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 $\mu g\ g^{-1}$. 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.■