rice (*Oryza sativa*), barnyard millet (*Echinochloa frumentacea*), finger millet (*Eleusine coracana*), pigeon pea (*Cajanus cajan*), horse gram (*Macrotyloma uniflorum*), green gram (*Vigna radiata*), soyabean (*Glycine max*) and cowpea (*Vigna unguiculata*). The winter season crops are wheat (*Triticum aestivum*), mustard (*Brassica campestris*) and barley (*Hordeum vulgare*). Mixed agriculture is practiced in both rainfed and irrigated fields. No fallowing is done in irrigated fields but rainfed fields are fallowed in winter season in alternate years. Crop rotation is also present in rainfed fields. Use of chemical fertilizers and pesticides is absent. Leaf litter collected from oak forest is used alongwith cowdung for manuring fields. Agriculture is of subsistence type. Some of the rainfed fields have been abandoned. These fields are located at the margins of the village. These are characterized by broken terraces and a larger number of trees. The trees species establishing in the abandoned fields are similar to those found in the agricultural fields. Abandoned fields are used to graze cows and to collect fodder from the trees. Leaf litter from oak forest is collected and used as bedding in cowsheds. This is later mixed with cowdung and used as manure. Grazing in oak forests is done in summers while in winters, grazing is done in pine forests. Collection of wood is common in both pine and oak forests. Forest fires in the pre monsoon months are quite common and are usually associated with scrubs and pine forests and rarely with oak forests.

Sampling

Carbon density was estimated in three plots of 20x60 m (0.12 ha) in each of the five land use-land cover classes. Each plot was subdivided into three 20x20 m subplots for the enumerations of trees and shrubs.

Circumference at breast height (CBH, 1.3m) was measured and species identified based on Gaur (1999) for all trees with CBH > 10 cm. Three $1m^2$ quadrats were laid in each plot and grasses, herbs and saplings were collected, oven dried at 65 ± 5^0C and weighed. Litter was also collected from three 1 m^2 quadrats in each plot. Soil samples were collected from three pits with the help of a corer in following horizons: 0-10, 10-20, 20-30, 30-50, and 50-100 cm in each plot. Fine roots (2 mm – 10 mm) were collected from three 0.09 m^2, 1m deep pits. These were oven dried at 65 ± 5^0C and their weight noted.

Physical and Chemical Analysis

Bulk density

A part of the soil collected by the corer was kept for drying in the oven at a temperature 105±5° C for 48 hours. The oven dried weight of the subsample was obtained to get the oven dried weight of the entire corer sample. Bulk density was obtained by dividing the oven dry weight by the volume of the corer (Anderson & Ingram, 1989). The volume of the corer was calculated as:

$\pi r^2 * l$ cc

$\pi \times (2.5)^2 * 6 = 117.5 \text{ cm}^3$

where,

r=radius of corer,

l=length of corer.

Soil carbon concentration

The soil samples were air dried and ground using mortar and pestle. The sample was passed through a 250μm sieve. A composite sample was prepared by mixing the soils belonging to the same horizon in the three pits from the same plot. Soil organic matter (SOM) C content was determined for each sample in the laboratory on three replicates by oxidation without external heating (Walkley and Black, 1934) as detailed below:

From each sample 0.3 gram soil was taken into a 250 ml conical flask. 5 ml of 1M $K_2Cr_2O_7$ solution was added into the flask with a pipette. Immediately, 10 ml of concentrated H_2SO_4 was added into the flask with the help of a measuring cylinder. After this, the flask was allowed to cool down to room temperature. 50

ml of distilled water was added to each flask after which its temperature rose again. The flask was allowed to cool down to room temperature. 2 to 3 drop of orthophenonthroline were added and titration was done against 0.2 M ferrous ammonium sulphate (FAS) solution. End point was observedby a change in colour from green to maroon. Blanks were also made and received the same treatment but had no soil in them. The volume of FAS consumed in each case was noted down. Percentage organic carbon was obtained using the following formula.

$\% \text{ OC} = T\text{x}0.2 \times 0.3/ \text{ sample weight}$

Where, T = titre value = $V_b - V_s$,

V_b = volume of FAS consumed by blank,

V_s = volume of FAS consumed by sample,

Sample weight = 0.3g

Calculations

Biomass estimation of aboveground part of trees present in oak and pine forests was done with the help of published allometric equations for the region (Tiwari and Singh, 1984). Estimation of aboveground biomass for agroforestry trees was done by developing allometric equations from the data supplied by Semwal *et. al.* (unpublished). Estimates of root biomass were obtained using allometric equation developed from the data provided by Enquist & Niklas (2002). Aboveground biomass, herbaceous cover, litter, fine roots and coarse roots were assumed to contain 50% C on dry weight basis. The C values obtained were converted to 10^6 g / ha or Mg/ha basis (1Mg = 10^6 g= 1 tonne).

Bulk density and percentage carbon were used to obtain amount of C in Mg/ha units. All C contents in soils are expressed on oven dried basis.

Statistical analysis

Least Significant Difference (LSD) values at $P= 0.05$ were used to find significance of difference between the means (Snedecor and Cochran,1967).

RESULTS

Tree density

The tree density was highest for oak forest (55.8 individuals ha^{-1}) and was significantly higher when compared to the other land use-cover types except for pine forest ($P<0.05$). The tree density of pine forest was significantly higher than in rainfed farmland and irrigated farmland. There was no significant difference between the tree density in pine forest and abandoned land and between abandoned land and irrigated farmland and rainfed farmland ($P>0.05$) (Table 1).

Basal area

There was no significant difference in the basal area of rainfed farmland, abandoned farmland and irrigated farmland. These sites had basal area (3.6-11.0 m^2ha^{-1}) much lower than that of pine forest (19.8 m^2ha^{-1}) and oak forest (28.2 m^2ha^{-1}) (Table 1).

Tree species

Tree community in different land use-land cover types varied in terms of species richness, composition, density and basal area. No species was common to all land use – land cover types. Seven species *viz.*, *Alangium salvifolium*, *Albizzia julibrissin*, *Albizzia* sps., *Emblica officinalis, Ficus palmata, Mallotus phillipensis* and *Syzigium cumini* were confined to abandoned agricultural land, two species *viz.*, *Citrus aurentifolia* and

Morus australis to irrigated agriculture. *Pinus roxburghii, Quercus leucotrichophora* and *Sapium insigne* were present in abandoned agricultural land and forest sites but absent in irrigated agriculture and rainfed agriculture. *Celtis australis* was the most dominant species in rainfed agriculture and irrigated agriculture, *Quercus leucotrichophora* in abandoned agricultural land and oak forest and *Pinus roxburghii* in pine forest. Oak forest had the highest basal area followed by pine forest, rainfed agriculture, abandoned agricultural land and rainfed agriculture. Abandoned agricultural land site had the highest species richness (18) followed by irrigated land (8), rainfed farmland (6), oak forest (5) and pine forest (3) (Table 1).

Soil depth

Mean soil depth varied from 56.7 cm in rainfed agriculture to 77.8 cm in pine forest. Soil depths in rainfed agriculture, irrigated agriculture, abandoned agricultural land, pine forest and oak forest were not significantly different from one another ($P>0.05$) (Table 2).

Bulk density

Bulk density of soil (large and hard components such as pebbles and stones were excluded while determining mass of a given volume of soil) varied with depth in all sites but the trends differed. In abandoned agricultural land, there was a consistent decrease in bulk density with increase in soil depth upto 100 cm. In agricultural land, bulk density of upper 0-10 cm soil layer was lower than that of 10-20 cm and 20-30 cm layers but higher than that of 30-50 and 50-100 cm layers. In pine and oak forests, bulk density did not change much upto a depth of 30 cm but declined significantly in lower depths (> 30 cm). Comparison of different land use- land cover types showed that the bulk density did not significantly differ in the 10-100 cm soil layers. Significant differences were found in the 0-10 cm layer. Bulk density of surface soil (0-10 cm) in abandoned agricultural land was significantly higher than agricultural lands, the bulk density of agricultural land being the lowest (Table 3).

Soil carbon concentration

Plotted on an individual horizon basis, carbon concentration (g C kg-^{1} soil) was similar in surface horizons (0-10 cm and 10-20 cm) of all the five land use – land cover types ($P>0.05$). In 20-30 cm horizon, C concentration was higher in abandoned agricultural land when compared to the other classes ($P<0.05$). In the 30 to 50 cm soil horizon, the C concentration in abandoned lands was not different from other land use-land cover classes except when compared to pine forest. In the 50-100 cm horizon as well no significant differences exist between the land use – land cover types.

In all sites, surface soil (0-10 cm) showed the highest concentration of soil organic carbon. However, the pattern of change in soil organic carbon with depth varied. In oak forest and irrigated agriculture, soil organic concentration decreased from 0-10 cm layer to 20-30 cm layer and remained the same upto 50-100 cm layer. In rainfed agriculture and pine forest, soil organic carbon level declined upto 30-50 cm and did not change beyond this depth. In abandoned agricultural land, soil organic carbon level declined consistently from 0-10 cm layer to 50-100 cm layer (Fig. 1).

Carbon content of soil

Carbon content of soil (Mg ha^{-1} to 1m depth) does not differ significantly in the various land use land cover types ($P>0.05$). The organic carbon content (Mg ha^{-1}) in complete profile varied from 51.74 in oak forest to 68.27 in irrigated agriculture followed by abandoned agricultural lands (64.26), rainfed agriculture (55.74), pine forest (52.22) and oak forest (51.74).

Carbon content of the 0-10 cm horizon is significantly higher in irrigated agriculture than in oak forests. Rainfed agriculture, irrigated agriculture and abandoned agricultural land had about 25% higher soil organic carbon in 10- 20 cm layer as compared to pine and oak forests.

In the 20-30 and 30-50 cm horizon abandoned agriculture has more carbon content than all other sites, except that difference between abandoned agricultural land and irrigated agriculture were not significant for 30- 50 cm layer. Soil organic carbon in 50- 100 cm layer showed a trend of irrigated agriculture > pine forest = oak forest > rainfed agriculture> abandoned agricultural land. Irrigated agriculture and pine forest had significantly lower amount of soil organic carbon in 20- 30 cm layer and oak forest in 0-10 cm layer as compared to other land use–land cover types. Pine forest had significantly higher amount in 0-10 cm layer and lower in 30-100 cm layer compared to oak forest. Total soil carbon averaged 64.26 and 55.74 Mg ha^{-1} for abandoned agricultural land and rainfed agriculture, respectively. Soil organic carbon for abandoned land increased by 11.7 Mg ha^{-1} in the 50 cm, but it declined by 3.2 Mg C ha^{-1} in the 50-100 cm horizon giving a net sequestration of 8.5 Mg ha^{-1}. Abandonment of rainfed agricultural fields resulted in a net carbon gain of 15%. Agricultural lands have a higher amount of SOC than forests. This increase is, in general, distributed across the profile. Abandoned agricultural land has higher soil carbon density (64.26 Mg ha^{-1}) than pine forest (52.23 Mg ha^{-1}) and oak forest (51.88 Mg ha^{-1}). Abandoned agricultural land has more C density in the top 50 cm horizons than in oak forest and pine forest but lower in the 50-100 cm horizon (Fig. 2).

Of the total carbon content present in pine forest 35% was contributed by the 0-10 cm horizon, the corresponding value being 32% for irrigated agricultural land. In the 10-20 cm horizon the %

contribution in all the land use/course types was almost same. In abandoned agricultural land the percentage contribution from the 20-30 cm horizon was higher (20%) in comparison to other land use-cover types. The 30-50cm horizon also showed a larger value for abandoned agricultural land when compared to others. Rainfed agriculture, irrigated agriculture, pine forest and oak forest had around 20-23% of their carbon content in the 50-100 cm horizon and the value being low for abandoned agricultural land (~12%) (Fig.3).

Total carbon density

Mean total C densities in the land use- land cover classes varied about threefold, from 62.68 Mg ha^{-1} in rainfed agricultural land to 177.16 Mg ha^{-1} in oak forest. The differences were largely due to the difference in the aboveground C density. Though rainfed agriculture had marginally higher C density in the aboveground tree component than irrigated agriculture, total C density in this system was lesser due to a lower C density in the soil. While the litter carbon densities in rainfed agriculture, irrigated agriculture and abandoned agricultural land are negligible they were relatively larger in oak forest and pine forest. The herbaceous cover was more prominent in rainfed agriculture and irrigated agriculture. Biomass C in herbaceous component in forest was negligible in comparison to that in bole, branches and litter. The site effect was very marked in terms of total aboveground biomass as well as contribution of different components to it. Bole carbon density was equal to the C density in the branches and twigs in oak forest while in pine forest the bole C density was twice that in branches and twigs. Bole biomass C in oak forest (52.5 Mg ha^{-1}) was 1.8, 7, 20.4 and 36.7 times higher than that in pine forest, abandoned agricultural land, rainfed agriculture and irrigated agriculture, respectively. Branch and twigs biomass C in oak forest (56.6 Mg ha^{-1}) was 4.1, 9.4, 27.5 and 57.2 times higher than that in pine forest, abandoned agricultural land, rainfed agriculture and irrigated agriculture, respectively. Total aboveground biomass C in oak forests (110.7 Mg ha^{-1}) was 2.5, 8, 18.2 and 20.1 times higher than that in pine forest, abandoned agricultural land, rainfed agriculture and irrigated agriculture, respectively. The differences between different land use- land cover types in total belowground C were not as marked as those in terms of contribution different belowground components *viz.* soil organic carbon, coarse roots and fine roots. C in roots in oak forests (14.57 Mg ha^{-1}) was 1.4, 5.5, 18.9 and 16.7 times higher than that in pine forest, abandoned agricultural land, irrigated agriculture and rainfed agriculture, respectively (Fig. 4). Proportion of C density in fine roots to coarse roots was higher in pine forest than in oak forest.

Soil organic carbon accounted for >90% total carbon in agricultural land compared to 80% in abandoned agricultural land, 50% in pine forest and 30% in oak forest (Fig. 5).

Table 1. Density (individuals ha^{-1}) and basal area (m^2 ha^{-1}) of woody perennials (tree and shrub species) in different land use-land cover types in Langasu village landscape (values rounded off to one place after decimal)

Species	**Sites**				
	Rainfed farmland	**Irrigated farmland**	**Abandoned farmland**	**Pine forest**	**Oak forest**
Alangium salviifolium	-	-	2.8 (0.1)	-	-
Albizzia julibrissin	-	-	5.6 (0.1)	-	-
Albizzia sps.	-	-	2.8 (0.4)	-	-
Bauhinia purpurea	25.0 (3.9)	-	2.8 (0.3)	-	8.3 (0.4)
Bombax ceiba	2.8 (0.1)	-	8.3 (0.1)	-	-
Celtis australis	36.1 (4.1)	13.9 (2.0)	16.7 (0.7)	-	-
Citrus aurentifolia	-	2.8 (0.1)	-	-	-
Emblica officinalis	-	-	5.6 (0.1)	-	-
Ficus auriculata	2.8 (0.2)	-	25.0 (0.9)	-	11.1 (0.2)
Ficus palmata	-	-	2.8 (0.3)	-	-
Ficus subincisa	8.3 (0.1)	8.3 (0.8)	16.7 (0.7)	-	-
Ficus relegiosa	-	2.8 (0.1)	-	-	-
Grewia optiva	30.6 (2.7)	11.1 (0.5)	8.3 (0.2)	-	-
Juglans regia	-	2.8 (0.2)	-	-	-
Mallotus phillipensis	-	-	25.0 (0.7)	-	-
Morus australis	-	5.6 (0.1)	-	-	-
Pinus roxburghii	-	-	19.5 (1.3)	463.9 (19.5)	2.8 (0.1)
Pyrus pashia	-	2.8 (0.1)	11.1 (0.1)	-	-
Rhus parviflora	-	-	19.5 (0.3)	-	-
Quercus leucotrichophora	-	-	44.5 (1.7)	8.3 (0.3)	516.7 (27.2)
Sapium insigne	-	-	5.6 (0.2)	2.8 (0.1)	5.6 (0.1)
Syzigium cumini	-	-	2.8 (0.1)	-	-
Others	-	2.8 (0.1)	36.3 (0.2)	-	13.9 (0.2)
Total	105.6±18.1 (11.04± 3.1)	52.8± 22.6 (3.6±2.0)	261.3 ± 74.8 (7.4 ± 1.9)	475 ± 97.2 (19.8 ± 3.1)	558.3± 128.1 (28.2 ± 3.7)

Table 2 . Soil depth (mean ± SEM) in different land use – land cover types

Land use-land cover type	**Soil depth (cm)**
Rainfed agriculture	60.0 ± 8.9
Irrigated agriculture	62.2 ± 9.8
Abandoned agricultural land	56.7 ± 8.7
Pine forest	77.8 ± 8.8
Oak forest	70.0 ± 9.7

Table 3 . Bulk density (mean ± SEM) (g cm^{-3}) of soil at varied depths in different land use – land cover types

Land use-land cover type	**Soil depth (cm)**				
	0-10	**10-20**	**20-30**	**30-50**	**50-100**
Rainfed agriculture	1.20 ± 0.02	1.31± 0.04	1.33 ±0.04	0.89 ±0.19	0.46 ±0.20
Irrigated agriculture	1.10 ± 0.08	1.29 ±0.06	1.29 ±0.04	0.99 ±0.19	0.43 ±0.22
Abandoned agricultural land	1.35 ± 0.02	1.26 ±0.03	1.26 ±0.06	1.02 ±0.20	0.34 ±0.23
Pine forest	1.24 ± 0.06	1.24 ±0.07	1.21 ±0.04	0.97 ±0.02	0.59 ±0.19
Oak forest	1.32 ± 0.05	1.26 ±0.05	1.29 ±0.02	1.14 ±0.15	0.57 ±0.22

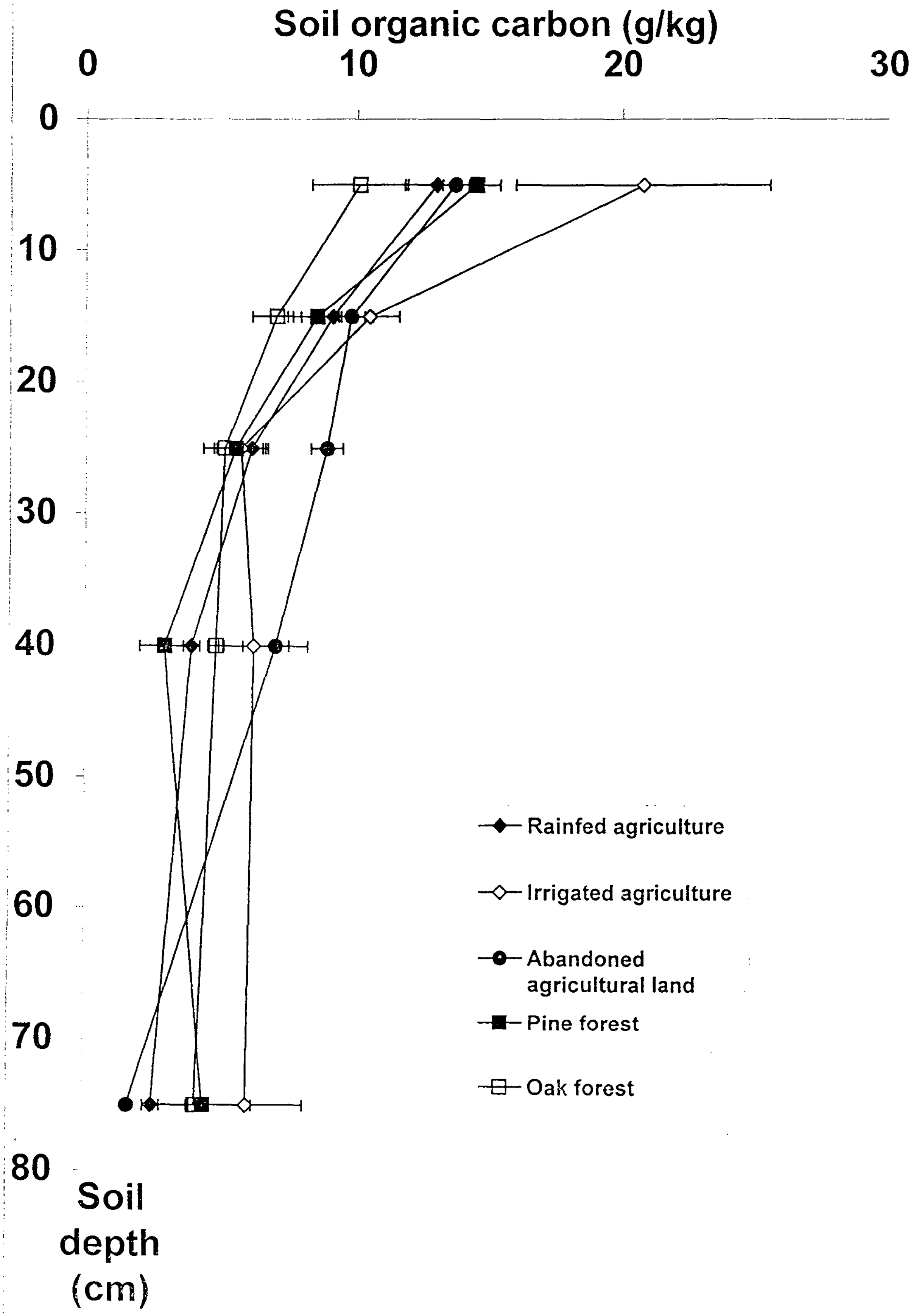

Fig. 1 Mean soil organic carbon concentration and standard errors to 1 m depth in different land use – land cover types.

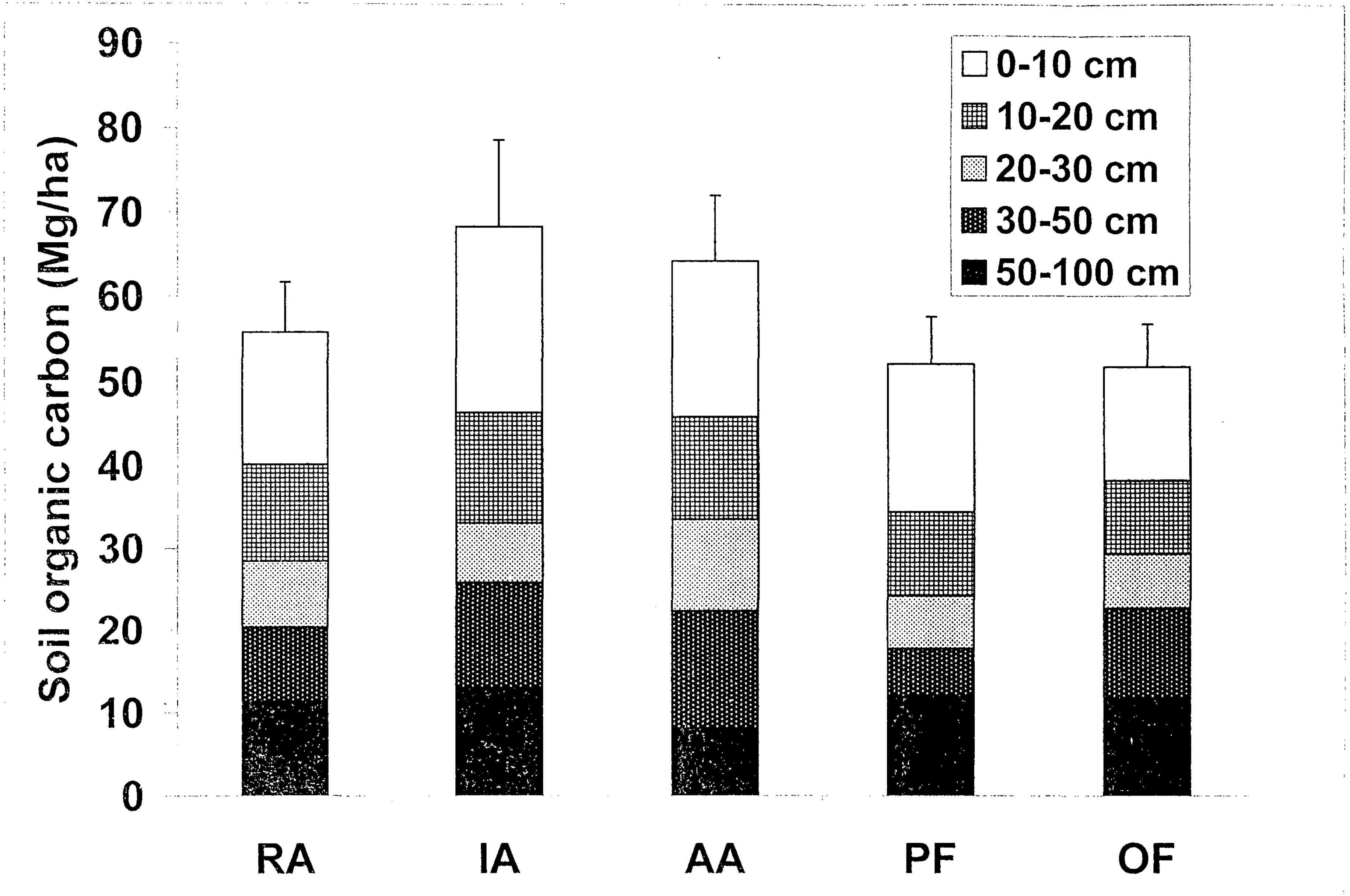

Fig. 2 Mean soil organic carbon content at different horizons in different land use – land cover types.

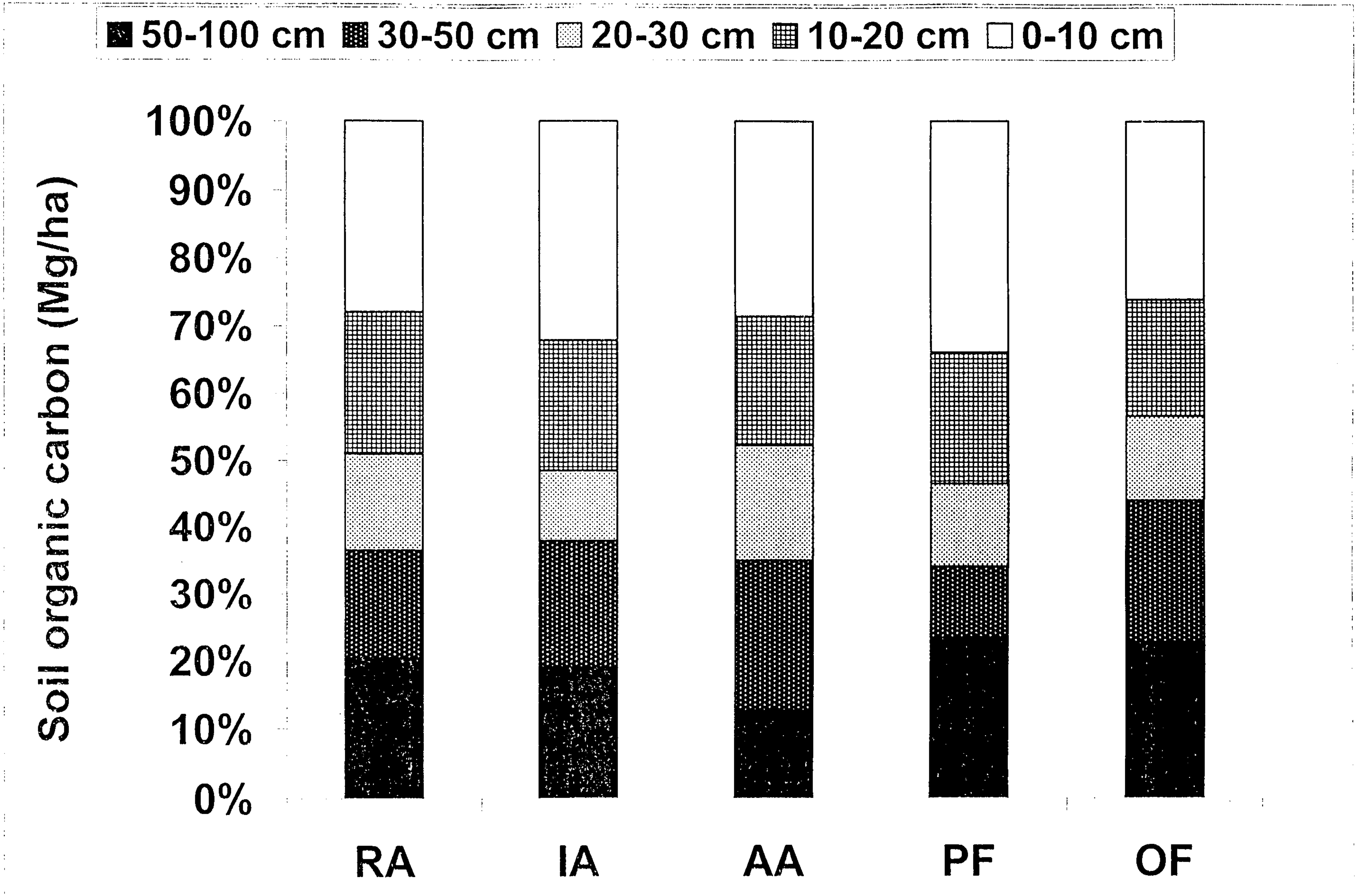

Fig. 3 Horizon wise(%)contribution to total soil organic carbon content in different land use – land cover types.

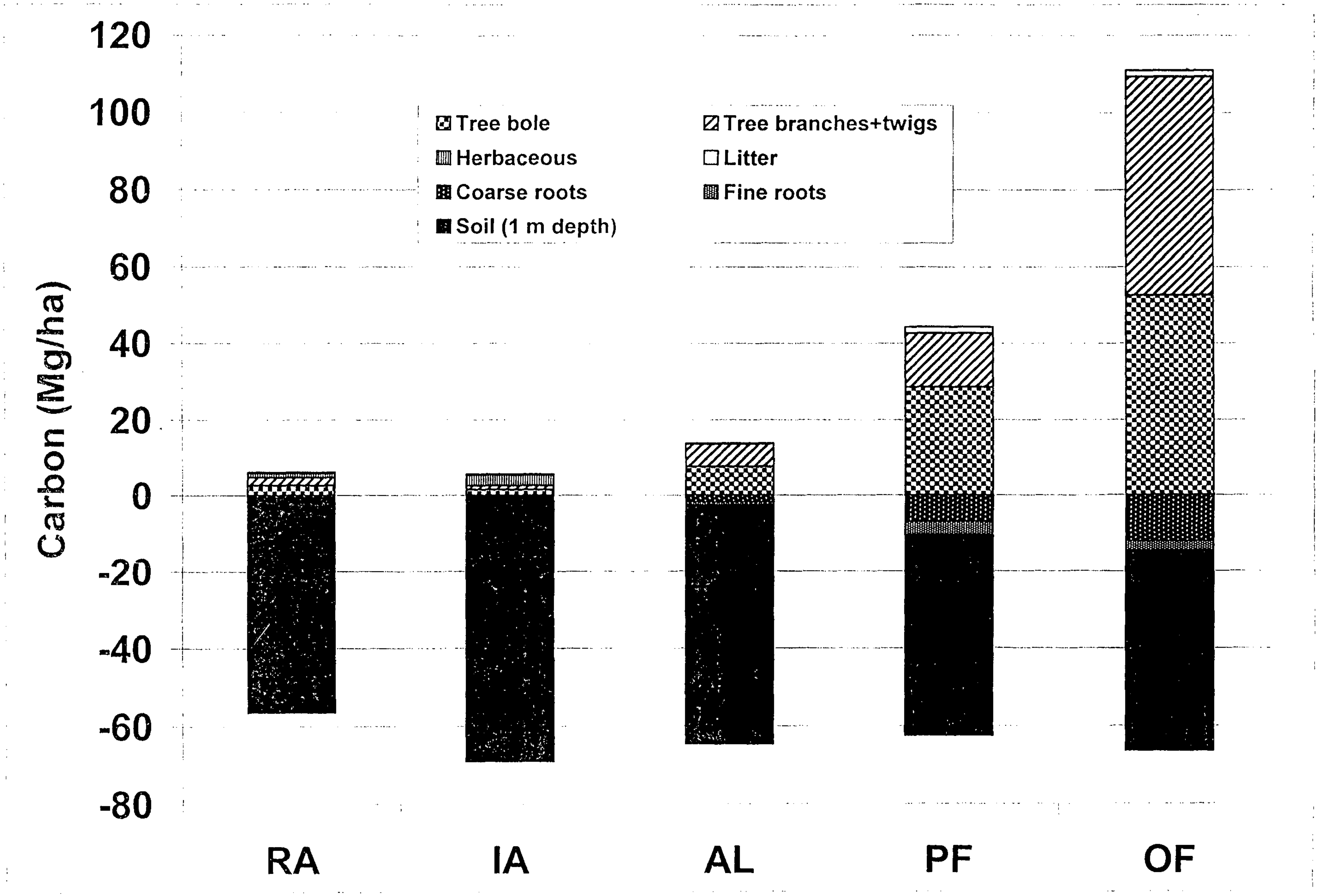

Fig. 4 Mean total carbon density in different land use – land cover types.

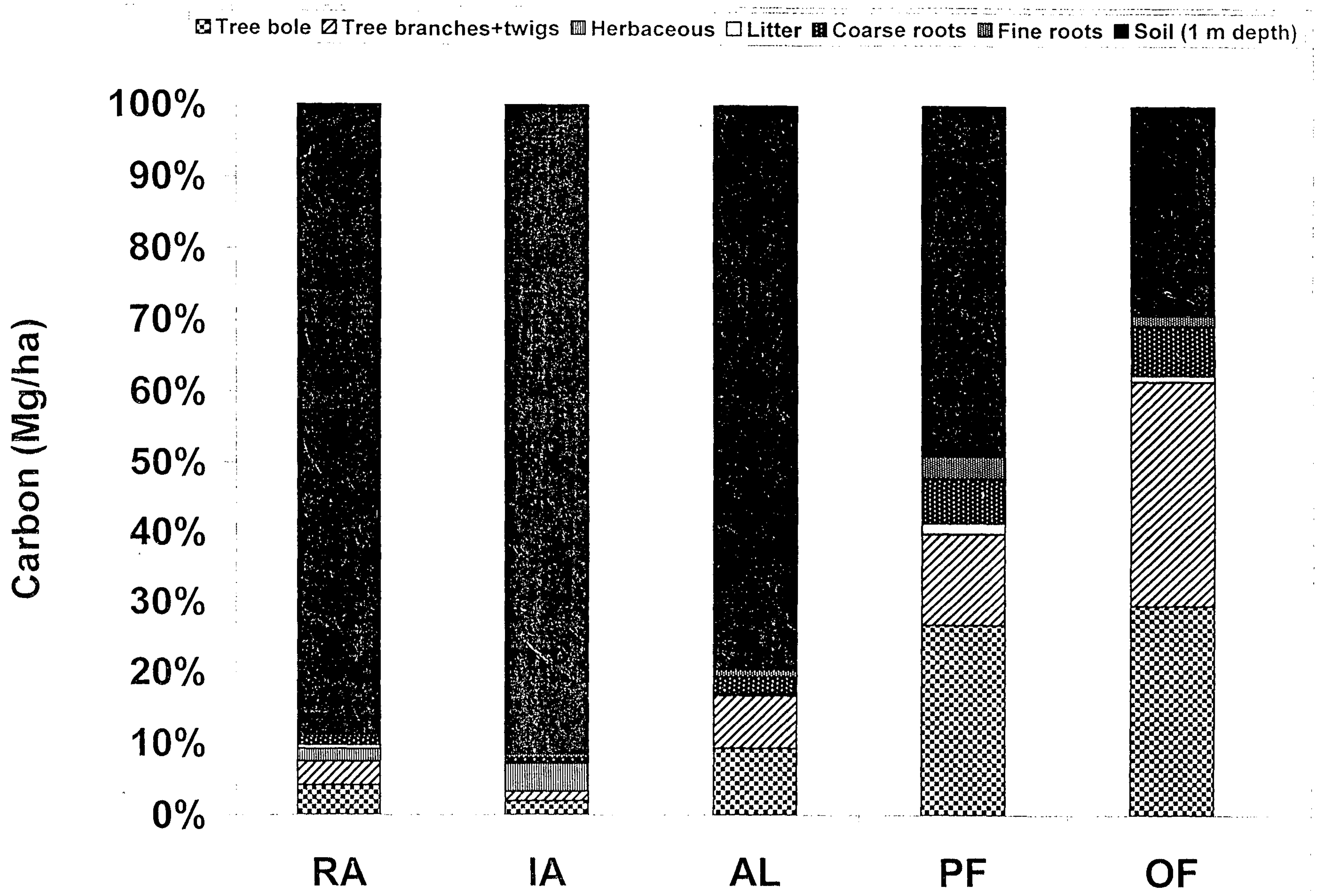

Fig. 5 Contribution (%) of different components in various land use – land cover types to total carbon density.

DISCUSSION

Differentiation of ecosystems in the landscape

Climax vegetation of the study area is described as 'Montane Wet Temperate Forest' distinguished by the dominance of broadleaved evergreen *Quercus leucotrichophora* trees without buttresses, epiphytic lichens and mosses on tree trunk and branches, and almost complete absence of lianas. The use of the term temperate is misleading in the sense that climate is not typically humid as is found in the true temperate forests of Northern Hemisphere. Compared to other ecological zones in the Himalaya, the temperate forest zone is very favourable for human habitations and hence disturbances such as lopping, fire and grazing are quite common in these forests. While occurrence of shifting cultivation in the distant past cannot be denied, it is a rare practice in the present times (Negi *et al.*, 1997). Crop-livestock mixed farming on terraced slopes is the predominant traditional agricultural land use in the region. Unlike many other mountain regions in developing countries, where conversion of forests for agriculture is continuing on a rapid scale, drastic changes such as conversion of natural ecosystems to agriculture in the Central Himalaya seem to have occurred in the distant past. Traditional human interventions are aimed at meeting the essential livelihood requirements rather than for maximization of land holdings or income from forests or agriculture. Expansion of agricultural land use was restricted by nationalization of forests way back in 1890s and by enforcement of forest conservation from 1950 onwards. Nevertheless, some expansion of agricultural land use did occur. Even now, agricultural land use constitutes hardly 20% of the total geographical area of Indian Himalaya. Policy interventions induced changes within traditional rainfed agriculture and forests decades ago. Organised forest management practices introduced in 1920s by the colonial regime, in many segments of Himalaya, favoured dominance of industrially/economically important tree species *Pinus roxburghii* (yielding resin) over that of the locally valuable climax species *Quercus leucotrichophora* (a high quality fuelwood, fodder and manure species). As income generation from economically valuable species was not a traditional practice and government allowed traditional uses of forest biomass (*viz.*, grazing, collection of fuelwood and a variety of other non-timber forest products, timber required for domestic needs) free of any cost even in nationalized forests, there were no people-policy conflicts in the initial stages. As people did not get any significant economic benefits from pine forests, they very often set ground fire to stimulate grass fodder production, a practice which is quite common even now. Local people cared more for integrity of oak forests which provide high quality leaf litter (required for traditional manure production), high quality fodder, fuelwood and timber and provide microhabitats for a variety of non-timber forest species extremely important for local livelihood. Policies have, however, restricted expansion of agricultural land use. In case of forests, policies have allowed use of forest resources free of any cost for meeting subsistence needs and not for economic gains from market to local people. Selective felling was allowed to government agencies till 1976 but subsequently it was banned.

Some part of traditional rainfed agriculture was changed to irrigated agriculture as a result of irrigation facilities established with full funding from the the government from 1950 onwards. However, area under irrigated agriculture, particularly on slopes, is negligible in comparison to the area under traditional rainfed agriculture. Abandonment of agricultural land use is a recent change observed in isolated locations. The abandonment is not because of weed problem or depletion of soil fertility but because of migration of rural households to urban areas in recent times. All agricultural land is privately owned and past or present policies have not discouraged or encouraged any annual crop. Government provides subsidy on fertilizers and other modern inputs but socio-economic conditions of hill farmers is such that use of these inputs is virtually absent.

Ecological attributes of a given land use-land cover type are determined by ecological processes operating within a given land use- land cover type and also by the exchanges of material and energy between different land use- land cover types. Transfer of huge amounts of organic matter and nutrients from forests to agroecosystems in the form of manure (forest leaf litter mixed with livestock excreta) and ash from burning fuelwood collected from forests is a feature that distinguishes the present landscape from many other landscapes.

Bulk density

Insignificant difference in bulk density of surface soil of climax oak forests and seral pine forests or between forests and abandoned agricultural land differs from a trend of increase in bulk density following conversion of primary to secondary forests or plantations reported elsewhere in the tropics (Weaver *et al.*, 1987; Schroth *et al.*, 2002). Smith *et al.* (2002) also did not find any significant difference in bulk density of natural forests and 20-30 year old plantations in lowland Amazonia. Osher *et al.* (2003) observed about 1.6 fold increase in bulk density following conversion of forests to sugarcane cultivation while we did not find any significant difference between bulk density of annual crop based rainfed agroforestry system and forest soils and only a marginal difference in bulk density of soil in irrigated agriculture and forests. The interaction of factors increasing bulk density such as compaction of soil by grazing animals, reduction in soil fauna activity due to fire as in pine forests or removal of litter from forest floor and those decreasing bulk density such as tillage and organic manuring in agricultural land in the present landscape are such that there are no any major differences between bulk density in different land use- land cover types.

Soil organic carbon concentration

As discussed above, the differences in soil organic matter between different land use-land cover types are because of factors other than bulk density, mineralogy and texture that influence organic carbon accumulation in soil. The range of C concentration in 0-10 layer reported (10-20 g Kg^{-1}) in this study is comparable to that reported by Schroth *et al.* (2002) (18-25 gKg^{-1}) in a radically different climate, soil and management system of Amazonia and substantially lower than the values reported by Sharrow and Ismail (2004) (2.5-2.9 g Kg^{-1})in a similar climate but different soil and management system in Oregon, USA. Such trends bring out the importance of a large number of factors and their interactions in determining soil carbon stocks. Many studies have shown a significant decline in organic carbon in surface soil following conversion of primary forests to agricultural land use (van Noordwijk *et al.*, 1997; Schroth *et al.*, 2002; Vitorello *et al.*, 1989; Detwiler, 1986; Johnson, 1992; Davidson and Ackerman, 1993) because of lower magnitude of organic inputs coupled with faster decomposition and mineralization in the latter compared to the former. Absence of such difference between rainfed agriculture and forest and abandoned agricultural land in the present case seems to be because of transfer of huge amount of organic residues from the latter to the former through organic manure derived from forest leaf litter and excreta of livestock fed on fodder in non-agricultural lands. Irrigated agriculture accumulated significantly higher amount of organic carbon content in 0-20 cm soil layer compared to other land use-land cover types and this could be attributed to greater quantities of organic manure input and root biomass production in an environment where water stress is ameliorated and flood irrigation during some part of the year (when paddy is grown) reduces oxidation of carbon due to somewhat anoxic conditions despite of a warmer regime. If forest: cropland ratio is very low and forests are highly degraded and dominated by poor quality fodder, litter and fuelwood species, removal of organic inputs in forest ecosystems may be reduced to an extent that forest soils become more depleted in organic carbon and nutrients than agricultural soils as widely found in the Nepal Himalaya (Pilbeam *et al.*, 2000).

Soil organic carbon

The depth of soil sampled is an important determinant of soil carbon stocks. For comparing the carbon accumulation capacity of different land use-land cover types, it is necessary that the carbon concentration in the complete profile is analysed as done in the present study and also some other studies (Sharrow and Ismail, 2004). An assertion that conversion of forests to agriculture or pastures accompanies a significant loss in soil organic carbon stock (as high as 22-50%) stems largely from the studies that have looked into top soil and not the complete soil profile (Detwiler, 1986; Vitorello *et al.*, 1989; Johnson, 1992; Davidson and Ackerman, 1993; Smith *et al.*, 2002; Osher *et al.*, 2003). The results presented here show that impact of land use-land cover type was more marked on soil organic carbon content in surface soil but not on soil C stocks in the complete soil profile (upto a depth of 100 cm). Thus, a land use-land cover type having higher carbon content in some layers of soil had lower contents in other layers as also reported elsewhere. Site effect is further reduced if total belowground organic carbon (soil organic carbon and root carbon) is compared. Schroth *et al.* (2002) did not find any significant difference between soil carbon stock (2 m depth) of secondary forests, agroforestry and monoculture plantations in lowland humid tropical of Brazilian Amazonia but observed a significant effect of land use-land cover was observed in 0-10 cm layer. De Jong *et al.* (1999) did not find any significant difference in soil C stock (upto 1 m depth) in diverse land use-land cover types, *viz.*, oak and evergreen cloud forests, pine-oak forests, pine forests, degraded and fragmented forests, cultivated land and pasture land in highlands of Chiapas in Mexico experiencing subtropical to temperate subhumid climate. Bashkin and Binkley (1998) found an increase in SOC of surface soil but not in complete profile due to afforestation in canefields on volcanic ash soils of Hawaii. Sharrow and Ismail (2004) found significant difference SOC density between pasture and plantation but not between agroforest and pasture or plantation on shallow soils (maximum depth 45 cm). However, unlike the present landscape, in most of these studies the land use-land cover types constituting the landscape were such that there was negligible transfer of organic matter from one ecosystem type to the other. Protection of naturally regenerating vegetation or enrichment through afforestation/ reforestation together with recycling of resources within the regenerating system may lead to significant increase in both carbon stock in soil as well as in aboveground biomass (Schroth *et al.*, 2002; Smith *et al.*, 2002). However, if resources are taken away from the regenerating system, there may be an increase in carbon accumulation in aboveground biomass and root biomass but not in soil carbon stock as evident from insignificant difference in SOC of rainfed cropland and abandoned agricultural land.

Aboveground biomass carbon

A significantly higher amount of carbon is stored in aboveground biomass in the forests having climax species (oak forests) than any other land use-land cover type as also observed by De Jong et al (1999) for resembling vegetation types under different ecological conditions. Higher biomass C in oak forests than pine forests in the present case could be attributed to more attention for sustainable use of the former rich in locally valued products than the latter rich in industrially valued products. Aboveground C density in forests (43 Mg ha $^{-1}$ for pine and 109 Mg ha^{-1} for oak) or abandoned agricultural land (14 mg ha^{-1}) reported in the present study are substantially lower than the values reported for comparable land use-land cover types

(120-230 Mg ha^{-1} for forests and 25-40 Mg ha^{-1} for abandoned land) elsewhere (Woomer *et al.*, 1994; De Jong *et al.*, 1999; Schroth *et al.*, 2002). Abandoned agricultural lands had higher species richness but lower aboveground or total biomass C when compared to forests. Similar observations were made by Lugo and Helmer (2004) in Puerto Rico. Irrigation did not improve total aboveground C stocks. However, C content that is stored in trees over longer time was higher in rainfed agriculture compared to that in irrigated agriculture because of higher density and low intensity of lopping of agroforestry trees in the former. Trees are heavily lopped in irrigated agriculture because the crops grown here are more sensitive to shade stress as compared to those grown in rainfed agriculture.

Conclusions

Sequestration of atmospheric carbon in the form of organic carbon stored in soil or that accumulated in biomass with slow mineralization is one of the options available for mitigating global warming due to greenhouse gases. A complete picture of carbon sequestration capacity of different land use-land cover types would only emerge only when carbon pools are estimated together with carbon fluxes. Yet, organic carbon pool analysis can provide some reflections on carbon sequestration capacity. Further, the issue of carbon sequestration needs to be looked not in isolation but in conjunction with other environmental problems such as loss of biodiversity, hydrological imbalance and soil erosion and economic problems. The major conclusions arising from this study are:

(a) conversion of oak forests to pine forests induced by past policies is economically profitable but such a change reduces carbon sequestration and socio-economic benefits to the local communities

(b) undisturbed forests indeed store huge amount of carbon compared to agricultural systems but complete abandonment of agriculture in mountain regions is not a viable alternative from the point of sustainable livelihood of people living in isolated and inaccessible hill villages

(c) impact of land use-land cover change is more marked in terms of biodiversity and aboveground carbon pools than in terms of soil carbon stocks

(d) carbon stock in top soil is sensitive to land use-land cover change but not the carbon stock of the complete profile

(e) irrigation as at present does not have any significant impact on total carbon stock in agricultural land use

(f) carbon sequestration capacity does not improve after abandonment of agricultural land use if disturbances of grazing, lopping and litter collection are continued, while abandonment followed a significant increase in species richness

(g) reduction in removals from forests and abandoned land may accompany a significant increase in carbon stocks but this can be feasible only when local communities are provided with better management options that sustain higher yields from agricultural land with lower rates of inputs of forest based resources; improved agroforestry offers such scope.

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