EVALUATION OF FOREST CARBON STOCK AND LAND USE OF SOLAN FOREST DIVISION

Thesis

by

SHIPRA SHAH

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CERTIFICATE-I

This is to certify that the thesis entitled, **“Evaluation of forest carbon stock and land use of Solan Forest Division”,** submitted in partial fulfillment of the requirements for the award of degree of **DOCTOR OF PHILOSOPHY** in **FORESTRY (SILVICULTURE)** to Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.) is a record of bonafide research work carried out by **Ms. Shipra Shah (F-2008-11-D)** under my guidance and supervision. No part of this thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of investigation has been fully acknowledged.

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This is to certify that the thesis entitled, **"Evaluation of forest carbon stock and land use of Solan Forest Division"**, submitted by **Ms. Shipra Shah (F-2008-11-D)** to Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.), in partial fulfillment of the requirements for the award of degree of **DOCTOR OF PHILOSOPHY** in **FORESTRY (SILVICULTURE)** has been approved by the Student's Advisory Committee after an oral examination of the same in collaboration with the external examiner.

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This is to certify that all the mistakes and errors pointed out by the external examiner have been incorporated in the thesis entitled, **“Evaluation of forest carbon stock and land use of Solan Forest Division”**, submitted to Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.) by **Ms. Shipra Shah (F-2008-11-D)** in partial fulfillment of the requirements for the award of degree of **DOCTOR OF PHILOSOPHY** in **FORESTRY (SILVICULTURE)**.

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Place: Nauni, Solan
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ABBREVIATIONS

%	Per cent
°C	Degree centigrade
AGB	Aboveground Biomass
AGBD	Aboveground Biomass Density
AGCD	Aboveground Carbon Density
ANOVA	Analysis of Variance
B	Band
BD	Bulk Density
BEF	Biomass Expansion Factor
BGBD	Belowground Biomass Density
BGCD	Belowground Carbon Density
C	Carbon
CLUE-s	Conversion of Land use and its Effects
cm	centimeter
CO_2	Carbon Dioxide
CSAE	Climate Signal Age Effects
d.b.h	Diameter at Breast Height
DEM	Digital Elevation Model
DFO	Divisional Forest Officer
DN	Digital Number
dS	Desisiemens
e.g.	For example
EC	Electrical Conductivity
et al	And Coworkers
ETM	Enhanced Thematic Mapper
FCC	False Colour Composite
Fig.	Figure
g	gram
GHG	Green House Gases
GIS	Geographic Information System
GPG	Good Practice Guidance
GRDSS	Geographic Resources Decision Support System
Gt	Gigaton
GWLF	Generalized Watershed Loading Function
ha	hectare

HP	Himachal Pradesh
i.e.	that is
IADF	Intra-Annual Density Fluctuations
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing
kg	kilogram
km	kilometer
LAI	Leaf Area Index
LISS	Linear Imaging Self Scanner
LUCC	Land Use/Cover Change
LULC	Land Use and Land Cover
LULUCF	Land use, land-use change and forestry
m	meter
m asl	meter above sea level
m^3	cubic meter
MAXLIKE	Maximum Likelihood Classifier
Mg	Megagram
MINDIST	Minimum Distance to Means Classifier
mm	millimeter
NDVI	Normalized Difference Vegetation Index
NFI	National Forest Inventory
NIR	Near Infra Red
NPP	Net Primary Productivity
NRSA	National Remote Sensing Agency
NW	North western
OC	Organic Carbon
OECD	Organization for Economic Co-Operation And Development
PDSI	Palmer Drought Severity Index
Pg	petagram
pH	Puissance d'hydrogen
PIPED	Parallelepiped
ppm	Parts per million
PVI	Perpendicular Vegetation Index
R^2	Coefficient of Multiple Determination
RATIO	Ratio Vegetation Index
RMSE	Root Mean Square Error

RRW	Raw Ring Width
RSR	Reduce Simple Ratio
RWI	Ring Width Index
SAVI	Soil-Adjusted Vegetation Index
SCOPE	Scientific Committee on Problems of the Environment
SD	Soil Depth
SLEUTH	Slope, Land use, Excluded land, Urban extent, Transportation, and Hillshading
SOC	SOIL Organic Carbon
SPSS	Statistical Package for Social Sciences
SWIR	Shortwave infrared
t	ton
Tg	teragram
TM	Thematic Mapper
UN	United Nations
UNFCCC	United Nations Framework Convention On Climate Change
USA	United States of America
VIs	Vegetative Indices
VOB	Volume over Bark
yr	year

Chapter-1

INTRODUCTION

Chapter-1

INTRODUCTION

The human influence on the earth's climate is becoming more and more obvious. Climate observations prove the existence of a global warming trend: global average temperature has increased by 0.8°C since 1900 (Hansen *et al.*, 2006) and the 12 hottest years observed globally since 1880 all occurred between 1990 and 2005 (IPCC, 2007). Concerns about climate change arise from two basic premises that are accepted by the scientific community. The first is that greenhouse gases such as carbon dioxide and methane help to warm the atmosphere by slowing down the rate at which the Earth loses heat (Hengeveld, 2000). The second is that concentrations of these gases are increasing, in part due to human activities (Houghton, 2001). The increasing atmospheric carbon dioxide (CO2) concentrations over the last 150 years and the increasingly dramatic effects of climate change on ecosystems and humankind have reinvigorated the need to understand the terrestrial global carbon cycle. The ability of forests to both sequester and emit greenhouse gases coupled with ongoing widespread deforestation, has resulted in forests and land-use change being included in the United Nations Framework Convention on Climate Change (UNFCCC) and in the Kyoto Protocol (Kyoto, 1997).This global importance of forest ecosystems emphasizes the need to accurately determine the amount of carbon stored in different forest ecosystems.

Carbon is an essential element present in the main greenhouse gases, especially carbon dioxide (CO_2) and methane (CH_4). The concentration of atmospheric CO2 has increased from 315 ppm (in 1958) to 387.35 ppm in 2009 (NOAA, 2010). Atmospheric carbon dioxide concentration is now higher than at any time in the past 10 million years (Kennedy and Hanson 2006). The world's forests contain about 830 Pg C (10^{15} g) in their vegetation and soil, with about 1.5 times as much in soil as in vegetation. It is estimated that forests (including associated soils, peat deposits and lake sediments) hold 62-78% of the world's terrestrial biospheric carbon (IPCC, 2001). Since forests sequester C from the atmosphere as part of the growth process, any increase in forest biomass constitutes a sink that will reduce the build-up of atmospheric carbon dioxide. This emphasizes the importance of forest ecosystems in the global carbon cycle and the necessity to accurately evaluate the amount of C stored in forest ecosystems (Korner, 2006). However, anthropogenic activities involving forests, such as land use change can alter the amount and temporal distribution of C storage. (Adams *et al*., 1993; Haynes *et al*., 1994).

Over the last decade there has been increasing interest in the impacts of global land use and land cover change. There is considerable diversity of opinion about what constitutes land use. The OECD defines land use as the ‘functional dimension of land for different human purposes or economic activities’. Land use refers to "man's activities on land which are directly related to the land" (Clawson and Stewart, 1965). It represents the human use of land (for example small scale agriculture, grazing, wildlife reserves or industrial zones). Land cover, on the other hand, describes, "the vegetational and artificial constructions covering the land surface" (Burley, 1961). Land-cover refers to the physical characteristics of earth’s surface, captured in the distribution of vegetation, water, soil and other physical features of the land, including those created solely by human activities e.g., settlements. It represents the biophysical cover (for example savannah, forest, tea or built up areas). Land use change is the change from one land use to another over time (for example from forest to cultivation or cultivation to grazing).

Much of the land use and land cover change is a result of human activity (Houghton, 1994; Lambin, 1994; Riebsame *et al*., 1994) and currently recognized as one of the critical gaps in our knowledge of the terrestrial carbon cycle, which in turn has implications for greenhouse gas accumulation in the atmosphere and potential climate change (IGBP, 1999). Digital land use and land cover change detection is the process of determining and/or describing changes in land-cover and land-use properties based on coregistered multi-temporal remote sensing data. The basic premise in using remote sensing data for change detection is that the process can identify change between two (or more) dates that is uncharacteristic of normal variation. Remote sensing and GIS based change detection studies focus on providing the knowledge of how much, where, what type of land use and land cover change has occurred. Therefore in the present study the evaluation of land use of Solan Forest Division was done with a view to better understand the dynamics in the land use of the region.

Studies on the temporal distribution of biomass and forest carbon stock are important to combat the pressing problem of climate change. Accurate estimation of forest biomass is required for greenhouse gas inventories and terrestrial carbon accounting. Forest inventory-based approaches to estimate carbon stocks and flows use the NFI (national forest inventory) approach or other sampling networks that cover a wide range of conditions across a country or region (Kurz and Apps, 1999; Liski *et al*., 2002). In India, forest departments in the respective states conduct continuous forest inventories of various forest types for preparation of forest working plans. These inventories are aimed at estimation of growing stocks in the existing forests and projecting these stocks for the coming years. On a national scale, changes in the biomass and carbon stocks of trees can be estimated based on NFI (National Forest Inventory) data. The change can be estimated based on the difference between two consecutive inventories or on estimated increment and losses (drain). These two approaches are also recommended by the IPCC.

For both developed and developing countries, there is a strong need to know what happens in relation to carbon dynamics within their territories in order to implement conservation policies, as well as forest management and conservation strategies for these environments. Therefore, studies that quantify carbon stocks are important for forests. No studies on the temporal change in forest carbon stock have yet been conducted in Solan Forest Division, so it was felt that there was a need to quantify the carbon stocks in the region and also to assess the change in these stocks based on inventory data and field measurements.

Given the rapid rise of temperature and possible average increase in precipitation of about 3.4 per cent globally per 1^0C temperature rise that we face

(Allen and Ingram, 2002) it is critical that we take climatic factors into consideration in the assessment of forest growth and prediction (Bonan *et al*., 1990) especially in areas where climate change is likely to affect site factors and resultant forest growth and cover. Rising greenhouse gases and changes in the reflective properties of the earth's surface are predicted to raise global temperatures by 1.1–6.4 °C by 2100, and high-latitude forest regions may warm by almost 10°C (Christensen *et al*., 2007). Predictions of the future development of forest resources cannot be made without studying the responses of trees to climate change.

Sensitive to changes in environmental conditions that influence their growth, tree rings can be considered the rain gages and thermometers of the past. Tree rings, when viewed as time series of annual increments, present a valuable, long-term record of tree growth across many forest environments. The pattern of radial growth in trees depends largely on the climatic conditions of different localities (Chowdhury, 1939; Chowdhury, 1940; Rao and Dave, 1981). Tree species are unique in their response to environmental conditions and can be used as a fingerprint of recent climate change (Parmesan and Yohe, 2003; Root *et al*., 2003) and a natural archive of past climate (Fritts, 1976).

Increased surface temperatures of more than 20°C above pre-industrial levels are very likely to result in substantial changes in the structure and function of forest ecosystems (Fischlin *et al*., 2007). While the majority of climate change impacts are likely to be negative – especially in the long-term – it should not be forgotten that management strategies should also be adapted to utilize opportunities where they arise (e.g. improved tree growth). Such benefits, even if they are only of temporary nature, could increase the adaptive capacity of the sector and support long-term adaptation and innovation to better cope with climate change. This information should be progressively used in policy development to improve the resilience of forests to future climate.

Interest to estimate the possible effects of site factors and climate change on forest growth has a particular importance when dealing with Chir pine forests, a major component of sub-tropical pine forests which occupy an area of 3853 km^2 (10.40%) of total forest area at an altitudinal range of 600 to 2300 m in Himachal Pradesh. The timber has been put to multifarious uses such as railway sleepers, electric transmission poles, packing cases, pulpwood, general carpentry works and building construction and plays an important role in rural economy. But due to imposition of ban on green felling since 1985 its ecological significance has increased to a greater extent and it is expected that due to the imposition of such a ban the forest carbon stocks of the hill state will most likely enhance.

Currently there is a tremendous amount and diversity being carried out related to forest and carbon accounting with a variety of methods used for measurement. Remote sensing provides local/global estimates of carbon fluxes in forests. The strengths of remote sensing come from its ability to provide spatially explicit information and repeated coverage including the possibility of covering large areas as well as remote areas that are difficult to access otherwise. Remote sensing is a very valuable application in carrying out assessments of how climate change might be having an impact on forests by tracking major disturbances, changes in growing season and Net Primary Productivity (NPP). Remote sensing has opened an effective way to estimate forest biomass and carbon (Rosenqvist *et al*., 2003). According to the IPCC GPG (Intergovernmental Panel on Climate Change, Good Practice Guidance) (IPCC, 2003), remote sensing methods are especially suitable for verifying the national LULUCF (Land Use, Land-Use Change, and Forestry) carbon pool estimates-particularly the aboveground biomass. The purpose of verifying national greenhouse gas inventories is to establish their reliability and to monitor the accuracy of the numbers reported by independent means. Carbon accounting is needed to support the objectives of international agreements to mitigate global climate change (UN, 1998). In conjunction with other spatial datasets such as climate, soil type, and tree height, the forest coverage is important in the carbon cycle model. Therefore the present study will be carried out in Solan Forest Division with the following objectives:

1. To study land use change in Solan Forest Division
2. To study temporal change in carbon stock of forest stands, and
3. To study the impact of climate change on forest growth.

Chapter-2

REVIEW OF LITERATURE

Chapter-2

REVIEW OF LITERATURE

The traditional way of collecting forest data is through manual, field based observations. This approach has the benefit of generating highly accurate measurements, but due to its labour intensive nature, high cost associated with the length of time spent in the field and often constrained by lack of access this approach is generally not practical for anything other than local scale studies. However, the implications of forest analysis extend well beyond the local scale, and there is considerable need for forest investigation at wider spatial scales. As a result, the technique of remote sensing has become common in forest investigation providing the only realistic and cost effective way of acquiring data over larger areas. The technique has gained considerable importance in vegetation mapping and monitoring over the last two decades. (Aplin, 2003).

Remote sensing has been used directly in ecological studies to; investigate landscape patterns, to exploit correlations among physical, chemical and biotic parameters and to extrapolate known relationships over wider geographic areas or longer time periods (Kasischke, 2004). Kerr and Ostrovsky (2003) describe three main areas of ecological remote sensing. First, simple land cover classification is useful for straightforward identification of vegetation types and derivation of habitats. Second, integrated ecosystem measurements are invaluable in providing estimates of ecosystem function over large areas (entire ecosystems). In particular, there has been considerable recent interest in using remote sensing to derive biophysical parameters such as leaf area index (LAI) and net primary productivity (NPP), using Normalised Difference Vegetation Indices (NDVI) (Goetz, 2002). Third, change detection is essential for ecological monitoring and, given the continuous and stable nature of spaceborne image acquisition, remote sensing provides an excellent source of data for this purpose (Coppin *et al.*, 2004). In this chapter the relevant information relating to the study “Evaluation of Forest Carbon Stock and Landuse of Solan Forest Division” has been reviewed in the context of available literature under the following heads.

2.1 Land use/ cover classification and change analysis

Quantifying land use/cover change on larger spatial scales has particular interest in light of recent developments in international climate change treaties, focusing on national to regional trends rather than local trends (Archard *et al*., 2006; Santilli *et al*., 2005). By quantifying land use/cover change it may be possible to estimate carbon stock losses and/or gains and understand mechanisms and drivers of land use/cover change in and around the region of interest.

Land use involves both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation-the purpose for which the land is used. (Turner *et al*., 1995) Land use change is the end result of numerous interacting factors arising from different levels of associations of human-environment systems, which differ in time and space. As human-induced changes occur at an increasingly rapid pace, and as Earth observation data become ubiquitous, remote-sensing-based monitoring systems are expected to play further crucial roles in environmental policy and decision-making. Accurate monitoring of land cover is a matter of utmost importance in many different fields. Satellite- or airborne-based monitoring of the Earth's surface provides information on the interactions between anthropogenic and environmental phenomena, providing the foundation to use natural resources better (Lu *et al*., 2004). It enables refined policy development and the capacity to address otherwise inaccessible science questions (Cohen and Goward, 2004).

Remote-sensing change detection, defined by Singh (1989) as 'the process of identifying differences in the state of an object or phenomenon by observing it at different times', provides a means to study and understand the patterns and processes of ecosystems at a range of geographical and temporal scales. While the knowledge of land-cover conditions at a given point in time is important, the dynamics or trends related to specific change conditions offer unique and often important insights, ranging from natural disaster management to atmospheric pollution dispersion. Indeed, remotely sensed imagery is an important source of data available to characterize change systematically and consistently in terrestrial ecosystems over time (Coops *et al*., 2006). The basis of using remote sensing data for change detection is that changes in land cover result in changes in radiance values which can be remotely sensed. Techniques to perform change detection with satellite imagery have become numerous as a result of increasing versatility in manipulating digital data and increasing computer power. The capacity for large geographical coverage, high temporal frequency and low cost, combined with an increasingly wide selection of spatial and spectral resolution options, further enhances the use of remotely sensed imagery for land-cover change detection. Over the past three decades, numerous studies have been conducted to explore the feasibility and accuracy of image analysis applications for monitoring land-cover change (Singh, 1989; Coppin and Bauer, 1996; Mas, 1999; Aplin, 2004; Coppin *et al*., 2004; Lu *et al*., 2004).

2.1.1 Land Use/Cover Change Causes

LUCC can occur through the direct and indirect consequences of human activities to secure essential resources. This may first have occurred by means of burning of areas to develop the availability of wild game and it accelerated with the birth of agriculture, resulting in extensive clearing such as deforestation and earth's terrestrial surface management that takes place today (Ellis and Pontius, 2006). Underlying causes of land use and land cover (LULC) change include rapid economic development, population growth, urban expansion, poverty, expansion and intensification of agricultural activities, changes in river regimes, the effects of shifting cultivation, the spread of erosion and desertification and so on.

Landuse/ cover change is known as a complex process which is caused by the mutual interactions between environmental and social factors at different spatial and temporal scales (Valbuena *et al*., 2008; Rindfuss *et al*., 2004). More recently, industrial activities and developments, the so-called industrialisation, has encouraged the concentration of population within urban areas. This is called urbanization, which includes depopulation of rural regions along with intensive farming in the most productive lands and the abandonment of marginal lands (Ellis and Pontius, 2006). Land use changes are increasingly known as the consequence of actors and factors' interactions (Bakker and van Doorn, 2009). These conversions and their consequences are obvious around the world and it has been becoming a disaster around the metropolitan areas in developing countries.

2.1.2 Consequences of Land Use Change

Through land use change there is an increase in the built up area and related changes in the urban land use patterns, causing loss of productive agricultural lands, forest cover, other forms of greenery, loss in surface water bodies, depletion in ground water aquifers and increasing levels of air and water pollution; causing environmental problems. (Giri *et al*., 2003). Broadly land use change has the following consequences.

Loss of Biodiversity

Biodiversity has been diminishing considerably by land use change. While lands change from a primary forested land to a farming type, the loss of forest species within deforested areas is immediate and hug. According to Ellis and Pontius (2006): The habitat suitability of forests and other ecosystems surrounding those under intensive use are also impacted by the fragmenting of existing habitat into smaller pieces, which exposes forest edges to external influences and decreases core habitat area.

Climate Change

Land use and cover change matters play a significant role in climate change at different scales such as regional, local and global scales. At global scale, LUCC is accountable for releasing greenhouse gases to the atmosphere, thus leading to global warming. LUCC is able to increase the carbon dioxide balance to the atmosphere by disturbance of terrestrial soils and vegetation. Furthermore, LUCC undoubtedly plays an essential role in greenhouse gas emissions.

Pollution

Tree harvesting, land clearing and other forms of biomass damage to the environment arising from land use change increase the pollution percentage of the environment. Vegetation removal makes soils vulnerable to a massive increase in wind and water soil erosion forms, particularly on steep topography. When accompanied by fire, pollutants to the atmosphere are released. Soil fertility degradation within time is not the only negative impact; it does not only cause damage to the land suitability for future farming, but also releases a huge amount of phosphorus, nitrogen, and sediments to aquatic ecosystems, causing multiple harmful impacts. All of these issues drive water, soil and air pollution at large scale. Besides, other agricultural activities such as using herbicides and pesticides also release toxics to the surface waters, which sometimes remain in the top soil.

Other Impacts

Other environmental impacts of LUCC include the destruction of stratospheric ozone by oxide release from agricultural land and altered regional and local hydrology. Moreover, the most urgent concern for a great part of the human population and most governments is the long-term supply and production of food and other fundamentals required in the future. (Pontius and Chen, 2006).

2.1.3 Driving Forces of the Land Use/Cover Changes

Assessing the driving forces behind LUCC is essential if previous patterns can explain and be utilised in forecasting future patterns. Land use and cover change can be caused by multiple driving forces that control some environmental, social and economic variables. These driving forces can contain any factor which influences human activities, including local culture, economic and financial matters, environmental circumstances (i.e. greenness, land quality, terrain situation, water availability and accessibility to recreation), current land policy and development plans, and also interactions between these factors. Therefore, these drivers have to be found to pursue these controlling variables. The driving forces will be utilised in order to manage land use change. Investigation of interrelations between the drivers of land use change needs a strong knowledge about methods and effective variables, as well as land policy (Ellis and Pontius, 2006). LUCC is frequently addressed through various selected biophysical and socioeconomic variables. In order to facilitate simulation, driving factors are mostly considered exogenous to the land use system (Verburg *et al*., 2004). Associations between driving forces and LUCC could be addressed qualitatively and quantitatively by means of appropriate approaches.

The expansion of agriculture through conversion of forests and grassland during the past 140 years has led to a net release of about 121 gigatons of carbon, of which about 60% has been emitted in the tropics, mostly during the last 50 years (IPCC, 2000). The U.S. Department of Agriculture (1972) reported that during the decade of the 1960's 730,000 acres (296,000 hectares) were urbanized each year, transportation land uses expanded by 130,000 acres (53,000 hectares) per year, and recreational area increased by about 1 million acres (409,000 hectares) per year.

Basnyet (1989) in a study classified land use of Kankani panchayat located in north-west of Kathmandu valley in the middle hills of Nepal into outward terrace, forest, flat terrace, scrub, crop, gullies and pasture and found that estimated percentage of each land use category to the total geographical area was as 37.1, 36.9, 12.8, 5.6, 5.4 and 2.2, respectively.

Flint and Richards (1991) studied the historical changes in land use and carbon stock of vegetation in south and southeast Asia. Three land-use change case studies in India and Burma were examined at the level of ecological zone to illustrate different processes of deforestation, viz. (1) agricultural expansion in the Burma Delta, (2) commercial overfelling in Chamba, Himachal Pradesh and (3) shifting cultivation in Meghalaya. For the entire study region, the estimated standing stock of carbon in biomass declined by 2.62 Gt over the century. Release by periods was 911 Mt for 1880-1920, 750 Mt for 1920-50, and 864 Mt for 1950-80. Forest-woodland and interrupted woods vegetation released carbon equivalent >90% of the total release. Both conversion of forest to other vegetation types and reduction over time of biomass within vegetation types contributed significantly to decrease in total standing carbon stock during the period.

Gupta (1996) investigated the land cover for Shimla district (H.P.). He used Landsat TM satellite data. The various land cover types reported were agriculture, mixed alpine, fir-spruce, oak, deodar-fir-spruce, grassland, broadleaved pine and snow. It was reported that minimum area was under deodar-fir-spruce (4.63%) and maximum area under miscellaneous tree species and snow cover.

Jaiswal *et al*. (1999) studied the application of remote sensing technology for land use/land cover change analysis over a period of 30 years in a part of Gohparu block, Shahdol district of Madhya Pradesh. Land use/ land cover maps were prepared by visual interpretation of two period remotely sensed data. Post-classification comparison technique was adopted for this purpose. The loss of vegetation cover was estimated to be 22 percent and 14 percent of the land was found to have been transformed into wasteland between 1967 and 1996. Overall rate of change was found to be 1.8 percent per year during this period.

Kumar (1999) classified the land use of Moul khad catchment in sub-humid mid-hill zone of Himachal Pradesh into cultivated, forest, scrub land, degraded grassland, built up and river bed. The area under each land use class was estimated to be 38.6, 29.4, 8.3, 9.8, 13.4 and 0.5 percent, respectively.

Pum Vicheth *et al*. (2001) conducted a study on landuse in Cambodia using Landsat MSS imageries of 1984 and 1985 and landsat TM imagery of 1991. The study area included 8 districts: Stung Trang district (110,155 ha), Kampong Siem (42,290 ha), Kampong Cham Provicial Town (2,597 ha), Kang Meas (38,220 ha), Batheay (68,122 ha), Chamkar Leu (55,054 ha), Cheung Prey (36,815 ha) and Prey Chhor (49,129 ha). Satellite imageries were classified by unsupervised classification into 5 major classes: settlement, agriculture, forest, water body and bareland. Land cover and land use in 1984 indicated that forests covered 40% of the study area, agriculture 50%, barren land 0.3% and settlement 1.3%. From 1984 to 1991, agriculture land increased by about 6% of total study area and loss in forest cover was about 6% (21710 ha).

Tomar *et al*. (2002) prepared a site specific action plan of Upper Shipra Watershed (USW) in Ri-Bhoi district of Meghalaya by integrating natural resources information generated from satellite data in conjunction with other conventional and socio-economic data. Forest was the main land use (76.4%) of the watershed followed by agriculture (shifting cultivation) and the remaining land was under settlement, pasture, barren hills, ponds, quarry, etc.

Ramachandra and Kumar (2004) studied land use and land cover dynamics of Kolar district in Karnataka using GRDSS (Geographic Resources Decision Support System). Land cover analysis was done by computing Normalized Difference Vegetation Index (NDVI) which showed 46.03 % area under vegetation and 53.98 % area under non-vegetation. Land use analysis was done by both supervised classification (accuracy 94.67 %) and unsupervised classification approach (accuracy 78.08 %) using Gaussian Maximum Likelihood Classifier (GMLC) to classify the data into five categories (agriculture, built-up, forest, plantation and waste land) The Land use analyses indicated increase of non-vegetation area from 451752 ha. (54.84% in 1998) to 495238 ha (60.17% in 2002). The results also showed decrement in forest area and increment in builtup (18.79 %), plantation (12.53 %) and waste land (41.38 %) in 2002 against that in 1998 builtup-(15.96%), plantation (8.53%) and waste land (38.88%).

Spadavecchia (2004) estimated land-use change for the Nhambita Community Forest, Mozambique by differencing the classifications for Landsat 2

MSS image 1979, Landsat 5 TM image 1991 and Landsat 7 ETM+ images 2000, 2003. Qualitative investigation of land-use change within the Nhambita region was carried out via calculation of Tasselled Cap components, and textural measures based on Fractal Dimension. Extensification of agricultural activity was evident from these images. Deforestation for agricultural conversion proceeded at a rate of about 0.6 km^2 $year^{-1}$ from 1991 to 2000, corresponding to an area of around 6 ± 1 km^2. Forest degradation in the region, as quantified by a 10% reduction in NDVI, proceeded at a rate of 2.4 km^2 $year^{-1}$. Estimation of forest degradation through change in canopy roughness indicated a rate of around 1.5 km^2 $year^{-1}$, corresponding to an area of 15 ± 1 km^2.

Jain *et al*. (2005) did the analysis of vegetation and land use change in Khecheopalri sacred lake watershed and concluded that anthropogenic pressure had led to land use/cover change of the watershed in the past decade with increase of agricultural land at the expense of forests. The pressure of grazing was also high resulting in removal of 47% of annual primary production of floor phytomass.

Semwal *et al*. (2005) reported that the root cause of changes among land use and land cover types in the Jaintia Hills of Meghalaya, was coal mining, by using remote sensing techniques. The overall rate of change was found as 2.16% per year. This includes 0.1% per year change due to coal mines. The agricultural land was reduced by 26.40 km^2 or 22.35% out of its total area and the land was transformed into coal mines, habitation related to coal mines and abandoned agricultural land classified as grassland/scrub.

Willson (2006) quantified forest cover and land use changes in a Tibetan-dominated rural township in northwest Yunnan, China—an ecologically important region affected by recent forest policy changes. Three sequences of Landsat satellite imagery dating from 1981 to late 1999 and other digital datasets were used in a rules-based hybrid classification approach. The results showed a decline in conifer forests of 23%, mostly due to an active logging industry. Much of this forest has converted to shrubland, which increased in area by over 100%. Grassland also increased, mainly at the expense of cultivation, as a response to increasing dependence on livestock by the rural communities, although high elevation rangelands decreased in area due to changing livelihoods and restrictions by the government on grazing and deliberate burning. Conversion analysis revealed significant forest–shrubland exchanges occurring even during the 1990s when reduction in overall forest cover slowed considerably.

Achard *et al*. (2006) revealed that human influence on the Russian forest landscape has been growing over recent decades, mainly as a consequence of logging activities and human-induced fires. Rapid land-cover change is not randomly or uniformly distributed but is clustered in some locations, e.g., high intensity logging mostly takes place in the European part of Russia (e.g., in the Karelian Isthmus) and along the southern border of the taiga. Annual forest cover change rates in areas identified as rapid change areas ranged from 0.26% for diffuse logging activities to 0.65% for areas affected by intense clear-cutting activities, up to 2.3% for areas affected by fires or a combination of fires and logging.

Brandt and Townsend (2006) followed supervised classification techniques, and spectral mixture analysis to characterize current landscape patterns and quantify land cover change from 1985 to 2003 in the Altiplano (2535-4671 m) and Intermediate Valley (Mountain) (1491-4623 m) physiographic zones in the Southeastern Bolivian Andes. Current land cover was mapped into six classes with an overall accuracy of 88% using traditional classification techniques and limited field data. The land cover change analysis showed that extensive deforestation, desertification, and agricultural expansion at a regional scale occurred in the last 20 years (17.3% of the mountain zone and 7.2% of the Altiplano).

Demirci *et al*. (2006) conducted a study on land use changes from 1963 to 2005 for Kucukcekmece lake watershed in Istanbul. Land uses classification was done by utilizing a Corona 1963 satellite image, an aerial photography from 1996 and a 2004 IKONOS high resolution image. There was a dramatic shift in the land use composition within the watershed from 1963 to 2005. In 1963, most of the land use was agricultural and open space (98%). Residential areas were sparse (1%) and there were no industrial buildings in the area. By 1996, the residential areas increased dramatically but still only occupied a small amount of the watershed area (16.92 %). There was considerable increase in residential growth from 1996 to 2004 (42%). In 2004, the watershed consisted of agricultural land (42%); residential areas (24%); open land including bushes and marsh around the lake (23%); industry and commercial land uses (4%); institutional lands including military, customs house, and a football stadium (3%); construction areas for new houses (2 %); a major expressway, Trans European Motorway (TEM), (1 %); mining (0.4%) and forest (0.2%).

Chen *et al*. (2006) used spatially explicit process-based biogeochemical model (Terrestrial Ecosystem Model [TEM] 4.3) to simulate the effects of cropland expansion and forest regrowth on the carbon dynamics in Southern United States. The pattern of land-cover change was primarily driven by the change of cropland, including cropland expansion and forest regrowth on abandoned cropland. The TEM simulation estimated that total carbon storage in 1860 was 36.8 Pg C, including 10.8 Pg C in the southeast and 26 Pg C in the south-central. During 1860-2003, a total of 9.4 Pg C, including 6.5 Pg C of vegetation and 2.9 Pg C of soil C pool, was released to the atmosphere in the southern United States. The net carbon flux due to cropland expansion and forest regrowth on abandoned cropland was approximately zero in the entire southern region between 1980 and 2003.

Wolter *et al*. (2006) while studying the land use / land cover change in the U.S. Great Lakes basin observed that 2.5% (798755 ha) of the U.S. portion of the Great Lakes watershed experienced change between 1992 and 2001. Transitions due to new construction included a 33.5% (158 858 ha) increase in low-intensity development and a 7.5% (140 240 ha) increase in road area. Agricultural and forest land each experienced 2.3% (259244 ha and 322463 ha, respectively) decrease in area. Despite the large and enduring agricultural losses observed (2.23% of 1992 agricultural area), the rate of agricultural land decrease between 1992 and 2001 was less than that reported by the EPA (-9.8%) for the previous 10-year period. Areas of new development were largely concentrated near coastal areas of the Great Lakes. Over 38% (6,014 ha) of wetland losses to development between 1992 and 2001 occurred within 10 km of a coastal area, and most of that area was within the nearest 1 kilometer.

Singh *et al*. (2007) studied land uses in Nagin watershed of Uttarakhand using GIS and remote sensing and observed that the agricultural area had reduced from 66.71 to 32.75% over a period of 42 years. At the same time, 13.51% area revealed that the forest area increased by approximately 100% including both dense and moderately dense forest.

Tian *et al*. (2007) used the TM imageries of 1986, 1996 and 2000 to study land use change in Haikou city. They found that urbanization was the driving force of land use change. From 1986 to 1996 the cultivated land, water and unused land decreased while the urban, rural settlement and construction site increased. From 1996 to 2000 the cultivated and construction land increased while the forest decreased. During the period of 1986 to 2000 the cultivated land decreased by 37.87% and the annual decrease rate was 3.34% and the forest lessened by 8%. Water decreased by 84% and annual decrease rate was 12.4%. The built-up area increased by 211% and the growth rate was 8.43% per year. The rural area increased by 94.76% and the growth rate was 4.87% per year. Construction increased by 51.95% and the growth rate was 3% per year.

Sharma and Rai (2007) on the basis of satellite imageries for 1988 and 2001, studied land-use cover change and associated carbon stock and flux in Mamlay watershed of Sikkim Himalaya, India. The total area of forest decreased by 28%, whereas open cropped area increased by more than 100%. Across the land-use cover, total mean carbon(C) densities ranged from 46 Mg ha^{-1} in open temperate cropped area to a high of 669 Mg ha^{-1} in temperate natural dense forest. The heavily converted areas lost an estimated 55% of their total 1988 C pools, whereas the low-impacted areas lost only 0.12%. Changes in land use released 7.78 Mg C ha^{-1} yr^{-1}, demonstrating that land-use changes significantly affected C flux.

Meyfroidt and Lambin (2008) estimated the forest transition in Vietnam and its environmental impacts. Using Fuzzy Kappa and other indicators, they compared forest cover estimates and spatial patterns from global and national land cover maps from the early and late 1990s, and compiled other available statistics for years before and after that period. This showed that a forest transition occurred in Vietnam: the forest cover dropped to 25-31% of the country area in 1991-1993, and then increased to 32-37% in 1999-2001. The carbon stock in forests followed a similar transition, decreasing to 903 (770-1307) Tg C in 1991-1993, and then increasing to 1374 (1058-1744) Tg C in 2005. However, forest density declined during the same period, with an increasing proportion of young and degraded forests. The effects on habitats measured with landscape pattern indices were contrasted: in several regions, reforestation decreased forest fragmentation, while in others, clearing of old-growth forests continued and/or forest fragmentation increased.

Li *et al.* (2008) while studying past, present and future land-use in Xishuangbanna, China and the implications for carbon dynamics found that land use/land cover change is an important driver of global change and changes in carbon stocks. They combined detailed land use change over a 27 year period based on satellite images and forest inventory data to estimate changes in biomass carbon stocks in the Xishuangbanna prefecture (1.9 million ha) of China. From 1976 to 2003, the mean deforestation rate was 13, 722 ha yr^{-1} (1.12%), and this resulted in the loss of 370 494 ha of forest, and by 2003 total biomass carbon stocks had been reduced to 80.85±2.64 Tg C. The annual carbon emissions due to land use change, mainly forest conversion to agriculture and rubber (*Hevea brasiliensis*) plantations, were 0.37±0.03 Tg C yr^{-1} between 1976 and 1988 and 0.13 ± 0.04 Tg C yr^{-1} between 1988 and 2003.

Reis (2008) investigated LULC changes in Rize, North-East Turkey. Supervised classification technique was applied to Landsat images acquired in 1976 and 2000. Image Classification of six reflective bands of two Landsat images was carried out by using maximum likelihood method with the aid of ground truth data obtained from aerial images dated 1973 and 2002. The second part focused on land use land cover changes by using change detection comparison (pixel by pixel). In third part of the study, the land cover changes were analyzed according to the topographic structure (slope and altitude) by using GIS functions. The results indicated that severe land cover changes occurred in agricultural (36.2%) (especially in tea gardens), urban (117%), pasture (-72.8%) and forestry (-12.8%) areas between 1976 and 2000. It was seen that the LULC changes mostly occurred in coastal areas and in areas having low slope values.

Halim *et al*. (2008) while studying the land use pattern change over a period of 18 years (1988-2006) in the West Bhanugach Reserved Forest, in Sylhet Forest Division of Bangladesh found that vegetation cover decreased drastically from the year 1988 to 1996 (1826 ha to 1714.85 ha), but increased gradually from the year 1996 to 2006 (1714.85 ha to 1847.83 ha) due to initiation of co-management practice involving local communities. The area of water bodies increased from the year 1988 to 1996 (307.67 ha to 379. 53 ha), but decreased from the year 1996 to 1997, then remained invariable from the year 1997 to 2006.

Sarma *et al*. (2008) studied land use change in Manas National Park using satellite imageries of 1977, 1998 and 2006. Results indicated a substantial increase in savannah grasslands (74.6%) accompanied by a decline in alluvial grasslands (46.8%) from 1977 to 2006. A total of 20.47 km^2 was also encroached during this period. Water sources also declined and there was a shift towards a drier and woodland type of vegetation. These land use changes were due to the non implementation of habitat management activities.

Tiwari *et al*. (2008) studied land use and biomass in Khanda watershed, Garhwal Himalaya using remote sensing data. The results reported total above ground biomass in oak forest, mixed oak forest and chir pine forest as 272.87 t ha^{-1}, 259.28 t ha^{-1} and 174.16 t ha^{-1}, respectively.

Lin *et al*. (2008) monitored and simulated urban sprawl and its effects on land-use patterns and hydrological processes in urbanized watersheds. A novel framework to the urban growth model was applied - Slope, Land use, Excluded land, Urban extent, Transportation, and Hillshading (SLEUTH) and land-use change with the Conversion of Land use and its Effects (CLUE-s) model using historical SPOT images to predict urban sprawl in the Paochiao watershed in Taipei County, Taiwan. The historical and predicted land-use data was input into Patch Analyst to obtain landscape metrics. This data was also input to the Generalized Watershed Loading Function (GWLF) model to analyze the effects of future urban sprawl on the land-use patterns and watershed hydrology. The landscape metrics of the historical SPOT images showed that land-use patterns changed between 1990–2000. The land-use patterns predicted by the SLEUTH and CLUE-s models showed the significant impact urban sprawl will have on land-use patterns in the Paochiao watershed. The historical and predicted land-use patterns in the watershed tended to fragment, had regular shapes and interspersion patterns, but were relatively less isolated in 2001–2025 and less interspersed from 2005–2025 compared with land-use pattern in 1990. During the study, the variability and magnitude of hydrological components based on the historical and predicted land-use patterns were cumulatively affected by urban sprawl in the watershed; specifically, surface runoff increased significantly by 22.0% and baseflow decreased by 18.0% during 1990–2025.

Reddy (2009) studied land cover classification using IRS – LISS III satellite image and Digital Elevation Model (DEM) in hilly environment of Nongkhyllem Wildlife Sanctuary, Meghalaya. Maximum likelihood classifier algorithm of ERDAS imagine 9.1 version was used to secure supervised classification of pixels into various land use types and vegetation types among the forest class cover. Normalised Difference Vegetation Index (NDVI) value of the LISS III satellite imagery was also computed. Digital Elevation Model of the Sanctuary was erected in the GIS domain. Such GIS database was integrated with remote sensing data in proof of Integrated Geographic Information System capabilities to achieve higher accuracy in classification. There was indeed marked increase in classification accuracy on account of such integration. Bivariate correlation analysis was performed between spectral and DEM variables to cross check the results.

Panigrahy *et al*. (2010) quantified change in forest area of the Western Ghats of Maharashtra over a 20 year time period (1985-87 to 2005) using visual interpretation technique at 1:250 K scale. The study was conducted using the Forest Survey of India vegetation maps for 1985-87, prepared using Landsat TM data and IRS LISS III imagery for 2005. The results revealed loss of dense forest at an annual rate of 0.72% and that of open forest at 0.49%. There was also an increase in mangrove vegetation and water bodies in the study area.

Sreenivasulu and Bhaskar (2010) prepared a landuse / landcover maps of Devak catchment for the years 1958,79,90 and 98 by image processing and visual interpretation technique from the analysis of the IRS-1A L2B2 (FCC) data for the year 1990, IRS-1C LISS-III (digital data) for the year 1998 and SOI topographic maps for the year 1958 and 1979. Level-I classification was adapted and the various categories of landuse were, mixed forest mainly pine, agriculture with sparse habitation, open scrub with scattered trees and water bodies (river). Results revealed a large change in the area of different landuse categories during the period from 1958 to 1998.The open scrub and scattered tress covering an area of about 46.17% in 1958 reduced to 9.90% in 1998, while the area under mixed forest increased from 36.68% in 1958 to 65.84% in 1998. The agriculture with sparse habitation also increased from 7.09 % in 1958 to 13.92 % in 1998.

Raj and Azeez (2010) conducted a study on the spatial and temporal changes in land use and land cover (LULC) using Remote Sensing and GIS of Bharathapuzha river basin, south India using multispectral LANDSAT imageries of 1973-2005 time periods. 31% depletion in the natural vegetation cover and 8.7% depletion in wetland agriculture area were seen in the basin during the period. On the other hand the urban spread in the basin increased by 32%.

Jeganathan *et al*. (2011) analysed the landuse and land cover change of Shimla District using Bayesian model, with the focus on the forests of the region. Land cover maps were prepared for the periods 1970's, 1980's and 1990's using remote sensing data. The actual positive changes (increase in forest) and negative changes (decrease in forest) derived from the time series land cover maps were used as evidence in the Bayesian model to derive the statistical weights for various environmental parameters. The environmental parameters were analysed under 4 major group of factors i.e. topographic, landuse, landscape and land-water. The probabilistic contribution (i.e. weight) of each attribute under each map was utilized within the weighted summation model to derive spatial maps of potential positive and negative change. Accuracy of the model was validated using actual change maps and was found to be 85% for the positive change and 80% for the negative change. The resultant predicted maps of positive and negative change were overlaid together and potential zones of conservation and afforestation were identified.

2.2 Carbon stock of forest stands and carbon storage potential

International concern about the effects on climate of increased atmospheric concentrations of greenhouse gases such as carbon dioxide has focused policy attention on the dynamics of carbon in terrestrial vegetation and soils. Forests absorb carbon dioxide (CO2) from the atmosphere during photosynthesis and release it during respiration and the decay of dead plant material. Approximately 120 billion tonnes of carbon (Gt C) is absorbed annually through photosynthesis and comparable amount is released through respiration and decomposition (Kartha, 2001). Carbon sequestration is the provision of long term storage of carbon in the terrestrial biosphere, belowground or the ocean so that the build up of CO_2 concentration in the atmosphere will reduce or slow down in order to improve environmental conditions and check the process of environmental degradation especially through forestry, horticulture and agriculture.

Many natural and artificial processes can act as atmospheric sponges that absorb carbon dioxide. Ocean, forests, most plants and algae collect carbon through the photosynthesis process. This capturing of atmospheric carbon by a healthy ecosystem is called a “Carbon Sink”. While all living plants matter absorbs CO2 as part of photosynthesis, trees process significantly more than smaller plants due to their large size and extensive root structure. In essence, trees, as kings of plants world, have much more “woody biomass” to store CO2 than smaller plants, and as a result are considered nature’s most efficient “Carbon Sinks”. The rate of carbon absorption and hence the magnitude of the carbon sink, is greatest in the earliest stages of regeneration and declines as forests mature. The amount of carbon stored in forests can change over time because of:

- natural variation in climatic factors such as temperature and rainfall;
- the natural developmental or successional dynamics of vegetation; or
- disturbances such as fires, storms, or pest and disease outbreaks.

Carbon sequestration is the process of removing additional carbon from the atmosphere and depositing it in other reservoir principally through changes in land use. In practical terms carbon sequestration occurs mostly through the expansion of the forests or by conserving them (Houghton, 1996). Therefore, terrestrial carbon sequestration is the net removal of CO2 from the atmosphere and storing it in terrestrial ecosystems (Sedjo and Marland, 2003). So, forest expansions and sustainable forests, as mitigation measures, have a significant contribution to the environmental benefit but any shrinkage of forests, as emission, has a long term influence and impact. (Levy *et al*., 2004).

Among all the terrestrial ecosystems, forests contain the largest store of C (IPCC, 2001; Schlesinger, 1997; SCOPE, 1984). The main C pools in forests are plant biomass (above and below-ground), coarse woody debris, litter and soil (Richards and Evans, 2004). These C pools continue to increase over the life cycle of a forest towards a state of equilibrium when respirational CO2 losses by plants and soils and decomposition of biomass equals rate of growth (Acker *et al.,* 2002; Smithwick *et al.,* 2002). Where forest growth is disturbed or the forest is destroyed, CO2 and other greenhouse gases i.e. methane, (CH4), nitrous oxide (N2O) are released back into the atmosphere via respiration, combustion or decomposition (IPCC, 2003; Richards and Evans, 2004). The need for reporting carbon stocks and stock changes for the Kyoto Protocol have placed additional demands for accurate surveying methods that are verifiable, specific in time and space, and that cover large areas at acceptable cost (IPCC, 2003; Krankina *et al*., 2004). The developing countries could receive investments from companies and governments wishing to offset their emission of greenhouse gases through the Kyoto Protocol's Clean Development Mechanism and other such future agreements (Fearnside, 1999).

Houghton *et al*. (1987) reported that deforestation in the tropics is responsible for an annual net release of carbon to the atmosphere, estimated for 1980 at 0.5-4.2 x 10^{15}g. Comparative carbon release from fossil fuel combustion in 1980 was 5.2 x 10^{15} g. The wide range of estimates for the tropical biota and soils has been primarily caused by different estimates of the rate of deforestation.

Rana *et al.* (1989) studied plant biomass and net primary productivity of a series of forests located along an altitudinal gradient (300–2200 m) in the Central Himalaya. The climate in most of the area is humid with the monsoon patttern of rainfall. The biomass ranged between 199 and 787 t ha^{-1}, the lower values being for early successional forests, such as chir pine (*Pinus roxburghii* Sarg.) forest. The net primary productivity was in the range 12.8–27.9 t ha^{-1}year^{-1} and was not related to the elevation. In fact the entire elevational range seems to have the potential to support high biomass and productivity values.

Brown *et al.*(1996) estimated that in high-latitude forests, about 2.4 Pg of C could be potentially sequestered and conserved by forest management practices from 1995 to 2050, and this is equivalent to about 0.46 tones of C sequestered and conserved per hectare per year. For Canada, 15 Pg of C was in vegetation and 76 Pg of C in soils, which resulted in a 0.08 Pg yr^{-1} of C sink.

Negi and Chauhan (2002) while working on biomass and productivity of Sal forest (*Shorea robusta)* concluded that Sal accounted for carbon storage between 18.5-98.1% of the total crop at 11 representative sites.

Goodale *et al*. (2002) studied forest sector carbon budgets for Canada, U.S.A., Russia, China and Europe and concluded a general agreement that terrestrial systems in the northern hemisphere provided a significant sink for atmospheric CO_2, Northern forests and woodlands provided a total sink of 0.6-0.7 Pg yr^{-1} of C per year during early 1990's, consisting of 0.21 Pg yr^{-1} in living biomass, 0.08 Pg yr^{-1} in forest products, 0.15 Pg yr^{-1} in dead wood and 0.13 Pg yr^{-1} in the forest floor and soil organic matter.

Kraenzel *et al.* (2003) estimated the carbon storage potential of 20 years old Panamanian teak (*Tectona grandis*) plantations. A regression relating diameter at breast height (DBH) to total tree carbon storage was constructed and used to estimate plantation-level tree carbon storage, which averaged 120 t/ha. Litter, undergrowth and soil compartments were estimated to contain 3.4, 2.6 and 225 t C/ha, respectively. The soil carbon was a one-time measurement, not an estimate of soil C accumulation. The carbon storage in Panamanian harvest-age teak plantations was estimated to be 351 t C/ha.

Jha and Gupta (2005) reported estimated biomass carbon of 48.90 mt in Himachal Pradesh, and 162.49 mt of carbon sink in forest biomass in the neighbouring states i.e. Haryana, Punjab, J & K and U.P.

Gera *et al.* (2006) studied carbon sequestration potential and cost effectiveness of tree growing operations on farm lands of Rupnagar district of Punjab (India). Project based – comprehensive mitigation analysis process (PRO-COMAP) was used to estimate the sequestration potential between 2005-2030 under three models namely; poplar block planting, poplar bund planting and eucalypt bund planting. The poplar block plantation gave maximum sequestration potential of 115 t/ha which was higher by 79.69% and 105.34% *w.r.t.* poplar bund plantation and eucalypt bund planting, respectively.

Sanneh (2007) worked on the status of carbon stock under different land use systems in wet temperate north-western Himalayas at different altitudinal gradients viz., 1500 m -1800 m a.s.l, 1800 m -2100 m a.s.l and 2100 m – 2400 m a.s.l. Result of his finding indicated that maximum above ground biomass (308.96 t ha^{-1}), below ground biomass (62.09 t ha^{-1}) and total biomass (371.06 t ha^{-1}) was in the forest land use system. It was followed by silvi-pasture, agri-silvipasture, agri-horticulture, agriculture and grassland systems, respectively. The rate of biomass production (t ha^{-1}) increased with increasing altitudinal ranges. The rate of total biomass production at 1500 m-1800 m, 1800 m- 2100 m, 2100 m-2400 m a.s.l was 106.31 t ha^{-1}, 113.19 t ha^{-1}, and 141.41 t ha^{-1}, respectively.

Ramachandran *et al*. (2007) felt the need for a carbon databank is in the context of mitigating climatic changes. As a pilot study, carbon stock in a natural forest area of Kolli hills, part of the Eastern Ghats of Tamil Nadu, India was estimated using geospatial technology. The total biomass, both above and below ground, was calculated and the total carbon stock estimated. Likewise, the sequestered soil organic carbon was also estimated. The biomass carbon estimated was 2.74 Tg and the soil carbon was 3.48 Tg. The lesser soil organic carbon indicated that the forest area was severely affected by degradation due to various need-based forestry practices and anthropogenic disturbances. A national-level carbon databank is envisaged for all types of forest in India to study the temporal change and carbon sequestration potential for better management of forests.

Fang *et al.* (2007) studied the biomass production and carbon sequestration potential of 10 years poplar plantations with different management patterns i.e. four planting densities (1111, 833, 625 and 500 stems ha^{-1}) and three poplar clones (NL-80351, I-69 and I-72). Based on the model of total biomass production developed, total plantation biomass production was significantly different in the plantations. The ranking of the plantation biomass production by planting density was 1111>833>>625>500 stems ha^{-1}, and by components was stem > root >> branch > leaf for all plantations. At 10 years, the highest total biomass in the plantation of 1111 stems ha^{-1} reached about 146 t ha^{-1}, which was 5.3%, 11.6% and 24.2% higher than the plantations of 833, 625 and 500 stems ha^{-1}, respectively. The annual increment of biomass production over 10 years differed significantly among initial planting densities and stand ages ($p<0.01$), but no significant difference was observed from age 7 to 10. Mean carbon concentration among all biomass components ranged from 42-50%, with the highest carbon concentrations in stems and the lowest in leaves.

Minj (2008) found that in low and mid hills of Western Himalayan during year 2004-06 the mean biomass carbon stock and CO_2 sequestration in Zone-I (sub montane low hills) was 2.09 times higher than in Zone-II (mid hills). Maximum mean total carbon stock (107.00t ha^{-1}) was observed in pure plantation system of poplar at an average density of 4066 trees/hectare. It was 2.68-4.86 times higher than other perennial plant based system and about 12.40-22.57 times higher than annual crops as pure grassland system.

Keith *et al*. (2009) from analysis of published global site biomass data (n = 136) from primary forests discovered that the world's highest known total biomass carbon density (living plus dead) of 1,867 tonnes carbon per ha (average value from 13 sites) occurs in Australian temperate moist *Eucalyptus regnans* forests, and average values of the global site biomass data were higher for sampled temperate moist forests (n =44) than for sampled tropical (n = 36) and boreal (n = 52) forests (n is number of sites per forest biome).

Jana *et al.* (2009) studied the carbon sequestration rate and aboveground biomass carbon potential of four young species i.e. *Shorea robusta, Albizzia lebbek, Tectona grandis* and *Artocarpus integrifolia.* The carbon sequestration rate (mean) from the ambient air during winter season as obtained by *Shorea robusta*, *Albizzia lebbek*, *Tectona grandis* and *Artocarpus integrifolia* were11.13, 14.86 and 2.57g ha^{-1} in overcast skies and 4.22 g ha^{-1}, respectively. The annual carbon sequestration rate from ambient air were estimated at 8.97 t C ha^{-1} by *Shorea robusta,* 11.97 t C ha^{-1} by *Albizzia lebbek,* 2.07 t C ha^{-1} by *Tectona grandis* and 3.33 t C ha^{-1} by *Artocarpus integrifolia.* The percentage of carbon content (except root) in the aboveground biomass of *Shorea robusta, Albizzia lebbek, Tectona grandis* and *Artocarpus integrifolia* were 47.45, 47.12, 45.45 and 43.33, respectively. The total aboveground biomass carbon stock per hectare as estimated for *Shorea robusta, Albizzia lebbek, Tectona grandis* and *Artocarpus integrifolia* were 5.22, 6.26, 7.97 and 7.28 t C ha^{-1}, respectively in these forest stands.

Nizami *et al.* (2009) estimated carbon stocks in sub-tropical pine (*P.roxburghii*) forests in two sites, Ghoragali and Lehterar, of Pakistan as 126+ 2.94 and 99+1.58 t ha^{-1}, respectively.

Metzker *et al*. (2011) conducted a study in five permanent monitoring plots (1 ha each) in the Rio Doce State Park (RDSP), the most continuous Atlantic Forest remaining in Minas Gerais, Brazil and considered one of the world's hotspots. The aboveground biomass ranged from 201 Mg/ha in the primary forest to 92 Mg/ha in the secondary forest. The recruitment rate (1.8) was higher than the mortality rate (1.1); however, the average diameter of dead trees was higher than that of the recruited trees. Notwithstanding this result, the internal diametric increment (ingrowth) in RDSP was compensated by the biomass loss of dead trees, producing positive growth in the annual biomass and increasing their carbon stocks by 1.0 Mg C/ha/yr.

Mohanraj *et al.* (2011) estimated the existing carbon stock in the above ground biomass, litter, debris and soils (up to 30 cm) of different forest types of Kolli forest, located in Eastern Ghats of Tamilnadu, India, within an area of 503 km^2. Floristic diversity of Kolli hills is rich of endemisms and includes about 150 tree species. To estimate the carbon stock, about 26 quadrates of 25 X 25 m size were established. The organic carbon content of forest soil varied from 1.71 to 12.59%. The total carbon stock of soil, surface litter, coarse wood debris and total above ground biomass were estimated as 5.54, 0.034, 0.001 and 4.49 Tg C, respectively.

2.2.1 Temporal change in forest carbon stock

In response to the twin specters of global climate change and worldwide habitat loss, networks of scientists began to create a science of sustainability during the late 20th century (Kates *et al*., 2001; Raven, 2002; Steffen *et al*., 2004). Participants in this endeavor searched for empirical regularities in our interactions with nature that could, if expedited by governments, accelerate the transition to a sustainable society (Kates *et al*., 2001). Alexander Mather coined the term 'the forest transition' to describe one of the first empirical generalizations to emerge from this work. Derived from historical studies of forests, this idea asserts that stocks of forests change in predictable ways as societies undergo economic development, industrialization and urbanization (Mather, 1990; Mather and Needle, 1998; Walker, 1993). A large decline in forest cover occurs; then the trend turns around, and a slow increase in forest cover takes place (Rudel, 1998). Forest transitions promise to slow the accumulation of greenhouse gases in the atmosphere by increasing carbon sequestration through the substitution of relatively carbon-rich secondary forests for carbon-poor agricultural land. As secondary forests age and the biomass per hectare increases, the amount of carbon sequestered per acre also increases (Houghton *et al*., 2001). For this reason the amount of carbon sequestered through a forest transition should increase over time as woody growth continues and the area covered by secondary growth expands. The total amounts of carbon sequestered this way have not been huge, but they have been visible. For example, carbon sequestered through secondary growth offset 3.3% of all of the carbon emitted through deforestation in the Amazon basin during the 1990s (Achard *et al*., 2004). Forest transitions begin during a period of deforestation. Initially, forests decline in extent as forests are cleared due to urbanization, industrialization and agriculture. In the hilly states a ban on green felling since

1985 has raised the possibility of an increase in forest cover. In places with stable or growing populations and little ability to import forest products, continued declines in forest cover spur increases in the prices of forest products, and the price increases induce landowners to plant trees instead of crops or pasture grasses. This dynamic explains the recent increase in forest cover in India (Foster and Rosenzweig, 2003).

Fearnside and Barbosa (1998) studied the soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. They found that soils in Brazilian Amazonia may contain up to 136 Gt of carbon to a depth of 8 m, of which 47 Gt are in the top metre. The current rapid conversion of Amazonian forest to cattle pasture was responsible for the release of carbon, with the upper 8 m releasing an average of 12 t C/ha in land maintained as pasture following deforestation.

Paivinen *et al*. (1998) found that the area of exploitable forest in Europe has not changed considerably since the first Forest Resources Assessment in 1950. It increased by approximately 0.6 % in 40 years. In the same time period the growing stock, however, increased from 13 billion m^3 in 1950 to 18.5 billion m^3 in 1990. This is a gain of volume in European forests of nearly 43%. A high increase in volume occurred, for example, in Austria, France, FRG, Italy, Poland and Sweden. Only few countries showed negative development between 1980 and 1990 (Albania, Greece, Portugal, Romania). The net increment increased even more rapidly than the growing stock. The gain of the net annual increment amounted to 55% in the 40-year period of the European countries reporting to UN-ECE/FAO. A large increase in the net increment was found in Austria, Finland, France, FRG, Poland, Spain and Sweden. Only two countries had a decreasing trend between 1980 and 1990 (Albania, Greece).

Kurz and Apps (1999) suggested that the role of forests in the C budget could change over time depending upon changes in the prevailing disturbance regimes. For instance, the forest ecosystems in Canada have been a sink of atmospheric C for the period 1920- 1980, and a source for the period of the 1980s because of a sharp increase in forest fire and insect disturbances starting about

1970. The disparate results can be attributed to different geographical regions, climate and weather patterns, vegetation and soil conditions, disturbance regimes, and different methods of estimating C stock.

Fang *et al*. (2001) studied changes in forest biomass carbon storage in China between 1949 and 1998. Their results suggested that Chinese forests released about 0.68 petagram of carbon between 1949 and 1980, for an annual emission rate of 0.022 pentagram of carbon. Carbon storage increased significantly after the late 1970s from 4.38 to 4.75 petagram of carbon by 1998, for a mean accumulation rate of 0.021 petagram of carbon per year, mainly due to forest expansion and regrowth.

Ni Jian (2002) applied BIOME3 model to simulate the distribution patterns and carbon storage of the horizontal, zonal boreal forests in northeast and northwest China using a mapping system for vegetation patterns combined with carbon density estimates from vegetation and soils. The BIOME3 prediction was in reasonable good agreement with the potential distribution of Chinese boreal forests. The effects of changing atmospheric CO_2 concentration had a nonlinear effect on boreal forest distribution, with 3.5-10.8% reduced areas for both increasing and decreasing CO_2. In contrast, the increased climate together with and without changing CO_2 concentration showed dramatic changes in geographic patterns, with 70% reduction in area and disappearance of boreal forests in northeast China. The baseline carbon storage in boreal forests of China was 4.60 Pg C (median estimate) based on the vegetation area of actual boreal forest distribution. If taking the large area of agricultural crops into account, the median value of potential carbon storage was 6.92 PgC. The increasing (340-500 ppmv) and decreasing CO_2 concentration (340-200 ppmv) led to decrease of carbon storage, 0.33 Pg C and 1.01 Pg C, respectively, compared to BIOME3 potential prediction under present climate and CO_2 conditions.

Sigurdsson *et al*. (2005) studied changes in understory biomass, forest floor carbon (C) stock and vegetation composition in six age-classes of Siberian larch (*Larix sibirica*) and two age-classes of native birch (*Betula pubescens*) in Iceland. The ground vegetation was less in larch during the thicket stage and in the old-growth birch compared to a treeless pasture. Understory biomass was strongly related to canopy gap fraction across forest stands ($P < 0.001$), but not to soil pH or soil C/N ratio. Increased mass of dead wood and alterations in vegetation composition increased the forest floor C-stock of older forests. The forest floor had reached as high C-stock as the pasture's ground vegetation in 50 years in the managed larch plantations and in hundred years in the unmanaged birch forest. This study showed the importance of which time-step is used when changes in forest floor C-stocks are computed for afforestation areas.

Manhas *et al.* (2006) did the temporal assessment of growing stock, biomass and carbon stock of Indian forests, from 1984 to 1994. The forest area, wood biomass, GS, and carbon stock were 63.86 Mha, 4327.99 Mm^3, 2398.19 Mt and 1085.06 Mt, respectively in 1984 and with the reduction of forest area to 63.34 Mha in 1994, there was a significant reduction in wood biomass (2395.12 Mt) and carbon stock (1083.69 Mt). The conifers of temperate region stocked maximum carbon in their woods (28.88 to 65.21 t C ha^{-1}) followed by mangrove forests (28.24 t C ha^{-1}), dipterocarp forests (28.00 t C ha^{-1}) and *Shorea robusta* forests (24.07 t C ha^{-1}). Total 24.75 Mt C was lost during 1984-1994 and 21.35 Mt C during 1991-94 at a rate of 2.48 Mt C yr^{-1} and 5.35 Mt C yr^{-1}, respectively. The average C stock in the country was estimated to be 24.94 t C ha^{-1} in the year 1984 and 24.54 t C ha^{-1} in 1994. While in other parts of India negative change was due to multiple reasons like fuel wood, extraction of non-wood forest products (NWFPs), illicit felling etc., but in the northeastern region of the country shifting cultivation was found to be the only reason for deforestation. The order of carbon stocked in major forests decreased in the order : Miscellaneous forest > *Shorea robusta* forest > *Tectona grandis* forest > Temperate forest > Tropical forest > Bamboo forest etc.

Fang and Tian (2006) determined the dynamics of carbon stock and carbon sequestration in Chinese fir (*Cunninghamia lanceolata*) plantations at 10 (F1) and 14 (F2) years in Huitong, Hunan Province, China. The carbon stock of the plantation followed the order soil> trees> litter. Carbon stock of F1 and F2 was 120.52 and 171.40 t/hm^{-2}, respectively. Superiority of carbon storage in the trees gradually increased with the stand age growth, and carbon storage of the trees increased from 30.38 t/hm^{-2} (10 years old) to 61.24 t/hm^{-2} (14 years old), and occupied 25.21% and 38.50% of total carbon stock of the whole ecosystem respectively. Carbon storage of the different organs was in direct proportion with its biomass, with trunk having the greatest (47.17%) proportion, and increased with the stand age. Carbon storage in forest soil layers (0-60 cm) in F1 and F2 was 88.21 and 108.20 t/hm^{-2}, respectively, accounting for more than 63.13% of carbon storage in the whole ecosystem. The carbon storage ratio of aboveground to underground at F1 and F2 was 1:3.53 and 1:2.22, respectively, indicating a decrease with stand age. The respective annual net carbon amount of F1 and F2 was 5.488 and 9.285 t/hm^{-2}. Extant carbon storage, potential carbon storage and potentiality of carbon sequestration of Chinese fir forest vegetation in Hunan Province was 0.1916x108, 1.4710x108 and 1.2794x108 t, respectively, where extant carbon storage accounted for 13.03% of potential carbon storage, which was less than the whole national level (26.46%).

Alexandrov (2007) studied the relationship between the age of a forest stand and its biomass. According to him, as biomass increases with stand age, postponing harvesting to the age of biological maturity may result in the formation of a large carbon sink.

Smiley and Kroschel (2008) investigated the temporal development of cocoa–gliricidia carbon (C) stocks and soil organic carbon (SOC) in Napu and Palolo Valleys of Central Sulawesi, Indonesia. The Functional Branch Analysis (FBA) method was used to develop allometric equations for the above- and below-ground growth of cocoa and gliricidia. FBA resulted in shoot–root ratios of 2.54 and 2.05 for cocoa and gliricidia, respectively. In Napu and Palolo, the trunk diameter and carbon levels per gliricidia tree were always much greater than that of cocoa. The highest aerial carbon levels were attained at year four in Napu (aerial cocoa–gliricidia = 20,745.2 kg C ha-1) and at year five in Palolo (aerial cocoa–gliricidia = 38,857.0 kg C ha-1). After years four or five, however, the reduced stocking density of gliricidia attributed to a loss of aerial C. During the time spans in question, SOC remained fairly stable though slightly decreasing in Napu and slightly increasing in Palolo. The SOC harbored a vastly greater amount of system C (one-half and onethird of SOC in the 0–15 cm stratum in

Napu and Palolo, respectively) relative to tree components. Eight years (Napu) or 15 years (Palolo) after conversion of a rainforest to cocoa–gliricidia agroforestry caused an 88% and 87% reduction of aerial C-stocks in Napu and Palolo, respectively.

Smith *et al*. (2008) conducted a study on carbon stocks and temporal carbon stock changes over 251 million hectares located in 48 states of the United States of America using well-defined inventory data. The net amount of carbon stored—that is, annual incremental increase—by forests in the conterminous U.S. increased by an estimated 595 and 103 Tg CO2 eq. in 2005 for forest ecosystems and harvested wood products, respectively. Total Sequestration in 2005 was estimated to be 699 Tg CO2 eq. and the calculated 95% confidence interval for this flux was -890 to -513 Tg CO2 eq.. Compared to 1990, CO2 sequestered by forest systems was about 17% greater in 2005. Current total carbon stocks in forest ecosystems of the conterminous United States are estimated at about 150 Pg CO2 eq. Estimates of net annual change calculated as the difference between two successive inventories were found sensitive to changes in forestland over the interval as well as changes in average carbon density.

Kaul *et al*. (2010) studied the carbon storage and sequestration potential of selected tree species in India. A dynamic growth model (CO_2FIX) was used for estimating the carbon sequestration potential of sal (*Shorea robusta* Gaertn. f.), Eucalyptus (*Eucalyptus tereticornis* Sm.), poplar (*Populus deltoides* Marsh), and teak (*Tectona grandis* Linn. f.) forests in India. The results indicated that long-term total carbon storage ranged from 101 to 156 Mg C ha^{-1}, with the largest carbon stock in the living biomass of long rotation sal forests (82 Mg C ha^{-1}). The net annual carbon sequestration rates were achieved for fast growing short rotation poplar (8 Mg C $ha^{-1}yr^{-1}$) and Eucalyptus (6 Mg C $ha^{-1}yr^{-1}$) plantations followed by moderate growing teak forests (2 Mg C $ha^{-1}yr^{-1}$) and slow growing long rotation sal forests (1 Mg C $ha^{-1}yr^{-1}$). Due to fast growth rate and adaptability to a range of environments, short rotation plantations, in addition to carbon storage rapidly produce biomass for energy and contribute to reduced greenhouse gas emissions. The model was used to evaluate the effect of changing rotation length and thinning regime on carbon stocks of forest ecosystem (trees +

soil) and wood products, respectively for sal and teak forests. The carbon stock in soil and products was less sensitive than carbon stock of trees to the change in rotation length. Extending rotation length from the recommended 120 to 150 years increased the average carbon stock of forest ecosystem (trees + soil) by 12%. The net primary productivity was highest (3.7 Mg $ha^{-1}yr^{-1}$) when a 60-year rotation length was applied but decreased with increasing rotation length (e.g., 1.7 Mg $ha^{-1}yr^{-1}$) at 150 years.

Ravindranath *et al*. (2008) reported that afforestion is increasing and currently 67.83 m ha of area is under forest cover. Assuming that the current trend continues, the area under forest cover is projected to reach 72 m ha by 2030. Estimates of carbon stock in Indian forests in both soil and vegetation range from 8.58 to 9.57 Gt C. The carbon stock in existing forests is projected to be nearly stable over the next 25 year period at 8.79 Gt C. However, if the current rate of afforestation and reforestation is assumed to continue, the carbon stock could increase from 8.79 Gt C in 2006 to 9.75 Gt C by 2030 an increase of 11%.

Guo *et al*. (2010) applied three methods [mean biomass density method (MBM), mean ratio method (MRM), and continuous biomass expansion factor (BEF) method (abbreviated as CBM)] to forest inventory data to estimate China's forest biomass C stocks and their changes from 1984 to 2003. The three methods generated various estimates of the biomass C stocks: the lowest (4.0–5.9 Pg C) from CBM and the highest (5.7–7.7 Pg C) from MBM, with an intermediate estimate (4.2–6.2 Pg C) from MRM.

2.2.2 Forest inventory data for the assessment of forest carbon stock

Forest inventory data is very useful in studying the temporal change in biomass and carbon stock of forest stands. The comparison of the forest inventory data and the data of old and recent literature revealed that the area of Algerian forest has decreased significantly, and the principal forest types except the pine forest with *Pinus halepensis* and *Pinus pinaster* showed regressive dynamics. The area of Cedar decreased by more than 60%. The area of Holm oak forests decreased by 15-30% and cork oak has lost 52% area. The degradation of cork oak forest resulted in the extension of Aleppo Pine forest (*Pinus halepensis)* in the west of Algeria and Maritime Pine (*Pinus pinaster*) in the east, with an increase from 38,000 ha to 57,727 ha (Boudy, 1955; Kadik, 1983).

Brown and Gaston (1995) used the stand tables from forest inventories representing more than 22* 10^6 ha of forests, for computing the aboveground biomass of tropical forests of south and southeast Asia. The mean inventory based biomass for moist forests (225Mg/ha) was lower than that reported by direct measurements for mature forests in the same region (350 Mg/ha), whereas the mean inventory-based biomass for dry forests (82 Mg/ha) was higher than estimates based on direct measurements (55Mg/ha). It was also found that human use of forests in tropical Asia is intense leading to their degradation. Between two national forest inventories of Peninsular Malaysia in 1972 and 1981, the total area and biomass of forests declined by 18% and 28% respectively.

Sokolov (2004) studied the dynamics of Siberian forests (22 million ha total forested area in 1998, or about 42% of the total area of Russian forests) using a database which contained data of the Forest State Account from 1961 to 2000. During this period, the total area of Siberian forest fund increased by 1.8 million ha. However, while East Siberia's forest area increased by 11.5 million ha, in West Siberia the area decreased by 9.7 million ha. The reasons for the reduction were the transformation of previously forest area to oil and gas production areas, the development of infrastructure and urbanization and the acceleration of disturbances, in particular fire and insect outbreaks. The total growing stock in mature and overmature forest stands decreased by 2.6 billion m^3. The total losses of growing stock during the period considered amounted to 13.5 billion m^3 of which 4.5 billion m^3 was harvested wood. The evident acceleration of natural disturbances in Siberia during the last decade (in particular, in 1996-2003) is explained by unusual climatic conditions (significantly warmer and drier than the long-term average), which occurred over most of the region during this period.

Lehtonen (2005) developed methods for quantifying carbon stocks and fluxes at national scale based on forest inventory data. To estimate tree biomass of forests, representative BEFs (biomass expansion factors) with uncertainty estimate were developed for Finland. A method for quantifying carbon flux of branches to soil was also developed. Both biomass and branch litterfall estimates were tested against independent measurements. Biomass estimation method and litterfall estimates were applied with Finnish forest inventory data to estimate carbon stocks and their changes for Finnish forests for 1922-2004. In this application main sources of litter were quantified based on forest inventory data and fed into dynamic soil decomposition model in order to estimate soil carbon stocks and its changes. Application of BEFs, litterfall estimates and soil model gave time series of carbon stocks in Finnish forests. Results showed that tree carbon stock of Finland increased from 510 Tg to 780 Tg, while carbon in mineral soils increased from 850 Tg to 960 Tg during 80 year period. It was also found that there were high inter annual variation with soil and tree carbon stocks caused by harvestings and temperature. According to the results, the NPP (net primary production) of Finnish forests increased from 0.3 to 0.4 kg m^{-2} during studied period, while NBP (net biome production) was positive since 1970s.

Muukkonen and Heiskanen (2007) demonstrated the potential of standwise forest inventory data, and ASTER and MODIS satellite data for estimating stand volume (m^3 ha^{-1}) and aboveground biomass (t ha^{-1}) over a large area of boreal forests in southern Finland. The regression models, developed using standwise forest inventory data and standwise averages of moderate spatial resolution ASTER data (15 m× 15 m), were utilized to estimate stand volume for coarse resolution MODIS pixels (250 m× 250 m). The MODIS datasets for three 8-day periods produced slightly different predictions, but the averaged MODIS data produced the most accurate estimates. The inaccuracy in radiometric calibration between the datasets, the effect of gridding and compositing artifacts and phenological variability were the probable reasons for this variability. The estimates obtained were significantly close to the district-level mean values provided by the Finnish National Forest Inventory; the relative RMSE was 9.9%. They concluded that the use of finer spatial resolution data is an essential step to integrate ground measurements with coarse spatial resolution data. Furthermore, the use of standwise forest inventory data reduces co-registration errors and helps in solving the scaling problem between the datasets. The approach employed here can be used for estimating the stand volume and biomass, and as required independent verification data.

Lettens *et al*. (2008) computed biomass organic carbon (BOC) stocks of spatially explicit forested landscape units (LSU) in Belgium based on data collected in the regional forest inventories of 1984 (Wallonia region only) and 2000 (Wallonia and Flanders). C stock changes between 1984 and 2000 were estimated for Wallonia. The total BOC pool stored in Belgian forests in 2000 amounted to 57.8 Mt C in 6 222 km^2, or 10.0 kg C m^{-2} in broadleaf, 9.5 kg C m^{-2} in coniferous and 8.7 kg C m^{-2} in mixed forest. Based on previous soil organic carbon (SOC) analysis for the same LSU, BOC and SOC stock per LSU appeared only weakly correlated. The total BOC sequestration between 1984 and 2000 equals 5.7 Mt C over an area of 5 107 km^2, resulting in a flux of 0.07 kg C m^{-2} y^{-1}. The BOC content of broadleaf forest in Wallonia increased by 6%, of coniferous forest by 32% and of mixed forest by 11%. The observed regional differences in BOC stocks and in BOC sequestration rates were explained by the forest age-class distribution and site productivity.

2.2.3 Remote sensing for mapping of biomass and carbon

The traditional approach of biomass assessment relying heavily on field measurements is often time consuming, labour intensive and difficult to implement, especially in remote areas. While for small scale biomass assessment the conventional method is good, they cannot provide the spatial distribution of biomass and carbon over large areas. The challenging issues of carbon sequestration require biomass estimation over large areas. Remote sensing techniques have been extensively used for vegetation mapping and monitoring (Brown *et al*., 2000; Boyd *et al*., 2002; Lu *et al*., 2004; Ingram *et al*., 2005; Maynard *et al*., 2007). Use of remote sensing data has been employed in many studies on biomass assessment (Steininger, 2000; Dong *et al*., 2003; Foody *et al*., 2003; Lu *et al*., 2004; Zheng *et al*., 2004; Heiskanen, 2006; Maynard *et al*., 2007). Remote sensing may be the only feasible way to acquire forest stand parameter information at a reasonable cost, with acceptable accuracy and feasible effort because of its data advantages which include repeated data collection, multi spectral and multi temporal images, synoptic view, fast digital processing of large quantities of data and compatibility with geographic information systems (GIS). Remote sensing also allows independent monitoring of resources. These advantages of remotely sensed data and observed high correlations between spectral data and vegetation parameters in many cases make it the primary source for large scale aboveground biomass (AGB) mapping. In general the AGB can be estimated using remotely sensed data with different approaches like multiple regression analysis, K- nearest-neighbour and neutral network (Lu, 2006). Biomass cannot be directly measured from space but, remotely sensed spectral signatures can be used to estimate biomass (Dong *et al*., 2003). The biomass measurements from sample plots can then be integrated into remote sensing techniques to get cost effective and large spatial information on AGB distribution.

The possibility of estimating biomass by satellite remote sensing has been investigated in several studies at various spatial scales and environments (Heiskanen *et al*., 2006). Biomass estimation using remote sensing has remained a challenging task, especially in areas with complex forest stand structures and environmental conditions (Lu, 2006). A good understanding of the relationships between forest biomass and remote sensing spectral data is a prerequisite for developing appropriate biomass estimation models (Steininger, 2000). Identifying the spectral wavelengths or wavelength combinations that are most suitable to use to acquire information about a specific biophysical parameter in a given study area is difficult (Lu *et al*., 2004). Vegetation indices (VIs) and band ratio based models are most commonly used to produce estimates of biomass (Hurcom and Harrison, 1998; Foody *et al*., 2003; Schlerf *et al*., 2005 and Zheng *et al*., 2004). A variety of VIs have been developed with the most popular ones using Red and near-infrared wavelengths to emphasize the difference between the strong absorption of Red electromagnetic radiation and the strong scatter of near infrared radiation. VIs are used to remove the variability caused by canopy geometry, soil background, sun view angles and atmospheric conditions when measuring biophysical properties (Lu, 2006). Nonetheless, VIs are also sensitive to internal (such as canopy geometry, terrain factors, species composition) and external factors (such as sun elevation angle, zenith view angle, atmospheric conditions) that effect vegetation reflectance (Lu *et al*., 2004). There is a wide disagreement in nature as regards the biomass-VIs relationship. Many studies report a significantly positive relationship between the values of VIs and the biomass at least upto the reflectance asymptote of the canopy (Hurcom and Harrison, 1998; Boyd *et al*., 1999; Steininger, 2000; Zheng *et al*., 2004; Heiskanen, 2006 and Maynard *et al*., 2007), however, some studies have shown poor relationships (Foody *et al*., 2003 and Schlerf *et al*., 2005).

The normalized difference vegetation index (NDVI) is one of the most commonly used VIs in many applications relevant to the analysis of biophysical parameters of the forest. The strength of NDVI is in its ratioing concept, which reduces many forms of multiplicative noise (illumination differences, cloud shadows, atmospheric attenuation, certain topographic variations) present in multiple bands (Huete, 2002). However, conclusions about its value vary, depending on the use of specific biophysical parameters and the characteristics of the study area. Foody *et al*., 2003 tested several VIs and found that NDVI was never among the top 10 indices defined in terms of the strength of the correlation with biomass of the sample plots. Although in some cases NDVI have shown good correlation with leaf-area index (LAI) it did not appear to be a good predictor of stand structure variables such as height, basal area or total biomass in uneven aged and mixed broadleaved forest (Lu *et al*., 2004). Zheng *et al*., 2004 used five VIs and found best results with corrected NDVI (NDVIc) in predicting AGB. NDVIc is calculated from Red, near-infrared (NIR) and middle-infrared (MIR). NDVIc can help account for understorey effects and is useful in secondary forests. Simple ratio, SR (ratio of NIR and Red) is another commonly used VI for the study of forest biophysical variables (Schlerf *et al*., 2005). Heiskanen, 2006 and Lu *et al*., 2004 found SR to be significantly correlated with AGB.

Vegetation has a high near-infrared reflectance, due to scattering by leaf mesophyll cells and a low Red reflectance due to absorption by chlorophyll pigments. The value of NDVI for vegetation will hence tend to one. By contrast clouds, water and snow have a larger Red reflectance than near-infrared reflectance and these features thus yield negative NDVI values. Rock and bare soil areas have similar reflectances in the two bands and thus result in NDVI values near zero.

Previous studies have shown that middle-infrared reflectance have strongly negative relationships with biomass (Boyd *et al*., 1999; Lu, 2006 and Steininger, 2000). Schlerf *et al*., 2005 observed better relation between middle-infrared VI (MVI: ratio of NIR and MIR) and tree crown volume than SR and NDVI and concluded that the MIR band in combination with NIR band contain more information relevant to the characterization of forest canopies than the combination of Red and NIR bands.

Shortwave infrared (SWIR) modification to simple ratio called Reduce Simple Ratio (RSR) can also be used to study the relationship with biomass as it has been found to be sensitive to change in LAI, reduces the effect of background reflectance, negates the effect of higher NIR reflectance in deciduous canopies and unifies deciduous and coniferous species in LAI retrieval from remote sensing data (Brown *et al*., 2000). The Enhanced Vegetation Index (EVI) was developed to optimize the vegetation signal with improved sensitivity in high biomass regions and improved vegetation monitoring through a de-coupling of the canopy background signal and a reduction in atmospheric influences (Huete, 2002).

A number of soil adjusted vegetation indices also exist to reduce the effect of the soil background reflectance. However, in the forested environment the bare soil is rarely visible and the definition of soil line is difficult and the line is discontinuous (Heiskanen, 2006). Hence, the application of soil adjusted vegetation indices becomes futile.

Mabowe (2006) did the aboveground biomass assessment in Serowe woodlands in Botswana. An IKONOS image of 2002 was used to derive spectral vegetation indices namely: Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), Enhanced Vegetation Index (EVI) and Perpendicular Vegetation Index (PVI). Vegetation maps were overlaid with the plot shapefile and the mean vegetation indices values were extracted and correlated with AGB (kg/m^2) per plot. However poor correlation was observed between AGB and the vegetation indices (NDVI= 0.024, EVI= 0.083, SAVI= 0.077, PVI= 0.060).

Deo (2008) used remote sensing data to assess the biomass and carbon sequestration in a cool temperate forest in Wangqing, North East China. The biomass density of the forest using polynomial, Chinese and IPCC equations were 81.88±5.63, 97.11±6.43 and 112.12±7.48 t/ha respectively. The average carbon sequestration rate was 1.88±0.12 t/ha/yr. for remote sensing based assessment an empirical relationship of forest plot biomass and annual carbon sequestration was sought with Landsat TM spectral data. Although poor a significant linear relationship was observed with corrected NDVI for both the forest parameters thereby implying that biomass did not show a saturation effect of the VI. The average forest biomass and annual carbon sequestration estimated using remote sensing data were 65.36 t/ha and 1.52 t/ha respectively.

Pareta and Pareta (2011) estimated the carbon stock for Sagar District (M.P.) using remote sensing. Some resent methodology i.e. sample plot-hybrid ground based method, RS-LULC based method, vegetation index (NDVI) based method, ESRI-ArcGIS based InVEST-Model, modified 3PGS-model, and NLLUF-KP10 model were used in this study. Satellite remote sensing data was used as a primary data source for forest classification, land use - land cover mapping, forest carbon management, biomass estimation, landuse-forest-carbon change detection and ecology mapping. High carbon stock in Sagar district was distributed in Behrol, Baraitha, Dalpatpur, Jaisinghnagar, Jalandhar, Madanpur, Rahatgarh, and Rajuwa respectively; while, Khurai, Parsoriya had the lowest carbon stock. The estimated carbon stock in Sagar district was 220.04 Million Mg for the year 2010.

2.2.4 Carbon sequestration thorough soils

Soil

Soil Organic Carbon (SOC) refers to the carbon in soils associated with the products of living organisms. It is a heterogenous mixture of simple and complex organic carbon compounds which can be divided into different pools which serve different functions to soil ecosystems. The use of soil to sequester carbon needs to consider at least 3 significant soil carbon pools. These carbon pools are the labile, less labile (recalcitrant) and inert fractions. The labile soil carbon pool consists mainly of soil organisms, polysaccharides, celluloses and hemi-celluloses with a half life in soils varying from weeks to months. The recalcitrant pool consists of lignins, lipid polymers, suberins, resins, fats, and waxes with half lives varying from years to decades. This pool also contains humified products formed by biological transformation of carbon compounds. The inert pool consists of charcoal and pyrolysed carbon with half lives of centuries to millennia. (Chan *et al.*, 2008).

Soil organic carbon sequestration refers to the storage of carbon in soil and is being considered as a strategy for mitigating climate change. Globally as well as for some individual countries, it has been estimated that SOC sequestration has the potential to mitigate 5-14% of total annual greenhouse gas emissions for the next 50- 100 years. However, whether this potential is achieved depends on economic, social and political factors.

The quantity of organic carbon in soils is spatially and temporally variable, depending on the balance of inputs versus outputs. The inputs are due to the absorption of carbon dioxide from the atmosphere in the process of photosynthesis and its incorporation into the soil by the residues of plants and animals. The outputs are due to the decomposition of soil organic matter, which releases carbon dioxide under aerobic conditions and methane under anaerobic conditions (both $CO2$ and $CH4$ being greenhouse gases).

Soil organic C is the largest C reservoir in many terrestrial ecosystems including grasslands, savannas, boreal forests, tundra, some temperate forests, and cultivated systems, comprising as much as 98% of ecosystem C stocks in some systems (Schlesinger, 1977). A substantial portion of C fixed by vegetation is transferred to the soil annually (Raich and Nadelhoffer, 1989), a portion of which is refractory material with long turnover times the rest decomposes relatively rapidly and is returned to the atmosphere as $CO2$ (Falloon and Smith, 2000). Thus soil C is a large, relatively dynamic component of terrestrial C stocks.

Globally carbon stocks in the soil exceed carbon stocks in vegetation by a factor of about 5. The ratio ranges from 1:1 in tropical forests to 5:1 in boreal forest and much larger factors in grasslands and wetlands (IPCC, 2000). Soil is the largest pool of terrestrial carbon, estimated as 2200 Pg; tropical top soils contain about 13% of world soil carbon (Young, 1997).

Forest vegetation and soils contain about 1240 Pg of C (Dixon *et al*., 1994) and the C stock varies widely among latitudes. Of the total terrestrial C stock in forest biomass, 37 % is in low latitude forests, 14% in mid latitudes and 49% in high latitudes. The above-ground plant C density increases with decreasing latitude from tundra to tropical rain forest (Fisher, 1995). Typical plant C density ranges from 40 to 60 C/ha in boreal forests, 60 to 130 Mg C ha^{-1} in temperate forests and 120 to 194 Mg C/ha in tropical forests, with the C density of an undisturbed TRF (Tropical Rain Forest) as high as 250 Mg C/ha. None the less, as much as two-third of the terrestrial C in forest ecosystems is contained in soil (Dixon *et al*., 1994). The soil C stock may comprise as much as 85 % of the terrestrial C stock in the boreal forest, 60 % in temperate forests and 50% in TRF (Tropical Rain Forest) (Dixon *et al*., 1994). The ratio of soil: plant C stock may be 3 for high latitude, 1.2 to 3 for mid-latitude and 0.9 to 1.2 for low latitude.

Sharma (1991) and Malik (1992) conducted a study on soils under Chir pine in Solan forest division of H. P. and found that the organic carbon was in the range of 0.17-3.37 and 0.33-3.27 per cent, respectively and they further observed a decreasing trend in its distribution down the soil profile.

In northern Belgium, Schanvlieghe and Lust (1999) assessed C budgets under different land use systems. The total C stock was 128 Mg/ ha under pasture, 173 Mg ha-1 under 29 year old forest and 232 Mg ha-1 under 69 year old stand. The total C stock was 117 Mg/ ha under 27 year old pine oak stand. In east central Minnesota, an average increase in SOC stock at the rate of 0.8 Mg C ha-1 yr-1 in the mineral soil over a 40 year period was reported due to afforestation of degraded agricultural soils.

Banfield *et al*.(2002) reported that in the boreal forest ecosystem of West Alberta, Canada, the regional average above-ground C stock ranged from 43 to 50 Mg C/ha, with SOC stock of 83- 156 Mg C/ha.

Guo and Gifford (2002) reported that when pasture changes to a secondary broad leaf forest, soil carbon stock is not affected while when arable land is converted to forest an increase in soil C is usually apparent.

Chhabra *et al*. (2003) measured soil organic carbon (with depth) containing information on location, soil type, texture, measured/estimated bulk density and forest type in Indian forests. It was used for estimating soil organic C densities for various forest types for two-depth classes (0-50 and 0-100 cm). The mean soil organic C density estimates for top 50 cm based on 175 observations ranged from 37.5 t/ha in tropical dry deciduous forest to 92.1 t/ha in littoral and swamp forest. The mean soil organic C density estimates based on 136 observations ranged from 70 t/ha in tropical dry deciduous forest to 162 t/ha in montane temperate forest for top 1 m soil depth. The estimated soil organic C densities were combined with remote sensing based recent forest area inventory (64.20 Mha^{-1}) by Forest Survey of India to arrive at estimates of soil organic C pool by major forest types of India. The total soil organic C pools in Indian forests have been estimated as 4.13 PgC in top 50 cm and 6.81 PgC in top 1 m soil depth.

Soil carbon sink under different forest types in Himachal Pradesh (India) was studied by Jha and Gupta (2005). Maximum SOC pool of 117.36 Mt was observed under mixed conifer forest in 1984, followed by chir (43.80 mt), upland hardwood (35.07 mt) and miscellaneous forest (15.04 Mt). During a span of 10 yrs (1984-1994) an increase of 21.60 % in the carbon sink was recorded in silver fir and spruce forest soil followed by 18.55% in Deodar, 17.19 % in Kail, 17.32 % in hardwood and conifers and 6.81% in upland hardwood. On the other hand during this period 39.21 % decrease in soil C sink was recorded under kail followed by 38.80% in bamboo and 22.60 % in miscellaneous forests. Overall 7.54 % increase in soil carbon sink was observed in Himachal Pradesh during 10 years period. SOC pools up to 30 cm depth of 16 old plantations were studied by

Jha *et al*. (1997). SOC store was higher in *Eucalyptus* (99.6 t ha^{-1}) followed by *Shisham* (98.4 t/ha), *Khair* (79.6 t ha^{-1}), *Teak* (68.0 t ha^{-1}) and Chir (57.2 t ha^{-1}).

Ussiri *et al*. (2006) reported that after 10 years of conversion of pasture land to Australian pine (*Casuarina* species) forests in the reclaimed mine soils of southern Ohio showed increased SOC pool in the top 50 cm by 6 Mg ha^{-1} in 10 year. However, the nitrogen pool in the top 50 cm was not affected by land use conversion from pasture to Australian pine. Conversion to Black locust increased the SOC pool in the top 50 cm by 24 Mg ha^{-1} (42%) while the N pool increased by 10 % under Black locust in 10 years. The increase in the SOC pool was accompanied by an increase in the 20 to 50 cm depth. Establishment of tree plantation has a greater potential for SOC sequestration than pastures in the reclaimed mine soils.

Melo and Durigan (2006) studied the carbon sequestration of native and planted riparian forests growing in different soil conditions (cerrado and forest soils) with ages ranging from 1 to 28 years, in the Paranapanema valley, Sao Paulo State Brazil. The carbon storage in the mature native stands was 79.7 t/ha in forest soils and 50 t /ha in cerrado soil. That means the carbon storage potential was approximately 60% higher in the fertile and clayish forest soils than in the sandy and poor cerrado soils in that region.

Ramchandran *et al*. (2007) estimated 3.48 Tg soil carbon in the natural forests in Eastern Ghats of Tamil Nadu, India. Forests show the best mitigation potential followed by agroforestry, plantation and agriculture. A projection of carbon stocks for small holder agroforestry systems in the tropics indicated C sequestration rates ranging from 1.5 to 3.5 Mg C ha-1 yr-1 and a tripling of C stocks in a twenty year period to 70 Mg ha-1 (Watson *et al*., 2000).

Jina *et al*. (2008) studied the rate of carbon sequestration of degraded and nondegraded oak and pine forest of central Himalaya. They reported that in degraded and non-degraded sites of ban oak, the rate of carbon sequestration potential (CSP) was 1.47 and 6.23 t ha^{-1} yr^{-1}, respectively. Whereas, in the chir pine forest the rate of CSP was 1.07 and 6.66 t ha^{-1} yr^{-1}, respectively.

Kurbatova *et al*. (2008) measured the net ecosystem carbon exchange (NEE) with eddy covariance method for two adjacent forests located at the southern boundary of European taiga in Russia in 1999–2004. The two spruce forests shared similar vegetation composition but differed in soil conditions. The wet spruce forest (WSF) possessed a thick peat layer (60 cm) with a high water table seasonally close to or above the soil surface. The dry spruce forest (DSF) had a relatively thin organic layer (5 cm) with a deep water table (>60 cm). The measured multi-year average NEE fluxes (2000 and – 1440 kgC ha−1yr−1 for WSF and DSF, respectively) indicated that WSF was a source while DSF a sink of atmospheric carbon dioxide (CO2) during the experimental years.

Sheikh *et al*. (2009) carried out a study in the coniferous subtropical and broadleaf temperate forests of Garhwal Himalaya. The stocks of SOC were found to be decreasing with altitude: from 185.6 to 160.8 t C ha^{-1} and from 141.6 to 124.8 t C ha^{-1} in temperature (*Quercus leucotrichophora*) and subtropical (*Pinus roxburghii*) forests, respectively.

2.3 The effect of climate change on forest carbon stock

2.3.1 Climate change and its impact on forest ecosystems

The earth's climate is a complicated, multi-component system which has experienced many changes and variations throughout its history. Climate change has been one of the most engaging environmental subjects of debate in recent times. Intergovernmental Panel on Climate Change (IPCC) (2007) states that "Climate change is a change in the state of the climate that can be identified by changes in the mean and / or the variability of its properties and that persists for an extended period typically decades or longer". Nigeria's First National Communication on climate change under United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as a change of climate which is attributed directly or indirectly to human activities that alter the composition of the global atmosphere and which are in addition to natural climate variability, observed over comparable time period. Okali (2004) defines climate change by first of all defining climate as the "average weather" together with the variability from the average; it is the synthesis of the weather in a given place over a period of at least 30 years. He listed the main elements of weather to include temperature, rainfall, dew, humidity, wind, sunshine, mist, haze and cloud. It is the collective pattern of expressions of these elements overtime that is described as the climate of the place. Climate change is thus a change in these collective patterns of expression, not just in one element of weather. It is the permanent departure of climatic patterns from mean values of observed climate indices (Obioh, 2002).

The fourth assessment report of the IPCC specifies the linear trend of global mean surface temperatures over the last century – from 1906 to 2005 – with 0.74°C ±0.18°C. Climate warming is by now unequivocal, as it is evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (IPCC, 2007).

Forests are particularly sensitive to climate change, because the long life-span of trees does not allow for rapid adaptation to environmental changes. Unlike in agriculture, adaptation measures for forestry need to be planned well in advance of expected changes in growing conditions because the forests regenerated today will have to cope with the future climate conditions of at least several decades, often even more than 100 years. It is also important to understand the response of unmanaged natural forests to changing climate because it is possible to adapt forest management practices to a changing environment (Lopatin *et al*., 2008).

Rising atmospheric CO2 concentration, higher temperatures, changes in precipitation, flooding, drought duration and frequency will have significant effects on trees growth. Tree-line fluctuations (Payette and Lavoie 1994; Kullman, 2002) and changes in vitality are well known responses to changes in climate. Rowe, 1967, reported a northward migration rate of 150 m per year for the boreal forests in Canada and Bruce and Hengeveld, 1985 suggested that treelines in Canada would gradually migrate 100 km northward for every Celcius degree of warming. Species dominance, species distribution, species survival and fecundity (Payette and Lavoie 1994; Mysterud *et al*., 2000; Kullman, 2002) and also phenological phases (Cleland *et al.*, 2007) are likely to be effected by climate change.

The lengthening of the growing season due to changes in the temperature and precipitation regime coupled with increasing CO_2 and nitrogen deposition (Makinen *et al.*, 2003; Spiecker, 2002) are assumed to cause increased forest growth. Recent studies suggest that the turnover and growth rates of tropical forests have increased in the last few decades due to stimulation of forest growth caused by increase in CO_2 concentrations in the atmosphere (Malhi and Grace, 2000; Baker, 2004; Lewis, 2006; Phillips, 2009). Many CO2 enrichment experiments, conducted at the plant or stand scale, have consistently reported positive effects of elevated [CO2] on tree growth (Amthor, 1995; Tissue *et al.*, 1997; Norby *et al.*, 1999; Telewski *et al.*, 1999). Tree ring analysis has been commonly applied to test whether atmospheric CO2 fertilization is presently enhancing natural tree growth. Increasing ring widths in recent decades in subalpine pines in New Mexico, Colorado and California (LaMarche *et al.*, 1984) in *Pinus uncinata* at the tree line in the Pyrenees (Badeau *et al.*, 1996) and in subalpine *Pinus cembra* in the central Alps (Nicolussi *et al.*, 1995) have been cited as evidence of possible CO2 enhanced growth. Finally, strong evidence for CO2 growth enhancement comes from tree ring analyses of *Quercus ilex* continuously exposed to about 650 ppm CO2 near natural CO2 vents in Italy. These trees have grown about 12% faster than those growing in ambient CO2 nearby, especially when the trees were young and during dry seasons (Hattenschwiler *et al*. 1997). Across northern latitudes, ring width analyses suggest that forests started growing faster after 1850, well before the warming that occurred in the first half of the 20th century, but when CO2 levels first started to increase (Briffa *et al*., 1998).

Climatic changes have been recorded by different natural systems such as pollen records, ice cores, corals, caves, varves, and tree-rings which can be utilized as archival records of past climates (Bradley, 1992). The use of tree-ring series has also recently spread to climate model validation in the context of global warming assessment. The most important premises for applying the tree-ring studies to forest dynamics are 1) to find out the existence of critically good and bad years for tree growth, 2) to define them objectively and quantitatively, and 3) to find out the common factors that are responsible for the growth fluctuation.

Annual tree-ring growth functions under a limiting growth factor, a biologic principle known as “Liebig’s Law of the Minimum” that states that the growth of an organism (such as a tree) cannot proceed faster than is allowed by its most limiting factor. For trees, the limiting factor can be either internal (biologic) or external (environmental or climatic). Some of these factors can be a limit in nutrient availability or growing conditions such as precipitation and temperature. However, it is important to realize the interconnectedness of these two factors. Internal processes cannot operate without supplies delivered by external forces which enhance the environment signal in tree-ring growth (Fritts, 1976).

Papadopol (1990) envisaged impact of climate warming on forests in Ontario; the results indicated a temperature increase of about 0.76^{o}C per century and consequences of this on; northward shifts of ecological conditions, forest productivity; forest physiology and health.

According to Graybill and Idso (1993) CO_2 fertilization is detectable in certain pine species growing at high elevations of the southwestern United States, but only if they show a strip-bark growth form. In trees with a strip-bark morphology, any added CO_2 should be allocated primarily to the active cambial region, resulting in a greater response.

Spiecker *et al*. (1996) found that in many areas in Europe the increment of trees was higher in recent years than in the past and site productivity has also been increasing for several decades. The results derived from long-term observations on permanent plots and from tree analysis were supported by inventory results which were representative of large areas, but covered generally shorter observation periods. Annual tree height increment increased in the order of 2-5 cm, varying with species, site and age of the trees. Site productivity, in terms of wood volume, increased on various sites in recent decades by up to 50%, in some cases even more. Possible causes may be increasing temperature, change in precipitation pattern, elevated CO2 concentrations and nitrogen deposition.

Kellomaki and Vaisanen (1997) envisaged the effect of possible increase in temperature on boreal forests; the results of such increase in temperature are; prolonged growing seasons, increased productivity of forest ecosystems, changes in the relative proportion of species and northward shifts in the southern boundary of the boreal zone.

Ishii *et al* (1998) studied the relationship between forest volume and atmospheric temperature in Northern Honshu, Japan. An increase in air temperature resulted in an increase in volume and decrease of watershed discharge.

Rohle (1998) studied the growth behaviour of spruce for two regions. Growth of spruce in South Bavaria was investigated on 26 plots of 9 experimental areas. The investigations in Erzgebirge Mountains were based on 9 trial plots located on ridges and on 35 trial plots at medium and lower altitudes. In South Bavaria (sites of high productivity) mature spruce stands achieved growing stock volumes of up to 1600 m^3 ha^{-1} as well as current volume increments of more than 18.0 m^3 ha^{-1} y^{-1}. Analyses of sample trees showed that the phase of hypertrophic growth had begun in 1960. The increase of growth was readily apparent from the comparison of the preceding and succeeding generations.

Talkari *et al*. (1999) investigated the relationship between tree growth and temperature by determining parameter values for the temperature function from data generated by means of a physiological model. The results demonstrated that the growth and development of a tree stand was linked with climate and soil through photosynthesis, respiration, transpiration, uptake of water and nitrogen and differences in volume and total production were greater at the site in optimum temperature than at the sites in maximum and minimum temperature.

Ahmad *et al*. (1999) qualitatively analyzed the impact of global warming on forest resources of Bangladesh with special reference to the Sundarbans. A high evapotranspiration resulted in increased soil salinity and severe effects on species preferring freshwater. The degradation of forest quality might cause a gradual depletion of the rich diversity of the forest flora and fauna of the sundarbans ecosystem.

Parker *et al*. (2000) demonstrated impact of increased temperature, elevated atmospheric CO_2 concentration and altered precipitation regimes on forests and forest management; the results suggested impact will be on forest vegetation through their influence on physiological (e.g. photosynthesis; respiration) and ecological processes (e.g. net primary production, decomposition) and may result in dramatic northward shifts in the natural range of species as well as change in forest productivity.

Coops and Waring (2001) assessed forest growth across southwestern Oregon under a range of current and future global change scenarios using a process model, 3-PG, to evaluate the degree to which maximum periodic mean annual increment (PAI) of forests could be predicted at a set of 448 forest inventory plots. They then ran model simulations to evaluate the constraints imposed by (i) soil fertility under current climatic conditions, (ii) the effect of doubling monthly precipitation across the region, and (iii) a widely used climatic change scenario that involves modifications in monthly mean temperatures and precipitation, as well as a doubling in atmospheric CO_2 concentrations. These analyses showed that optimum soil fertility would more than double growth. Doubling the precipitation increased productivity in the pine type (> 50%) with reduced responses elsewhere. The climate change scenario with doubled atmospheric CO_2 increased growth by 50% on average across all forest types, primarily as a result of a projected 33% increase in photosynthetic capacity.

Rehfeldt *et al*. (2001) updated the temperature functions for 125 *Pinus contorta* populations to assess the impact of 16 climate change scenarios on forest productivity. Impact was considered according to the transient effects of a changing climate governed by physiological plasticity in the contemporary generation and long term evolutionary adjustments that provide adaptedness and optimize productivity in future generations.

Lasch *et al*. (2002) used process based forest model 4 C (FORESEE) to investigate changes in forest productivity under current climate and future climate change scenarios. The sensitivity of net primary production, growth and mortality with respect to changes in climate and atmospheric CO_2 was analyzed using a set of temperature and precipitation scenarios and tree scenarios. Changes in forest productivity were analyzed in terms of mean annual increments. Simulation runs were carried out for current climate and two climate change scenarios; ECHAM4 and HADEM2. The results show increasing productivity under the HADEM2 scenario and stable and decreasing productivity under the ECHAM4 scenario.

Nabuurs *et al*. (2002) conducted a study in which seven process-based growth models were applied to 14 representative forest sites across Europe under one climate change scenario. The chosen scenario was the HadCM2 run, based on emission scenario IS92a, and resulted in an increase in mean temperature of 2.5 °C between 1990 and 2050, and an increase in annual precipitation of 5–15%. The information from those runs was incorporated in a transient way in a large-scale forest resource scenario model, EFISCEN (European forest information scenario). European scale forest resource projections were made for 28 countries covering 131.7 million ha of forest under two management scenarios for the period until 2050. The results showed that net annual increments in stemwood of European forests under climate change will further increase with an additional 0.9 $m^3\ ha^{-1}\ y^{-1}$ in 2030 compared to the ongoing increase under a current climate scenario, i.e. an extra 18% increase. After 2030 the extra increment increase will reduce to 0.79 $m^3\ ha^{-1}\ y^{-1}$ in 2050. Under climate change, absolute net annual increments will increase from the present 4.95, on average for Europe, to 5.93 $m^3\ ha^{-1}\ y^{-1}$ in 2025. After 2025, increments in all scenarios will start to decline owing to ageing of the forest and the high growing stocks being reached.

Hernandez *et al*. (2003) demonstrated that production in terrestrial arid ecosystems was influenced by climate especially temperature. The findings showed that temperature influences the photosynthetic rate, high temperature makes deserts one of the least productive terrestrial ecosystems and this was further supported by the evidence that there always exists a linear relationship between temperature and productivity.

Negi *et al*. (2003) conducted a study on the evidences of climate change and its impact on structure and function of forest ecosystems in and around Doon Valley. Available data on meteorological observation, phytosociological studies, population dynamics and biomass in moist Sal forests of Doon Valley and adjacent dry deciduous forests were utilized to understand the structure and functioning of the ecosystem. Seventy years mean maximum and mean minimum daily temperature and rainfall were analysed for each of the five year interval (1931-2000). It was observed that there was an increase of 0.5^0C in mean maximum temperature and a decline of 1.1^0C in mean minimum temperature. Total rains declined by 17% during 70 year of period, whereas the local rains increased by 27% since 1981 onwards. Fluctuations in temperature and rainfall have pronounced effect on the distribution of evergreen and deciduous tree species. Further change in climatic pattern and microclimate conditions as a result of deforestation has a noticeable impact on forest decline. Atmospheric CO_2 enrichment has put a positive response in enhancing productivity of these ecosystems.

Bergh *et al*. (2003) found that the net primary production (NPP) of cold-temperate and boreal forests may respond substantially to elevated temperature and atmospheric CO2 concentration. They used the process-based growth model BIOMASS to estimate the effect of elevated temperature and [CO2] on NPP in the Nordic coniferous forests (excluding Iceland). The two regional climate scenarios that were used to drive the simulations were based on two different emission scenarios giving a [CO2] of 600 and 825 mmol CO2 mol^{-1} in year 2100. Estimates of NPP from these simulations were for the period 2070 to 2100 and these were compared with estimates for 1970 to 2000 from simulations driven with observed climate. The comparison of NPP estimates was stratified for three different age-classes (young, mature, and old) of Scots pine and Norway spruce. For most Nordic regions the relative increase in NPP was 10-30% for both species and climate scenarios. The simulation driven by the climate for the higher emission scenario resulted in a 5-15% higher NPP than in the simulation driven by climate for the lower emission estimates. While the relative increase in NPP was 5-10% higher for Scots pine than Norway spruce, but the absolute response of Norway spruce was higher because of its higher yield.

Nigh *et al*. (2004) developed statistical models to predict site index from climatic data such as mean annual temperature, mean temperature of the warmest and coldest months, latitude, longitude and elevation. The models were used to investigate the current relationship between climate particularly temperature and site productivity, the productivity increased as temperature increases.

Hyuncheol *et al*. (2004) studied correlation between productivity and altitude with environmental factors (temperature) in *Castanopsis cuspidate* forests. *Castanopsis cuspidate* forest showed a high correlation with elevation, temperature in the first axis and Mg, Ca (moisture) on the second axis.

Guanghua and Yuezhong (2004) studied the influence of climatic factors such as air temperature, relative humidity, precipitation and illuminating hours on height growth. The results showed that correlation of the modeling was significant. Air temperature was believed to have the most significant influence on the height growth while precipitation had the least effect.

Yue and Hashino (2005) interpreted that forest growth increased with increase in temperature in Samera basin, located in Shikoku islands of Japan in the period from 1953 to 1994.

Yarie and Parton (2005) developed a set of simulations related to the carbon dynamics of interior Alaska taiga forest types using the CENTURY ecosystem model. The functional dynamics of three age classes (young, middle and mature) of three ecosystem types (white spruce, black spruce, and hardwood) were compared using a typical climate that was present prior to 1980 to the climate from 1980 to 2000. Results indicated a distinct difference between ecosystem types in their response to climate change. Estimates for above- and below-ground production indicated a major decrease in tree carbon capture for the hardwood stands at all three age classes summed across the 20- year climate change. White spruce displayed increases in carbon capture for the three age classes, but the magnitude of the increases was approximately 10 to 20% of the decrease observed for hardwoods. Young and mid-aged black spruce stands showed a decrease in carbon capture again at a level that was about 10% of the hardwood stands. The carbon capture of the old growth black spruce stand was unchanged. Hardwood ecosystems showed carbon capture increases in both the young and old age classes and a loss in the middle age class. White spruce ecosystems showed an average increase of 2443 g/m2 carbon for the 20- year climate period and black spruce showed a significant decrease (3193 g/m2) in ecosystem carbon over the past twenty years. Based on the landscape area covered by each vegetation type it can be suggested that the net effect of climate warming over the past twenty years has been a substantial increase in carbon release from the forests of interior Alaska.

Mayer *et al*. (2005) used comparative trend analysis to demonstrate the significant effect of temperature on forest productivity and forest management. The results showed an average increase of the mean temperature values by 0.22^0C which increased the volume of forest growing stock.

Johnston and Williamson (2005) explored the effects of increasing temperature on future stand yields and their results suggested that under most future scenarios, stand productivity will increase and optimum economic rotation age under future increasing temperature will be lower than that under present temperature conditions.

Rodriguez and Gracia (2006) assessed a likely gradient in the response of tree species to temperature. Cross correlation spectral and wavelet analysis techniques were used to assess the relation of growth with temperature. Species growth was positively correlated to temperature while with precipitation, it was not.

Zhao and Zhou (2006) studied the carbon storage of forest vegetation in China and its relationship with climatic factors and found that total carbon storage and mean carbon density of forest vegetation in China were 3.8 Pg C (about 1.1% of the global vegetation carbon stock) and 41.32 Mg/ha, respectively. In addition, based on linear multiple regression equation and factor analysis method, contributions of biotic and abiotic factors (including mean forest age, mean annual temperature, annual precipitation, and altitude) to forest carbon storage was analyzed. The results indicated that forest vegetation carbon storage was more sensitive to changes of mean annual temperature than other factors, suggesting that global warming would seriously affect the forest carbon storage.

Boisvenue and Running (2006) reviewed at finer spatial scales that temperature seemed to have a generally positive impact on forest productivity when water was not limiting. The combined and interacting effects of temperature, radiation and precipitation resulted in increased productivity.

Ravindranath *et al*. (2006) assessed that increasing atmospheric temperature could result in a doubling of net primary productivity under A_2 (740 ppm CO2) scenario and nearly 70% increase under the B2 (575 ppm) CO_2 scenario, therefore impact of temperature (climate change) on forest ecosystem should be incorporated in forest sector long term planning process.

Younghui *et al*. (2006) suggested the effect of temperature and precipitation increase on forest growing stock, d.b.h and tree height. According to their study, the effect of temperature and precipitation increase on forest growing stock could cause an increase of forest growing stock by 2.5-8.0 per cent per degree centigrade and 10 per cent per 100 mm, respectively.

Su *et al*. (2007) simulated *Picea schrenkiana* forest productivity under climatic changes and atmospheric CO_2 increase in Tianshan Mountains, Xinjiang Autonomous Region, China. A process-based model, BIOME-BGC, was used to investigate the response of *Picea schrenkiana* forest to future climate changes and atmospheric carbon dioxide (CO_2) concentration increases. The results showed that NPP increased moderately (about 18.6%) for all sites when both temperature and precipitation changes were taken into account. The main factor contributing to NPP increase was an increase in precipitation, which tended to alleviate moisture stress for *P. schrenkiana* forest growth. NPP increase was relatively low (about 2.7%) when the physiological fertilizing effect of the doubled atmospheric CO_2 concentration was considered alone, in part because of nitrogen limitation and low temperatures. When both climatic changes and doubling of atmospheric CO_2 concentration were taken into account, NPP increased more dramatically (from 26.4% to 37.2%).

McMahon *et al*. (2010) conducted a study to corroborate the fact that forest biomass is increasing due to climate change. However, without knowing the disturbance history of a forest, it is likely that growth could also be caused by normal recovery from unknown disturbances, therefore they used a unique dataset of tree biomass collected over the past 22 years from 55 temperate forest plots with known land-use histories and stand ages ranging from 5 to 250 years and it was found that recent biomass accumulation greatly exceeded the expected growth caused by natural recovery. Over 100 years of local weather measurements and 17 years of on-site atmospheric CO2 measurements were also collected that showed consistent increases in line with globally observed climate-change patterns. These results signal a pressing need to better understand the changes in growth rates in forest systems, which influence current and future states of the atmosphere and biosphere.

Toledo *et al*. (2011) examined the effects of climate, soil and logging disturbances on diameter growth rates at the tree and stand level, using 165 1-ha permanent sample plots distributed across Bolivian tropical lowland forests. Across the 165 plots they found positive basal area increases at the stand level, which agree with the generally reported biomass increases in tropical forests. Multiple regression analysis demonstrated that climate variables, in particular water availability, were the strongest drivers of tree growth. More rainfall, a shorter and less intense dry period and higher temperatures led to higher tree growth rates. Tree growth increased modestly with soil fertility and basal area growth was greatest at intermediate soil fertility. Tree growth showed little or no relationship with total soil nitrogen or plant available soil phosphorus. Growth rates increased in logged plots just after logging, but this effect disappeared after 6 years. Hence, it was concluded that climate is the strongest driver of spatial variation in tree growth, and climate change may therefore have large consequences for forest productivity and carbon sequestration. The negative impact of decreased rainfall and increased rainfall seasonality on tree growth might be partly offset by the positive impact of increased temperature in these forests.

2.3.2 Effect of climate change on weather parameters

The changing climate and warming of the atmosphere has a large impact on physical weather elements of a region or a country. Variations in the frequency and intensity of extreme weather events, such as floods, droughts, cyclones and western disturbances, and the occurrence of weather events such as heat and cold waves over India allow scientific communities to examine if parameters associated with these events can be considered as evidence for climate change.

Some past studies relating to changes in rainfall over India have concluded that there is no clear trend of increase or decrease in average annual rainfall over the country (Mooley and Parthasarathy, 1984; Sarker and Thapliyal, 1988; Thapliyal and Kulshreshtha, 1991; Lal, 2001). Though no trend in the monsoon rainfall in India is found over a long period of time, particularly on the all-India scale, pockets of significant long term rainfall changes have been identified (Koteswaram and Alvi, 1969; Jagannathan and Parthasarathy, 1973; Raghavendra, 1974; Chaudhary and Abhyankar, 1979; Kumar *et al*., 2005; Dash *et al*., 2007; Kumar and Jain, 2009).

Several observational studies show significant temperature and precipitation changes in India over the long term. Studies by (Khan *et al*., 2000; Shrestha *et al*., 2000; Mirza, 2002; Lal, 2003; Min *et al*., 2003; Dash *et al*., 2007) show that, in general, the frequency of more intense rainfall events in many parts of Asia has increased, while the number of rainy days and total annual amount of precipitation has decreased. Goswami *et al*. (2006) used daily rainfall data to show the significant rising trends in the frequency and magnitude of extreme rain events, and a significant decreasing trend in the frequency of moderate events over central India during the monsoon seasons from 1951 to 2000. Shekhar *et al*. (2010) revealed that different ranges of the western Himalaya show significant variations in temperature and snowfall trends in the past few decades.

Kothawale and Kumar (2005) reported that the all India mean annual temperature increased by 0.58 °C during 1901-2003. This increase is consistent with the expected effects from global warming. The trend in the pre-monsoon (March-May) temperature over the western Himalaya has been studied by Yadav *et al*. (2004) using observations and reconstructions from tree rings. They found the pre-monsoon minimum temperature tended to decrease during the late 20th century. They also found that the rate of decrease of minimum temperature is three times that of the rate of decrease of maximum temperature, indicating that the minimum temperature is the larger contributor to the cooling trend in the pre-monsoon mean temperature. The temperature and precipitation trends over north and south India for different phases of the monsoon were investigated by Dash and Hunt (2007) and Dash *et al*. (2007). They found large differences in trends in minimum temperature and cloud cover between north and south India and asymmetry in increasing temperature trends between different seasons. They also found a reduction in the summer monsoon (June-September) rainfall over India, and suggested this reduction can be explained by both climate change and the mesoscale effects of the mountains on monsoon flow.

Long term trends in the maximum, minimum and mean temperatures over the north-western Himalaya during the 20th century (Bhutiyani *et al*., 2007) suggest a significant rise in air temperature in the north-western Himalaya, with winter warming occurring at a faster rate. The study also shows that significant warming started in the late 1960s, with the highest rate of increase between 1990 and 2009. Dimri and Ganju (2007) simulated wintertime temperature and precipitation over the western Himalaya. They used a regional climate model and found that temperature is underestimated and precipitation overestimated in the Himalayas. However, studies by Fowler and Archer (2006) show some conflicting results. Using Upper Indus Basin (UIB) data, they show a decreasing trend in mean annual temperature since the 1960s which has become more pronounced since the 1970s. In contrast, they found an increasing trend in mean winter (December-February) temperature during 1960-2000. The changing trends of temperature and precipitation over the western Himalaya were examined by Dimri and Kumar (2008), who calculated the number of warm and cold events during winter (December-February) for 1975-2006. They found a trend of increasing temperature and decreasing precipitation at some specific locations. Observational studies by Kripalani *et al*. (2003) revealed that the area of spring snow cover across the western Himalaya has been declining and the snow has been melting faster from winter to spring since 1993, which may be due to global warming.

It is expected that changes in temperature due to climate change in the atmosphere lead to a change in the pattern of snowfall over different ranges in the western Himalaya. In general, more snowfall is expected in a warmer atmosphere, as a result of more evaporation followed by more cloud formation. However, a recent study shows reduced snowfall over the western Himalaya in a warming climate (Dimri and Kumar, 2008). Reduction of snowfall can be explained by the combined effect of climate change and mesoscale influences of the mountains.

The monsoon rainfall is associated with multiple spells of active and break-monsoon phases. The phenomenon of "monsoon break" is of great interest because long intense breaks are often associated with a pronounced decrease in rainfall in the major part of India. Such breaks have a large impact on rainfed agriculture and prolonged breaks create drought conditions. Examination of daily rainfall over India for the period 1951-2007 by Ramesh Kumar *et al*. (2009) revealed that there has been a significant increase in the incidence of prolonged monsoon breaks during the core monsoon rainy months of July and August in recent decades. Monsoon depressions are the main rainfall-producing synoptic weather system over India. Studies on the occurrence of monsoon depressions using the data of 1889-2002 showed a significant decrease in their seasonal frequency, with a maximum decrease in July, followed by August and September (Dash *et al*., 2004). Kumar *et al*. (2010) reported that for the whole of India, no significant trend was detected for annual, seasonal or monthly rainfall. Annual and monsoon rainfall decreased, while pre-monsoon, post-monsoon and winter rainfall increased at the national scale. Rainfall in June, July and September decreased, whereas in August it increased, at the national scale.

The western Himalayas are particularly prone to severe weather, due to the movement of western disturbances during the winter months. The synoptic aspects of western disturbances have been discussed by many authors (Pisharoty and Desai, 1956; Rao and Srinivasan, 1969; Kalsi, 1980; Azadi *et al*., 2002; Dimri, 2008) and are the primary sources of precipitation over the western Himalaya during winter, where the number of snowfall days and the amount of snowfall depend on the number of occurrences and the intensity of the western disturbances. In an observational study, Das *et al*. (2002) found that western disturbances in the Himalaya activate monsoons in certain areas of north-western India. They also studied trends in the annual pre-monsoon (March-May) frequency of western disturbances and the onset date of monsoon over north India for the period 1971-2000 and found that frequency of May western disturbances has significantly decreased over recent years.

2.3.3 Dendrochronology

Dendrochronology is the science of tree-ring dating. According to Fritts, 1987, the term *dendro* is from *dendron*, the Greek word for tree, and *chronology* means the assignment of dates to particular events in a time series. The study of past and present climate from tree rings is known as dendroclimatology (Fritts, 1976). The width of a specific tree-ring is closely related to the climate the tree experienced during the period of growth. This makes it possible to precisely date tree-ring samples through ring width variation pattern matching. In general, moisture and warmth promote growth, and lack of moisture and warmth inhibit growth. Of course, these are not the only factors that affect tree growth, but over long periods of time they are the most significant in many parts of the world.

Andrew E. Douglass is considered the founder of the discipline of Dendrochronology. He was an astronomer interested in sunspot events and a possible causal relationship between periodic sunspot activity and temporal variations in climate on earth. In order to prove his theory, Professor Douglass needed long term climatic and weather data. In Northern Arizona in 1901, Douglass noticed the similarities in tree-ring width variation patterns among several recently cut logs. He specifically noticed a series of very small rings located twenty-one rings inside the bark. He also examined a stump, which had been cut at an unknown time in the past. He noticed the same pattern of small rings on the stump's cross-section, but they were located eleven rings inside the bark. He concluded that the tree must have been cut ten years prior. Douglass knew that tree-rings grew as a function of climate; now he knew how to determine what year they represented. This was effectively the first recorded instance of tree-ring crossdating.

The fundamental scientific basis of dendrochronology, established by Douglass in the early 20th century, is that climate affects all trees in a given area consistently. This means that the pattern of *relative* ring width variation between different trees from close locations should be very similar for a given time period, even though their *absolute* ring widths may be quite different. This could be, for example, due to local soil conditions at a particular tree. Dendrochronology works on the principle that over a long period of time (especially 100 years or more) there is a pattern of tree-rings of wider and narrower rings which respectively reflect years favourable for the tree versus bad years and that the period during which any tree lived will be uniquely represented in its tree-ring pattern (considering all features, including ring-widths).

2.3.4 Tree-Ring Characteristics

Dendrochronologists call the lighter colored area of a ring *earlywood* and the darker colored area *latewood*. At the cellular level, earlywood consists of large, thin-walled cells and latewood consists of small, thick-walled cells. As their names suggest, earlywood grows at the beginning of the growing season and latewood grows toward the end of a growing season. The beginning of the growing season roughly corresponds to the spring and summer seasons and the end of the growing season roughly corresponds to late summer and early fall. In general spring and summer tend to be warmer and have more useful moisture than fall and winter, hence, the difference in tree growth rates.

Tree-rings are made up of cells called tracheids. Two kinds of tracheids make up the distinct light and dark parts of an annual growth ring, known as earlywood and latewood, respectively. A distinct pattern of light to dark color variation is noticed in tree-ring samples, especially from conifers. Light-colored earlywood forms in the spring at the beginning of a growing season and has tracheids that are large with thin cell walls. Latewood forms in the late summer/early fall or at the end of the growing season and is dark in color because the tracheids have constricted and their cell walls thickened. Other anatomical features found within the tree-ring record are resin ducts, woods rays (which carry resin and nutrients throughout the tree), sapwood (young wood), heartwood (old wood), and heart rot (rotten wood) (Fritts, 1976).

Tree-rings respond to climate with inter-annual variations in width and density. If growth factors are limited in the extreme, growth will be restricted and will result in a narrow ring. If all conditions are ideal and not limited, rings will be wide. Tree-rings also respond to climate with intra-annual density fluctuations. One such example of this, known as false rings, can occur in earlywood or latewood as a result of extended episodes of an environmental change. For example, if a tree experiences a cold spring, it will develop a narrow earlywood. If the spring is ideal, but a cold front settles in, this cold front will produce a few dense layers of tracheids within the earlywood, thus creating a false ring (Stokes and Smiley, 1968). Frost rings can also occur with sudden temperature changes. In this case, tracheids look ruptured and will appear as a line of broken cells. In extremely limited growth conditions, a tree may not initiate growth at all during the current growing season. This leads to absent rings which can compromise the accuracy of tree-ring paleoclimate data. All these variations in ring structure in response to climate are what produce indicator rings and the signature of a sensitive ring record which can then be related to other trees in order to establish a large scale climate signal. In some cases these “complicated rings” can be used to infer past climate events (e.g. mid season cold or frost events) but in some cases these “false” rings can be misinterpreted as a complete annual growth increment and can add complexity to resulting chronology.

Tree rings, when viewed as time series of annual increments, present a valuable, long-term record of tree growth across many forest environments. The pattern of radial growth in trees depends largely on the climatic conditions of different localities (Chowdhury, 1940; Rao and Dave, 1981). Trees respond to climate via complex interactions between ecological and physiological processes and microsite characteristics. Climate variability and climate change are processed at the tissue, individual tree, stand, and ecosystem scales. Tree species are unique in that their response to environmental conditions and can be used as a fingerprint of recent climate change (Parmesan and Yohe 2003; Root *et al*., 2003) and a natural archive of past climate (Fritts 1976). Tree rings, as natural archives, provide important proxy data for paleo-environmental studies and reconstructions (Bradley and Jones 1992; Luckmann, 1996).

2.3.5 Tree rings for the assessment of the impact of climate change on the growth of forests

Tree rings are the most important and widely used sources of long-term proxy data. Their major strengths as climate change indicators are (i) their annual resolution, (ii) the existence of large geographic-scale patterns of synchronic interannual variability, (iii) the increasing availability of extensive networks of tree-ring chronologies, and (iv) the possibility of using simple linear models of climate–growth relationships that can be easily verified and calibrated (Hughes, 2002). Their weaknesses include: (i) an intrinsic sampling bias, given that tree-ring information is available only for terrestrial regions of the globe, (ii) the fact that methods used to extract growth signals from tree-ring series retain only certain wavelengths of climate variability (IPCC, 2001) (iii) the complexity of biological responses to climate forcing, and (iv) the presence of nonclimatic variability in the series attributable to intrinsic growth trends and other nonclimatic disturbances (Fritts, 1976).

Matching of relatively fast and slow growth ring patterns among trees is called cross-dating (Swetnam *et al*., 1985). By coupling this to climate data (e.g. temperature), it is possible to establish a connection between critical climatic variables and tree growth. When tree rings are dated to the exact calendar year through the technique of crossdating (Stokes and Smiley, 1968), the science of dendroclimatology extracts the maximum amount of climatic information contained in the tree-ring record.

LaMarche *et al.* (1984) found that widths of annual rings of bristlecone (*Pinus longaeva*) and limber pine (*Pinus flexilis*) trees near timberline in central Nevada were 106 percent greater in the decade ending in 1983 than in the years 1850 to 1859 at one site and 73 percent greater at another. They explained that the observed increase in tree-ring widths was due to an increase in biomass due to elevated CO2. The CO2 fertilization hypothesis proposes that plants will grow faster under elevated atmospheric CO2 concentrations; that accelerated growth might take many forms like increase in underground root mass, increase in foliage, and increase in cambial activity and thus tree-ring width.

Cook *et al*. (1987) studied the effect of climate in tree rings; the study reflects changes with time in site factors which were due to elevated temperature (dominant component) competition, tree and stand age, fire and other disturbances.

Jozsa and Powell (1987) determined the biomass productivity for white spruce (*Picea glauca*) in the boreal forests of Alberta, the Northwest Territories and Manitoba. Comparisons were made between southern and northern locations, between eastern and western transect locations and between older (200+ years) and younger (110 years) trees. At 13 sampling locations, X ray densitometric tree ring data were obtained from the base of the stem, breast height and from five points equidistant along the stem. Markedly higher stem wood biomass productivity was found for the 110 year old trees than for the 210 years old trees in Alberta, average ring widths were 3.8 and1.2 g for the first 100 years of growth in 1 cm thick discs at breast height. These results suggested that climate warming since the end of the Little Ice Age (ca. 1850) has resulted in higher biomass productivity in the Canadian boreal forest.

Fritts and Dean (1992) did the dendrochronological modeling of the effects of climate change on tree ring width chronologies from the Chaco Canyon Area, Southwestern United States. Hypothesis about the causes of the growth and decline of the Chacoan regional interaction system between A.D. 900 and 1200 were evaluated against tree ring evidence and the results of an empirical model (PRECON) that computed the statistical relationship between climate and ring width indices during the 20th century and applied the results to the hypothesized precipitation or temperature changes. The statistical responses of 23 indexed conifer ring width chronologies from New Mexico and Colorado to variations in monthly temperature and precipitation were calculated. Simulated decreases in prior autumn-winter precipitation and winter temperature markedly reduced ring widths. It was found that favourable climatic conditions in the 10 th, 11th and early 12 th centuries fostered growth of the Chacoan system. Dry autumn-winter and summer conditions in the middle 1100's contributed to the downfall of the system.

Cook (1995) evaluated and compared recent temperature trends in tree-ring and coral proxy temperature histories in an effort to objectively determine how anomalous twentieth century temperature changes have been. These histories mostly reflected regional variations in summer warmth from the tree rings and annual warmth from the corals. At northern latitudes, these histories included temperature-sensitive tree-ring series for northern Alaska, the north Polar Urals, and the Arctic as a whole. All three of these series indicated unusual 20th century warming. In the Southern Hemisphere, the tree-ring temperature histories from South America showed no indication of recent warming, which was in accordance with local instrumental records. In contrast, the tree-ring records from Tasmania and New Zealand indicated that the twentieth century has been unusually warm particularly since 1960. The coral temperature histories from the Galapagos Islands and the Great Barrier Reef were in broad agreement with the tree-ring temperature histories in those sectors, with the former showing recent cooling and the latter showing recent warming that may be unprecedented.

Nathsuda *et al*. (1995) from a network of teak chronologies in northern Thailand evaluated 75 trees within one province regarding their climatic signal. The raw tree-ring series revealed a high mean sensitivity of 0.50 and a moderate first-order autocorrelation of 0.48. The first principal component of the standardized data explained 44% of the total variation in the tree-ring data, indicating a considerable climatic influence on tree growth. The climate-growth relationship suggested that growth of teak in this study area was mainly controlled by rainfall from April to June. Thus, there is some promise that the whole network of teak chronologies in northern Thailand can contribute to reconstructing climate over at least the last three centuries.

Hasenauer *et al*. (1998) used the climate records from 20 weather stations and investigated changes in climate and tree growth between 1961 and 1995 by analyzing radial increment rates from tree rings over the same period. The results indicated: (1) no change in precipitation over the period; (2) a highly significant increase (α=0.01) in average annual temperature (1.13°C), minimum temperature (1.23°C), winter temperature (2.70° C) as well as a significant (α=0.05) increase in the length of the growing season (14 days) since 1961. For the early 1990s, lower radial increment rates as well as a decrease in the temperature related climate parameters were detectable. To understand the importance of climate on tree growth they used the ecosystem model FOREST-BGC and predicted the annual net primary production (NPP). The trends in NPP were consistent with observed diameter increment rates determined from 1179 increment cores for Norway spruce from all over Austria.

D'arrigo *et al*. (2000) found that in boreal conifers, maximum latewood density (MXD) of annual rings varied in response to warm-season temperatures. Vegetation productivity was estimated using the Normalized-Difference Vegetation Index (NDVI) calculated from satellite sensor data. Ground measurements related to productivity were accquired in order to evaluate these estimates. MXD from three boreal sites was compared with estimates of net primary productivity (NPP) for 1982–1990 produced by the CASA (Carnegie-Ames-Stanford-Approach) model from FASIR (Fourier adjustments, solar zenith angle correction, interpolation at high latitudes, and reconstruction of tropical values) NDVI. All three density series correlated significantly with the CASA estimates, suggesting that in boreal conifers MXD may be an appropriate index for productivity or canopy growth in regions where productivity is strongly temperature-related.

Henn Parn (2002) used dendrochronological techniques to evaluate the influence of climatic factors and the prior growth on radial growth of Scots pines. Two sites were selected for this study in the northeastern industrial region of

Estonia. The Narva site was located approximately 11 km north and the Jouga site approximately 45 km south-westward from the oil shale fired Baltic Power Plant, the main source of atmospheric pollution in this area. The climate–growth relationships were studied during two periods, from 1923 to 1960 (the pre-pollution period) and from 1961 to 1994, during which the oil shale fly ash emissions reached the maximum amounts. The classical stepwise multiple regression procedure was used. During the period when the dust pollution load on trees increased the radial growth became more sensitive to precipitation. The temperature in winter months during the first period had a positive correlation with radial growth. The temperature in the preceding December had an inverse relationship with the radial growth during the second period. In the case of the Narva site the regression models using the SP chronologies explained more of the total variance in tree-ring indices than other models. At the Jouga site the models based on NE performed better.

Solberg (2002) studied the relationships between monthly mean temperature, monthly precipitation and large scale climate indexes (North Atlantic Oscillation (NAO), Arctic oscillation (AO), Zonal Index (ZI) and Meridional Index (MI)), and radial growth of *Pinus sylvestris* in central Norway. Nine Scots pine tree-ring width chronologies were compared regarding growth variability and response to climate along a gradient of oceanicity-continentality. The study revealed higher growth variance and stronger response to climate in the oceanic area west of the Scandinavian Mountains, compared to the more continental areas further east. Pine growth responded positively to summer temperatures in the western areas, and positively to summer precipitation in the east. Generally, pine growth showed a weaker relationship with the North Atlantic Oscillation (NAO) than with temperature and precipitation.

Makinen *et al*. (2003) studied the annual radial increment variation and its dependence on temperature and precipitation in 13 severely damaged and 12 healthy stands of Norway spruce [*Picea abies* (L.) Karst.] on mineral soil and peatlands in southern Finland. An intervention analysis revealed that the presently dead trees had experienced severe growth reductions since the late 1980s. Even though annual growth variation between the stands was fairly similar, differences in the relationship between radial growth and weather variation were found between healthy and damaged stands. High temperature in May increased radial growth in the healthy stands. This was not observed in the damaged stands, where summer temperature was negatively correlated with growth. In addition, high temperature during the previous summer decreased tree growth in next summer. Tree-ring indices showed a strong positive correlation with June precipitation in the damaged stands. Correlation of June precipitation and growth was much weaker in the healthy stands. This result suggests that the damage is connected to drought and is likely to occur at drought sensitive sites. The finding also fits in well with the fact that many of the damaged sites were rocky or stony.

Oberhuber (2004) studied radial growth variability and response to interannual climate variation of Cembran pine (*Pinus cembra* L.) in the timberline ecotone on Mt. Patscherkofel (2246 m a.s.l.) in the inner alpine dry region of the Central Austrian Alps. The accuracy of dating of tree ring series was checked with the COFECHA program and standard and residual chronologies for all sampled stands were calculated by the ARSTAN program. Radial growth at the timberline was positively correlated with temperature in July and was also strongly correlated with mild temperatures in the previous autumn and high precipitation in winter (January–March). At the tree line, temperatures in the previous autumn and precipitation in late winter (March) also controlled radial growth, whereas July temperature was not significantly correlated with ring width.

Alekseev and Soroka (2004) studied the growth trends of Scots pine (*Pinus sylvestris*) at its northernmost extent on Kola Peninsula and moderate extent in the Leningrad region. Wood cores were taken from 175 Scots pine trees located on 17 sample plots on Kola Peninsula using a Pressler borer. Different age-classes were sampled as follows: 21-40 yrs: 63 trees, 41-60 yrs: 20 trees, 61-80 yrs: 18 trees, 81-100 yrs: 11 trees, 101-200 yrs: 41 trees and >200 yrs: 22 trees. The widths of 16,954 tree rings that appeared between 1660 and 1992 were measured. In the Leningrad region, cores were taken from 467 trees located on 118 sample plots regularly distributed over the whole area. A total number of

33845 tree rings appearing between 1815 and 1995 were measured. After removing age-trends from the data, a time-series analysis of annual radial increment over the last few decades compared with the period of the last registered warming (maximum around 1930-40) revealed elevated growth in 78 % for trees 0 to 20 years old, 56% for trees 21 to 40 years old, 21% for trees 41 to 60 years old, and 10% for trees more than 101 years old for the Kola Peninsula area. The same analysis for the data collected from Scots pine tree stands of Leningrad region gives the opposite result of no increase of tree growth. Moreover, for 67% of the sample plots they found a decline in mean increment for the period 1985-1995 compared with the 1975-1985 by more than 10%.

Fichtler *et al*. (2004) studied the dendroclimatic potential of two dominant species from dry forests in northern Namibia. Both species (*Burkea africana* Hook and *Pterocarpus angolensis* DC) were sampled at two sites (ca. 900 km apart), and the response to several climatic variables, including ENSO indices, was studied. All specimens showed distinct growth rings and crossdating between radii was successful for all trees. Species specific mean curves were built for both sites. The mean curves of different species of the same site synchronized significantly, allowing the construction of a site-specific chronology. Synchronisation between sites was not possible, but spectral analysis of the chronologies implied that both showed similar long-term (6.7 year) oscillation patterns. *B. africana* was more sensitive to rainfall variation than *P. angolensis* at both sites. Growth response to rainfall was positive, but a time-lag in the reaction occurred between the sites, corresponding to the time-lag of the beginning of the rainy season. Air temperature showed a negative correlation with stem increment at both sites. The response at the westernmost site to two ENSO indices indicated a tree growth decrease during El Nino years, which are generally dry in southern Africa.

Wang *et al*. (2006) found the evidence of an atmospheric CO2 fertilization effect on radial growth rates for open-grown white spruce in a mixed-grass prairie of southwestern Manitoba, Canada. About 61% of the total variation in radial growth index was explained by climate for both young and old trees, residuals from young trees for the period of 1955–1999 demonstrated a stronger upward trend (R250.551, Po0.0001) than old trees for the period of 1900–1996 (R250.020, P50.167). Similar to young trees, the residuals from the early growth period (1900–1929) of old trees also demonstrated a stronger upward trend (R250.480, Po0.0001) than the period of 1900–1996. Likewise, a comparable period (1970–1999) of young trees also demonstrated a stronger upward trend (R250.619, Po0.0001) than the early growth period (1900–1929) of old trees. In addition, post drought growth response was much stronger for young trees (1970–1999) compared with old trees at the same development stage (1900–1929) (P50.011) or within the same time period (1970–1999) (P50.014). There was no difference (P50.221) in drought recovery between the early (1900–1929) period and the late (1970–1999) period within old trees. Together, their results suggested that (1) open-grown white spruce trees improved their growth with time at the early developmental stage, and (2) at the same developmental stage, a greater growth response occurred in the late period when atmospheric CO2 concentration, and the rate of atmospheric CO2 increase were both relatively high.

Fortus (2006) analyzed a series of tree-ring indices to understand whether they can be indicators of long-term climate change by calculating the synchronous cross-correlation coefficients (CCs) for all possible pairs composed of nine series, of which only one CC (for a pair of the longest series) proved to be sufficiently high (0.72). Their results revealed a time interval for which this CC is equal to 0.88. Similar calculations for a series using a low-frequency filter (with allowance for periods of 100 or more years) led to a noticeable decrease in almost all CCs. Hence they confirmed that tree-ring chronologies include climate signals with characteristic times of several decades and that the secular and super secular oscillations are significantly distorted as a result of standardization and cross-linking.

Carrer and Urbinati (2006) used tree-ring width chronologies of *Larix deciduas* (European larch) from 17 sites and monthly temperatures and precipitation data for the period 1800–1999. Climate–growth relationships were assessed with correlation and response functions, and their stationarity and consistency over time were measured using moving correlation. Tree-ring chronologies showed similar interannual variations over the last two centuries, suggesting that the same climatic factors synchronously limited growth at most sites.

Stratton (2007) studied the tree-ring records of late holocene climate change in the Hangay mountains, Mongolia in Siberian larch. Trees were sampled from Egiin Davaa region of the central Hangay reaching altitudes in excess of 3500 m. Analysis of ring widths employed the computer programs CRONOL and YUX. Twentieth Century growth in the Egiin Davaa trees was consistent with both the increasing temperature and increasing precipitation shown by the available data as well as the periods of severe drought between 1965 and 1980. Records obtained by the MATRIP (Mongolian-American tree ring project) group (Jacoby et al, 2003) from Sol Dav, an elevational timberline site in the Hangay (approximately 100 km northwest of Egiin Davaa) showed consistent growth increases in the 20th Century. Of note in the Egiin Davaa record was the sustained overall increase in growth despite aging of the trees, which suggests that growth conditions were considerably more favorable in the 20th Century.

Feliksik and Wilczynski (2008) studied the climatic conditions affecting diameter growth of Sitka spruce introduced to Baltic Pomerania (Slawno Forest District). A significant positive correlation was found between radial increments of Sitka spruce and air temperatures of winter and spring months (January-April) and a negative relationship between radial increments and temperature of May. This study also showed a distinctly positive correlation between diameter growth and precipitation in July and November of the previous year, and precipitation in February and in summer season (June-August) of the current year. During years with low precipitation in summer or low temperatures in winter and spring all trees produced narrow tree-rings. The proportion of air temperature and precipitation in variation of radial increment of Sitka spruce, expressed by the coefficient of multiple determination, was 52%.

Bhoru and Gupta (2008) evaluated the effect of air temperatures, precipitation, number of rainy days and humidity on the tree-ring width and density of resin canals of *Pinus roxburghii* growing in a forest near the Forest Research Institute (FRI), Dehra Dun, between 30° 19' 55" and 30° 21' 16" North and 77° 58' 40" and 77° 1' East and 640.08 m a.s.l. The samples were collected from trees (Chakrata provenance) planted in the years 1928-1930. A Pressler increment borer was used to take the sample cores. The chronology of ring width was calculated as an average from both dendroscales. The analysed period was 1943-2006. Response function analysis indicated a positive relationship between number of rainy days and earlywood width. Non-significant or very weak relationships were observed between ring width and number of resin canals with temperature, humidity and pre-monsoon rains.

Cedro and Cedro (2008) studied the climatic response of spruce trees growing behind natural rangeland in southern coast of Baltic Sea. 80 trees samples were taken from 4 selected sites. They were used for construction of 4 local chronologies (from 1892 to 2003), which were used as a basis for dendroclimatological analyses (response function and signature years). It was found that trees from NW Poland were sensitive to February-March temperature and precipitation and to April-July precipitation (positive values correlation and regression). Positive signature years were connected with high humid spring/summer months.

Zunde *et al*. (2008) studied the influence of climatic factors on the radial growth of Scots pine in the Western part of Latvia. Samples of Scots pine tree-rings were taken at five sampling-sites (distance between sampling sites was 55 - 155 km). Correlation analysis and multiple regression analysis were performed between each sampling-site chronology and climatological factors. To determine years in which tree-ring width mainly was influenced by climatological factors, pointer-years were determined for the western part of Latvia and also for the territory of Baltic States. Mean temperatures and precipitation sum (season, autumn, winter, spring and summer) were compared with yearly radial increment of Scots pine in all years and in pointer-years. In the Western part of Latvia tree-ring width of Scots pine depended mostly on mean temperature in spring months (February, March and April). Precipitation sum had an unpredictable relation to the radial growth of Scots pine in Western part of Latvia and long-term trend or common trend between sampling-sites was observed. Climatological factors explained from 15.5 to 35.3% of the tree ring width variation in the five sampling-sites.

Friedrichs *et al*. (2008) analyzed interannual to multi-decadal growth variations of 555 oak trees from Central-West Germany. A network of 13 pedunculate oak (*Quercus robur* L.) and 33 sessile oak (*Quercus petraea* (Matt.) Liebl.) site chronologies was compared with gridded temperature, precipitation, cloud-cover, vapor pressure and drought (i.e., Palmer Drought Severity Index, PDSI) fluctuations. Correlation analysis with precipitation and vapor pressure revealed statistically significant (P _ 0.05) correlations for June (r = 0.51) and annual (r = 0.43) means. Growth of both species at dry sites correlated strongly with PDSI (r = 0.39, P _ 0.05), and weakly with temperature and cloud-cover. Twenty-one-year moving correlations showed positive significant growth response to both PDSI and precipitation throughout the 20th century, except for the 1940s – an anomalously warm decade during which all oak sites were characterized by an increased growth and an enhanced association with vapor pressure and temperature.

Lopatin *et al*. (2008) studied long term trends in radial growth of Siberian spruce and Scots pine in Komi Republic (northwestern Russia). Using radial growth measurements it was possible to attain positive long term trends of growth in Scots pine (*Pinus sylvestris*) and Siberian spruce (*Picea obovata*) in the Komi Republic. Increases in the radial growth of Siberian spruce in the forest – tundra were 134% while in the northern taiga zone it was 35% over successive 50 year periods from 1901 to 1950 and from 1951 to 2000. Respectively in the middle taiga zone a 76% increase in radial growth was found (over 100 years), whilst in the southern taiga zone the changes were not statistically significant. The increase in the radial growth of Scots pine in the northern taiga zone was 32%. In the middle taiga zone the radial growth increase in Scots pine was 55% and in the southern taiga zone the changes were not statistically significant. During the last 20 years, a temperature increase was recorded by all the meteorological stations in Komi Republic; whilst levels of precipitation have been increasing for the last 40 years ago. This is reflected in the radial increment of Siberian spruce and Scots pine. Thus, climate change could partly explain the increased site productivity. The total variance explained by temperature varied from 22% to 41% and precipitation from 19% to 38%. A statistically significant correlation between Normalized Difference Vegetation Index (NDVI) data and tree-ring width has been identified for the territory of the Komi Republic. The increased site productivity caused the increase in integrated NDVI values from June to August. This indicates that NDVI can be used as a proxy for estimating the forest growth trends of recent decades for generalization on a large scale.

Vieira *et al*. (2009) tested whether the radial-growth response to climate and the intra-annual density fluctuations (IADFs) of *Pinus pinaster* Ait. varied with age. Trees were sampled in Pinhal de Leiria (Portugal), and were divided in two age classes: young (<65 years old) and old (>115 years old). Young *P. pinaster* trees presented a higher frequency of IADFs compared with old trees. Most of the IADFs were located in latewood and were positively correlated to autumn precipitation.

Garcia-Suarez *et al*. (2009) studied climate signal in tree-ring chronologies in four common species growing in Northern Ireland. Their results suggested that beech and ash were the most sensitive to climate, with tree-ring widths more strongly influenced by precipitation and soil moisture in early summer than by temperature or sunshine. Oak was also sensitive to summer rainfall, whereas Scots pine was sensitive to maximum temperature and the soil temperature.

Salzer *et al*. (2009) found that the Great Basin bristlecone pine (*Pinus longaeva*) at 3 sites in western North America near the upper elevation limit of tree growth showed ring growth in the second half of the 20th century that was greater than during any other 50-year period in the last 3,700 years. The accelerated growth is suggestive of an environmental change unprecedented in the millennia. Both an independent proxy record of temperature and high-elevation meteorological temperature data were positively and significantly correlated with the ring width both before and during the high-growth interval. It was concluded that increasing temperature at high elevations is likely a prominent factor in the modern unprecedented level of growth for *Pinus longaeva* at these sites.

Zhu *et al*. (2009) described a 250-year February–April temperature reconstruction (TCBM) based on tree-ring widths of Korean Pines from the Changbai Mountain area, Northeast China. The reconstruction could account for 45.7% of the temperature variance in the instrumental period (1953 to 2001). Four cold periods including 1784–1815, 1827–1851, 1878–1889 and 1911–1945, and two warm periods of 1750–1783 and 1855–1877 were identified before the instrumental period. Four shifts were also detected at 1781, 1857, 1878 and 1989. Good agreements between TCBM and other temperature records of East Asia suggested that the reconstruction was of good reliability and captured the regional cold/warm periods of East Asia.

Borgaonkar *et al*. (2009) observed an anomalous higher growth during the last few decades was detected in the multi century tree-ring width chronologies of Himalayan conifers (*Cedrus deodara, Picea smithiana*) from high altitude near glacier areas of Kinnor and Gangotri region of Western Himalaya. These chronologies indicated strong relationship to the mean annual and winter (December-January February) temperatures of concurrent year. 553 years long master chronology prepared from the five individual chronologies showed few decadal and longer epochs of Little Ice Age (LIA) cooling during A.D. 1453-1590 and A.D. 1780-1930. Suppressed and released growth patterns in the chronology has been observed to be well related to the past glacial fluctuation records of the region. Analysis of instrumental period surface air temperature data over the region indicated significant increasing trend over the last century with a noticeable warming during the recent four decades. The time series of annual highest values of daily maximum and minimum temperatures also showed increasing trend. Direct significant relationship of winter temperature to the tree growth was mainly because of moisture availability for a longer period due to higher degree of snow melt. So far the relationship between climate change and the Himalayan cryosphere is not much attended and well understood. In view of this an extensive dendroclimatic and dendroglaciological investigation over high altitude Himalayan region may be useful to enhance our knowledge on snow and ice processes and their relevance to climate in the high mountain ranges.

Ahmed *et al*. (2010) evaluated tree-ring chronologies from the Upper Indus Basin of Karakorum range of Pakistan. Four coniferous species *i.e. Picea smithiana* (Wall.) Boiss, *Cedrus deodara* D. Don, *Pinus gerardiana* Wall. Ex Lamb. and *Juniperus excelsa* M. Bieb. were sampled. Core samples of these species showed good inter-and intra-species cross-matching, despite being collected from different areas. The quality control program, COFECHA showed that wood samples of these species exhibited 0.68 to 0.92 correlation with master chronologies and 0.23 to 0.42 mean sensitivity. Standardized dated chronologies of these species spanned from 212 years to 486 years with a wide range of growth rates. Residual chronologies showed higher mean sensitivity (0.205-0.411) while in general, higher serial correlation was recorded in Arstan chronologies.

Wils *et al*. (2010) did successful crossdating of *Juniperus procera* trees from North Gondar, Ethiopia. The trees formed annual rings in response to a unimodal rainfall regime. Crossdating was achieved by comparison of the wood anatomy directly on the surface of the core samples and purpose-adapted skeleton plotting. Wood-anatomical anomalies, such as false and indistinct rings, were regarded as potentially replicated features and used in crossdating. COFECHA yielded site-specific mean series inter-correlations between 0.52 and 0.59.

Hallman (2010) studied environmental conditions in order to identify microsite differences between trees growing at two different elevations on four aspects of a conical-shaped mountain in the White Mountains, California. Dendrochronological, environmental, correlational, and spectral methods were employed to explore differences in ring-width chronologies. Albedo, soil thickness, and percent slope led to ring-width variability. Northwestern upper site was most highly correlated with precipitation, while the Southeastern lower site showed a strong negative correlation with temperature. Morphological and physiological phenophases, dendrometer traces, and environmental data were collected throughout the summers of 2007 and 2008. No change was found in duration and timing of cambial activity suggesting that changes in cambial phenology are not an explanation for the increasing growth trend found at upper forest borders. On the other hand, changes in bud opening and pollination onset may be related to recent warming.

Sinha *et al*. (2011) studied climate related tree growth variability in teak, based on response function analysis from dry deciduous forests of Mundagod (Karnataka) and Chandrapur (Maharashtra), peninsular India, representing two ecological zones using dendrochronological techniques. Rainfall during the monsoon months of 2010 was found to be positively correlated with radial growth of teak at both sites, whereas premonsoon April rainfall was found to be negatively associated. Rainfall and temperature of 2010 during March had positive effect on the growth of teak at Chandrapur and Mundagod respectively. Besides, rainfall during October of the preceding year showed negative influence on tree growth at Mundagod and positive influence at Chandrapur, which might be due to difference in relative humidity and soil type at both the locations, apart from soil moisture.

Chapter-3

MATERIALS AND METHODS

Chapter-3

MATERIALS AND METHODS

The present investigations entitled "Evaluation of Forest Carbon Stock and Land use of Solan Forest Division" were conducted in Solan district of Himachal Pradesh. The details regarding experimental sites, materials and methodology adopted for undertaking this study are presented below.

3.1 DESCRIPTION OF SITE

Location

The study was carried out in Solan Division of Solan district of Himachal Pradesh, which is located between 30^{o} 45' 00'' to 31^{o} 10'00'' N latitude and 76^{o} 55'00'' to 77^{o} 15'00' E longitude, at elevation from 600m to 2260 m a.s.l, covering an area of about 57,158 ha. Original stock map is given in figure 1. The main Shimla-Kalka road (NH22) and railway line passes through the area. The main towns are Solan, head quarter of Solan District of Himachal Pradesh, Kandaghat, Kumarhatti, Dharampur and Parwanoo (located on Shimla-Kalka road), Subathu (located on Solan-Kunihar road) and Chail (known for its wildlife sanctuary). Main streams are Kawali Khad, Ashni Khad, Kuthar Nadi, Gamberpul Nadi Ghaggar Nadi and Kaushlaya Nadi. Highest peak is Karol (2260 m) near Kandaghat.

Climate

In the lower reaches the climate is sub-tropical and moist temperate in the upper reaches, especially in some parts of Kandaghat and Solan ranges. The seasons are well marked and there are distinct summer, rainy, autumn and winter seasons.

Precipitation is received both during the rainy and winter seasons, but the bulk of it is received during rainy season from the Southeast monsoon. The rainy season commences from the first week of July and continues upto the last week of August but sometimes extends upto mid of September. Winter rains generally commence from the last week of December and continue upto the end of February. April, May, October and November are relatively dry months.

Precipitation in the form of snow is received during January, February mainly around Karol but occasionally does come down to lower reaches due to variation in altitude.

Vegetation

The working plan has five working circles i.e. Chil Working Circle, Ban Oak Working Circle and Protection cum Rehabilitation Working Circle, Bamboo Working Circle and Soil and Water Conservation Working Circle. There are a total of 538 compartments. The Chil Working Circle has 161 forests, distributed in five forest ranges i.e. Dharampur, Parwanoo, Solan, Kandaghat and Subathu. The forests in Solan Forest division have pure crop of chil and mostly confirm to Champion and Seth's forest type 9C1a-Lower or Shiwalik chirpine forests. They lie between 900-2100 m a.m.s.l., elevation. Table1 gives the details of forest area under different Forest Ranges

The over storey vegetation comprises of *Pinus roxburghii*, *Quercus leucotricophora*, *Cedrus deodara*, *Terminalia tomentosa*, *Dalbergia sissoo*, *Pyrus pashia*, *Albizia chinensis*, *Juglans regia*, *Celtis australis*, *Acacia catechu*, etc, and the understory vegetation comprises of Berberis species, *Prinsepia utilis*, Indigofera species, Rosa species, *Sarcococca saligna*, Rubus species, *Hydera helix*, Euphorbia species etc.

Table1: Details of forest area under different Forest Ranges

Sr. No.	Forest Ranges	Area (ha)
1	**Dharampur**	3866.40
2.	**Parwanoo,**	4696.40
3.	**Solan**	1431.40
4.	**Kandaghat**	786.40
5.	**Subathu**	962.80
Total		11743.80

EXPERIMENT No. 1

3.2 Landuse change of Solan Forest Division

Source of Basic Data

The data used in this study includes inventory report and stock map (1:50,000) which were acquired from the office of the Solan Forest Division (Fig.1). In addition to satellite images, topographical maps and field data were used.

Computer Hardware and Software

Most of the processing was done using the package IDRISI TAIGA developed by Clark Labs, Clark University Worcester, USA. IDRISI TAIGA has the capability to display images in a 24-bit colour, which offers a superior image display and interpretation. Digitization was done in CARTALINX1.2, a data builder Geographical information application system developed by Clark lab Clark University, Worcester MA, USA.

Acquisition of Satellite Data

The IRS 1D (LISS-III) satellite data for two dates (1998 and 2010) were purchased from National Remote Sensing Agency (NRSA), Department of Space, Hyderabad, Govt. of India. The details of satellite data is given in Table 2. The date of image acquisition is an important consideration in the selection of an appropriate dataset. Depending on what variables are of importance to the project, imagery from certain seasons or times of the year will be desired. The selection of data sensed during winter is beneficial, as the ephemeral greenness that occurs mainly during the wetter summer months and that can confound the interpretation of the imagery, is not so likely to occur. If sensed in the early winter months, the imagery is also likely to have less contamination from smoke due to burning off (a feature of the autumn and later winter months).

Another consideration when selecting imagery is to ensure that it is as devoid as possible of features that degrade or mask the true ground brightness value of each pixel. This requires visual and/or statistical examination of the imagery to assess contamination by in-scene components such as clouds, smoke and haze or during data collection and transmission manifesting as line dropouts, striping and banding.

Table 2. Characteristics of IRS- 1D (LISS-III) satellite data.

Sensor	Path-Row	Acquisition Date	Bands (μm)	Resolution
IRS-1D (LISS-III)	95-49	26 December 1998	B2 (0.52-0.59), B3 (0.62-0.68) & B4 (0.77-0.86)	23.5 m
IRS-1D (LISS-III)		17 January 2010	B2 (0.52-0.59), B3 (0.62-0.68) & B4 (0.77-0.86)	23.5 m

Methodology

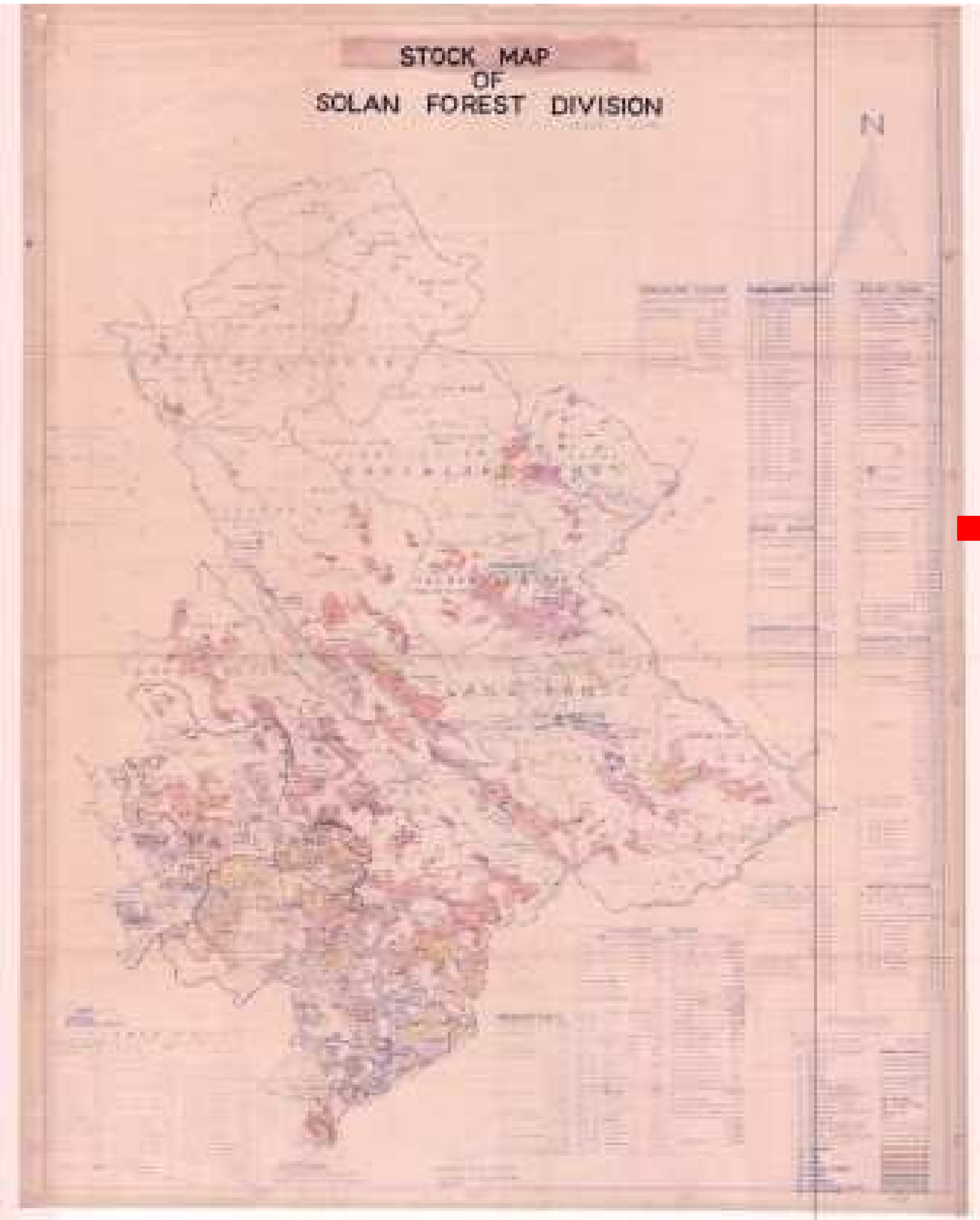
In the first step attributes like name of the forests, area and elevation of forests, compartments, name of forest vegetation, number of trees, volume, etc., given in the inventory report of Solan Forest Division, were entered in the database sheet under Database Management System to create the inventory database in GIS. (Appendix I, II). The second step of data processing was the preparation of different spatial layers using GIS software. The third step of data processing was the attribute adding and editing of spatial layers. Here in this stage all the attribute information such as name of the forest, name of the compartment, volume of growing stock, biomass and carbon were added with the spatial layer using GIS software.

(A) Digitization of Base Map Layers

To create GIS base map (Fig. 2) for the study area, the various features of stock map were transformed into digital form in various steps such as: i) scanning of stock map and ii) digitization of stock map and iii) editing of digitized features.

i) Scanning of Stock map

The Stock map which was acquired from the office of Solan Forest Division was scanned with the help of A0 size scanner (CS 500 Pro Colour Scanner- GRAFTEC) and saved as BMP file (Fig.1), which was then imported to CartaLinx (Data builder) for digitization.



Data layers

Forest Boundary

Forest Range

Compartments

Land Uses

Roads

Rivers and Streams

Fig. 1. Stockmap of Solan Forest Division

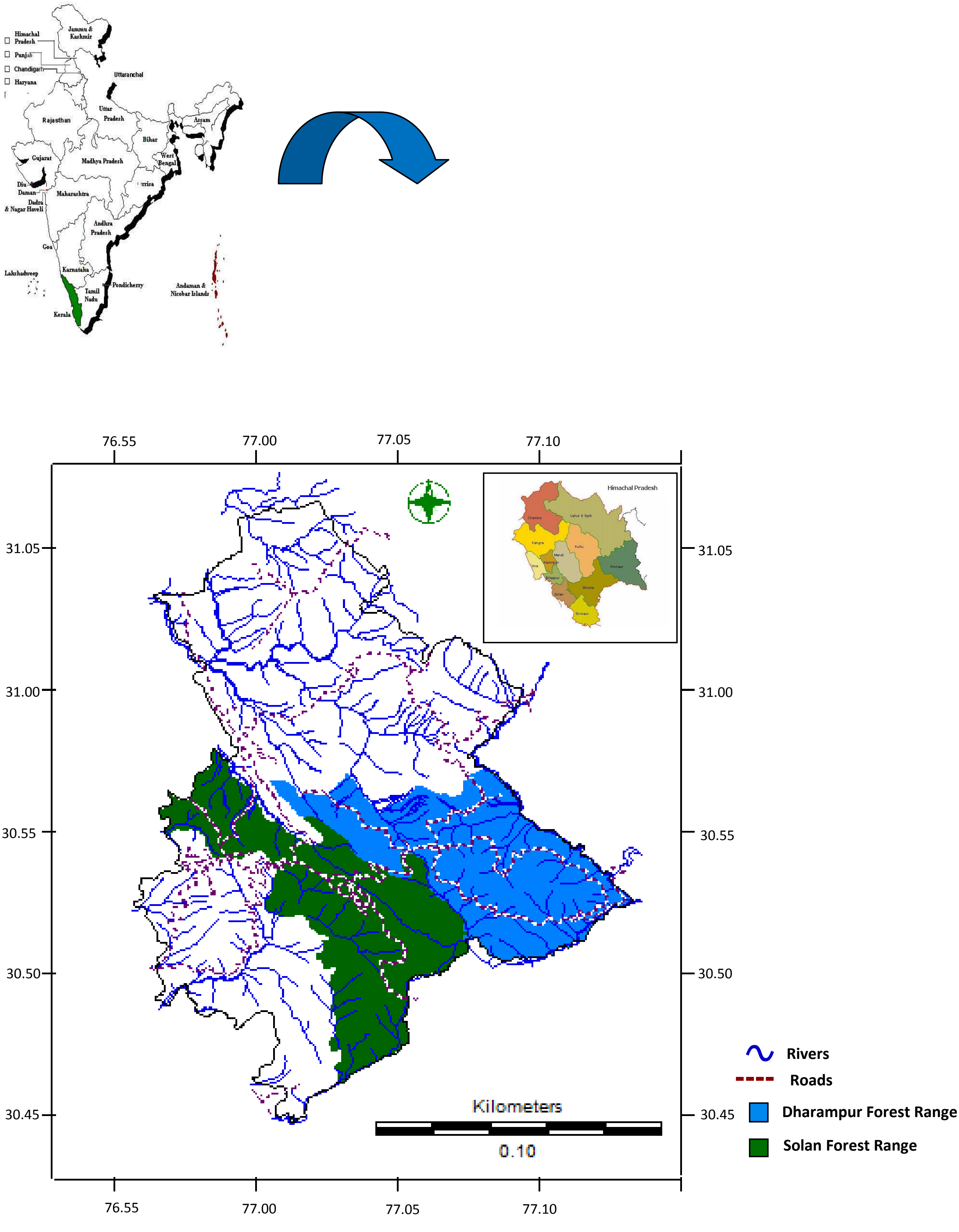


Fig. 2. Basemap of Solan Forest Division

ii) Digitization of Forest Stock map

To create various data layers, on-screen digitization for each feature type on the stock map of Solan Forest Division was performed in CARTALINX after displaying BMP file created in the previous step. Features like divisional forest boundary, roads, rivers and streams, territorial units (forest compartments), administrative units (forest ranges and beats) and land uses were digitized and saved in separate layers.

iii) Editing of digitized features.

A topological report was generated. The digitized features were edited in edit mode for removal of dangle arcs, duplicate arcs and pseudo nodes. Finally intersection report was generated and nodes which were not intersected were edited to produce polygons. Roads and rivers data layers were also checked for intersections and edited accordingly.

(B) Creation of Data Layers

Data layers created on digitization are presented in figures 3 to 6.

i) Forest Ranges

Vector Data layer pertaining to Forest Ranges is presented in Figure 3. There are five Forest Ranges in Solan Forest Division i.e. Solan, Kandaghat, Dharampur, Subathu and Parwanoo.

ii) Roads, rivers and streams

Figure 4 depicts main roads, rivers and streams that existed in the Solan Forest Division. The main Shimla-Kalka road (NH22) and railway line passes through the area. Main rivers and streams are Kawali Khad, Ashni Khad, Kuthar Nadi, Gamberpul Nadi, Ghaggar Nadi and Kaushlaya Nadi.

iii) Compartments

Compartment is a basic territorial unit of forest management. Vector data layer comprising of 256 compartments in Solan Forest Division is presented in Figure 5.

iv) Land uses

There are 9 land uses i.e. Chil, Ban Oak, Broad Leaved, Khair, Bamboo, Cultivation, Culturable Blank, Deodar and Barren which can be seen distributed in various Forest Ranges (Fig. 6) of the Solan Forest Division.

(C) Image processing

(i) Digital Processing of Satellite Data

The various steps followed to process the multispectral and multi-date satellite data are presented in Figure 7.

(ii) Import of Satellite Data

The satellite data for two dates (1998 and 2010) received from National Remote Sensing Agency, Hyderabad were imported into IDRISI using the TIFF module to create multi-spectral images.

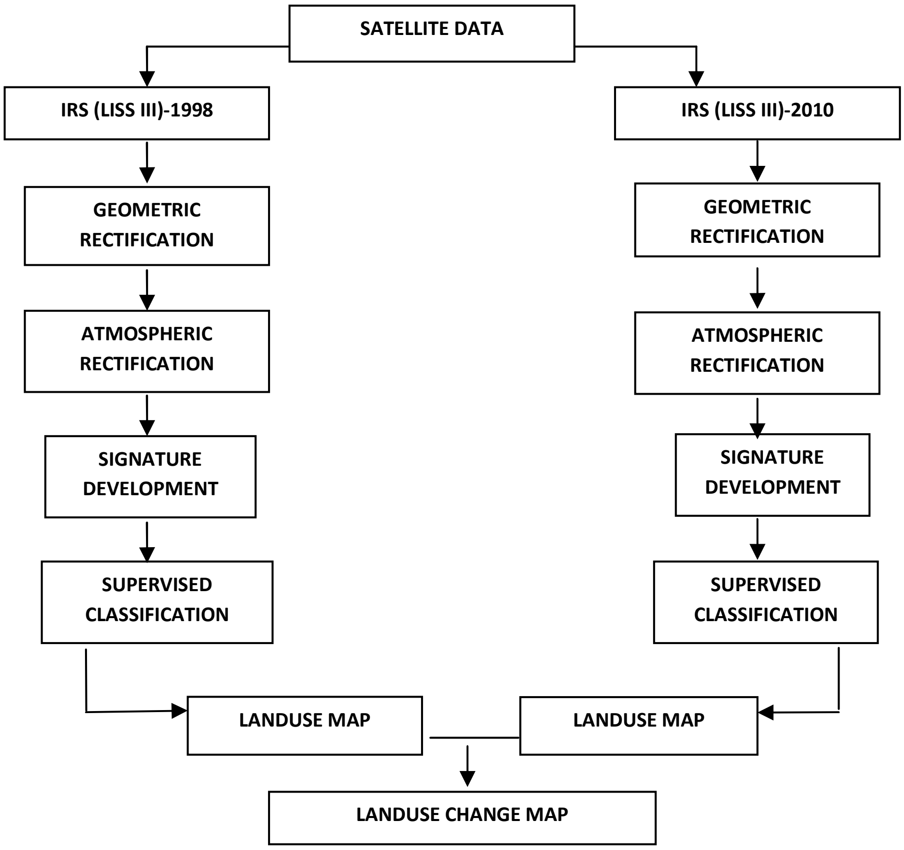


Fig. 7. Flow diagram of digital processing of satellite data

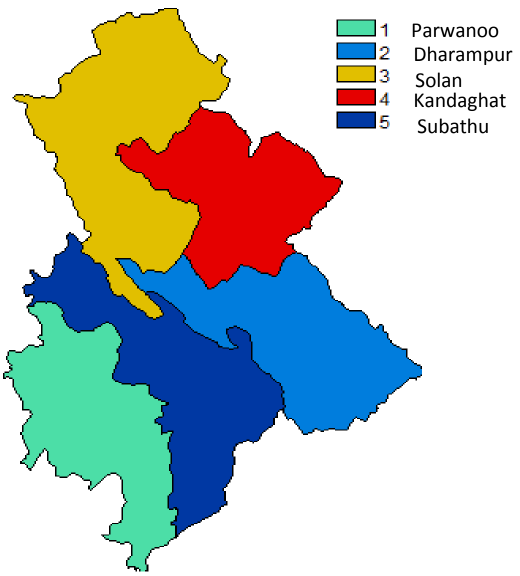


Fig. 3. Data layer of Forest Ranges

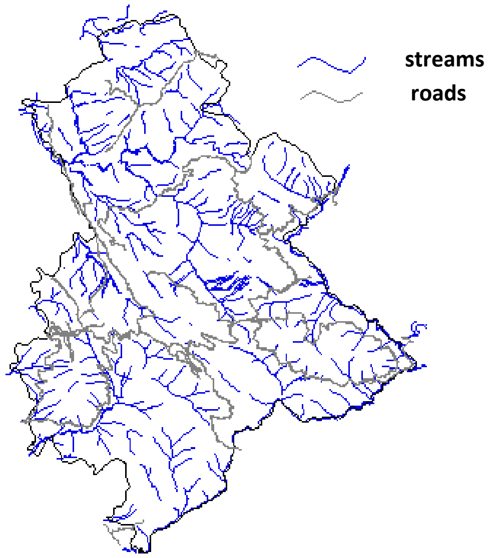


Fig. 4. Data layer of Rivers and Roads

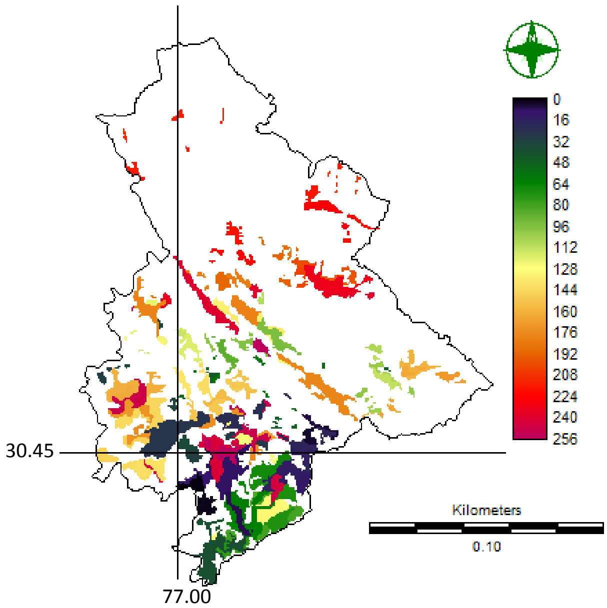


Fig. 5. Data layer of Forest Compartments

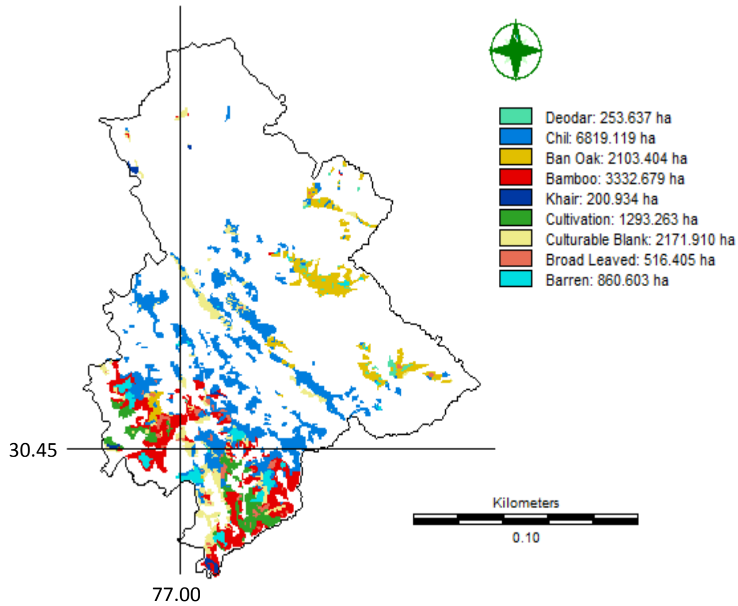


Fig. 6. Data layer of various Land Uses

(iii) Pre-processing of the Satellite Data

A high geometric accuracy and good geometric correlation should be needed between the images in order to perform successful data fusion. Prior to processing and analysis of the image data, various pre-processing routines, appropriate to the desired output, must be applied to the imagery. These enhance the quality of the image data by reducing or eliminating various radiometric and geometric errors caused by internal and external conditions.

(iv) Geometric correction

Geometric correction procedures address errors in the relative position of pixels due to factors such as variation in altitude, attitude and velocity of the sensor platform, earth's curvature, panoramic distortion, relief displacement and non-linearities in the sweep of a sensor. The two dates of images were rectified to a common latlong coordinate system. Nine ground control points (GCP's) were selected for resampling the 1998 imagery. The GCP's included permanent features such as road and drainage lines intersections and curvature, vegetation boundaries, and other well-defined features and were regularly distributed over the images. After the allocation of GCP's, a root mean square error (RMSE) was calculated in IDRISI, which computed the RMSE for each GCP relative to other GCP's. RMSE was less than 1 pixel (0.001465) pixels for the 1998 image. Twenty three ground control points (GCP's) were selected for resampling the 2010 imagery. RMSE was less than 1 pixel (0.000201) pixels. In both the cases, nearest neighbour resampling was used because it has the advantage of retaining the original digital number (DN) values (Jensen, 1986). The rectified datasets were visually examined by overlaying GIS layers of roads and streams and the boundary of Solan Forest Division created for the study area to validate the accuracy of the geo-rectification. This proved acceptable and the resampled images were used for further analysis. Image to image normalization was performed by registering the images of 2010 as reference image. This helped us to proceed further in using satellite data of both the dates simultaneously in the process. Each image was enhanced using linear contrast stretching and histogram equalization to improve the image to help identify ground control points in rectification based on 1:50 000 scale topographic maps. These data were resampled using the nearest Neighbor algorithm, so that the original brightness values of pixels were kept unchanged. The study area was then extracted from the scene using a boundary digitized from the stock map of Solan Forest Division, obtained from the D.F.O. Office, Solan. The bands used for further analysis of two dates (1998 and 2010) are given in Fig. 8. and Fig.9.

(v) Radiometric correction

Radiometric correction procedures account for errors that affect the brightness value of pixels due to both a sensor system detector error and an environmental attenuation error (e.g. changes in scene illumination, atmospheric conditions and viewing geometry. The minimisation or elimination of these errors, both between scenes and across time, is of particular importance when multitemporal or multispatial datasets are used as this allows 'normalisation' of conditions across time and space, hence direct radiometric and geometric comparison of the different images. The atmospheric scattering is common in remote sensing data and is generally more pronounced in the shorter wavelength regions (e.g., blue). The effect of atmospheric scattering is to contribute some additional spectral values to the ground reflectance (Gupta, 2003; Jensen, 1986). In this study, the LISS III image was corrected for atmospheric path radiance using dark object subtraction method (Chavez, 1988). The method is fast and easy, as it does not require information on atmospheric conditions at the time of image acquisition. To implement this method, the pixel (associated with the dark object) having minimum brightness value in the Near Infra Red (NIR) band was detected and the corresponding pixel values in all other bands were subtracted from the specific raw bands. This will result in an image that is corrected for atmospheric scattering.

(vi) Land Use Classification

Image classification refers to the extraction or grouping of a digital image from raw, remotely sensed, digital satellite data into different classes within a particular dataset, based on attribute values. It is done to replace visual analysis of the image data with quantitative techniques. Image classification is the computer assisted interpretation of remotely sensed images based on the

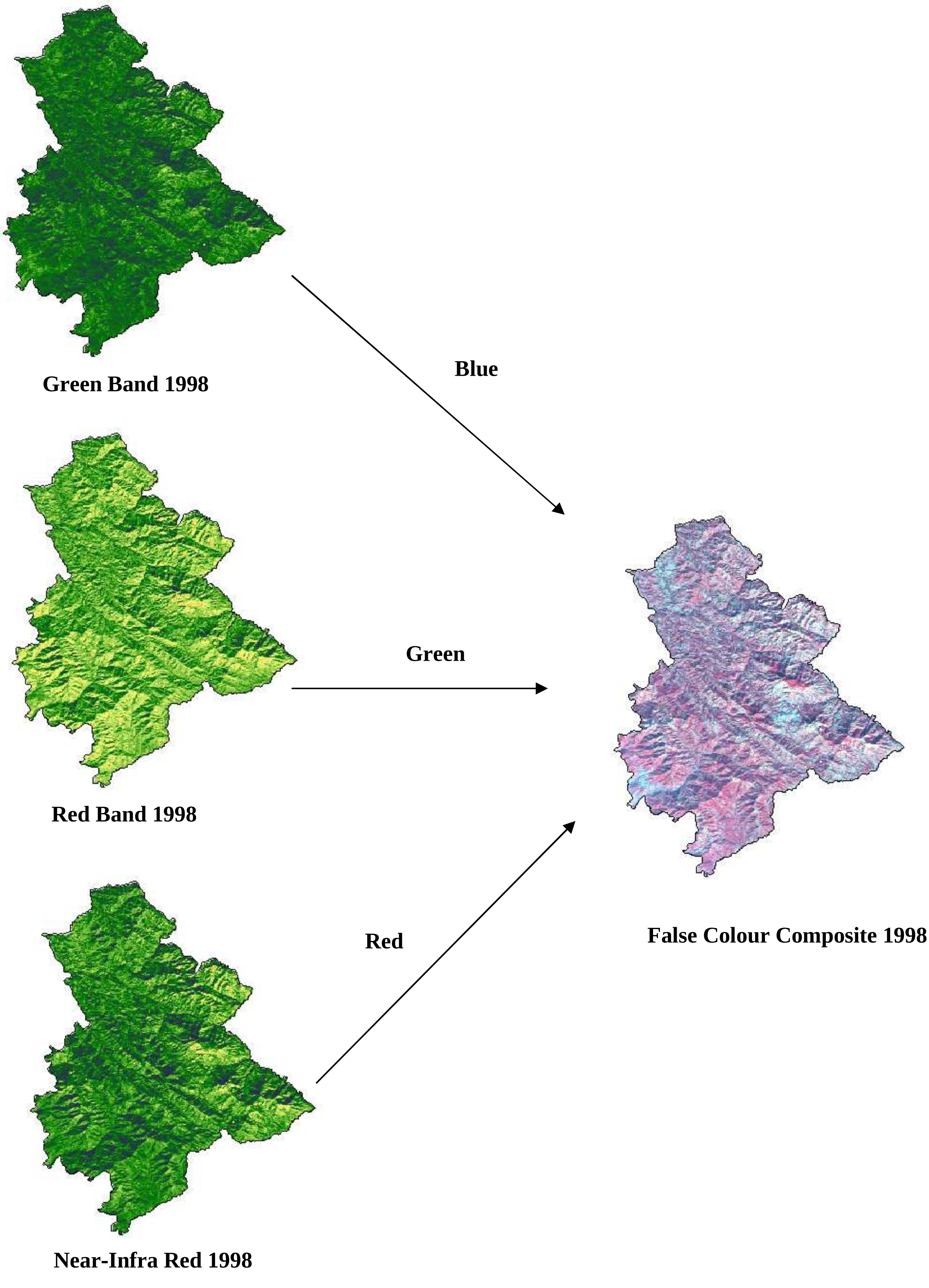


Fig.8. False Colour Composite derived from GREEN, RED and NIR bands showing Solan Forest Division for the year 1998

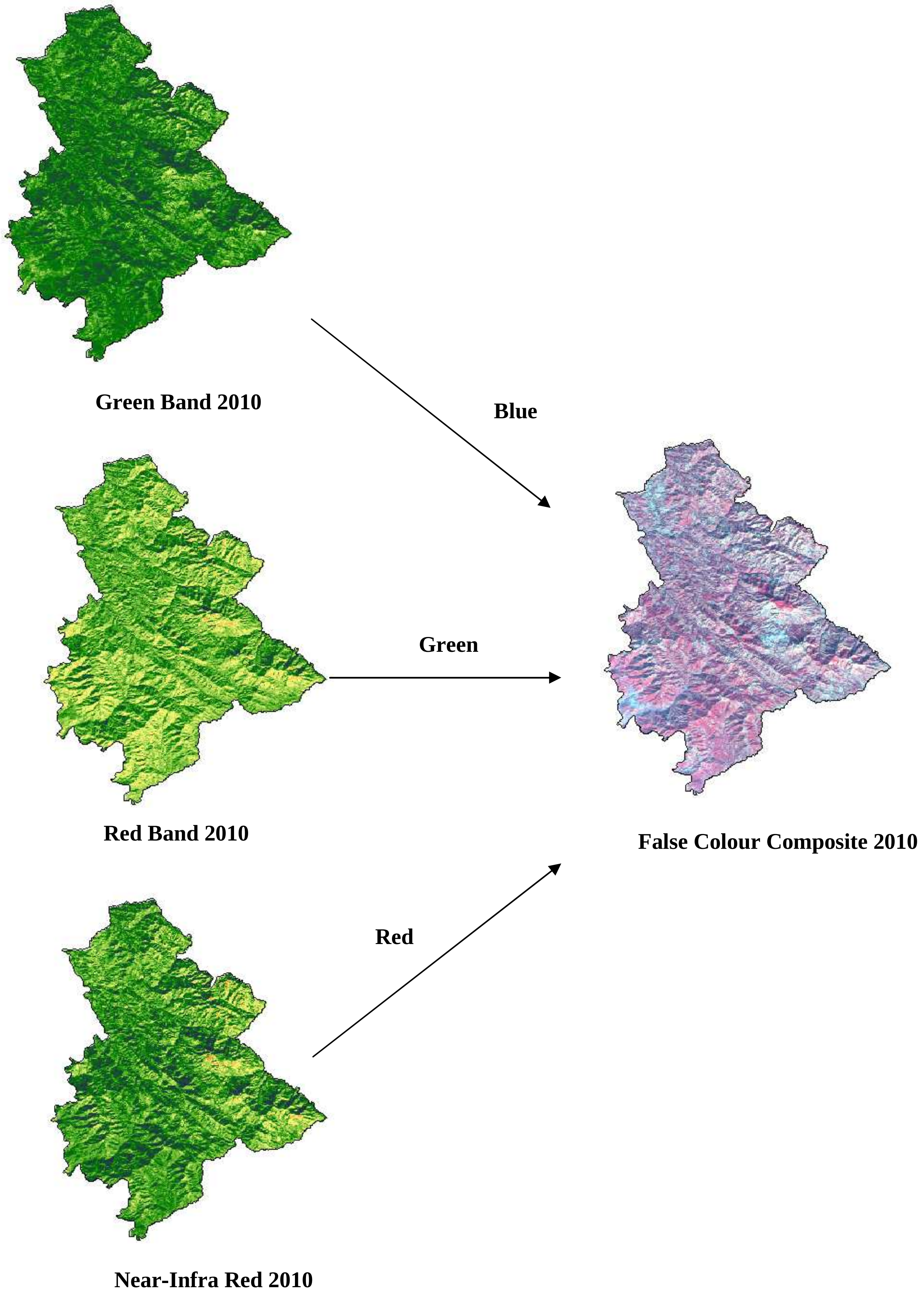


Fig.9. False Colour Composite derived from GREEN, RED and NIR bands showing Solan Forest Division for the year 2010

detection of the spectral signatures of land cover classes. The success with which this can be done depends on two things:

- The presence of distinctive signatures for the land cover classes of interest in the band set being used
- The ability to reliably distinguish these signatures from other spectral response patterns that may be present

Image classification can use either unsupervised or supervised classification method. In unsupervised classification, the software groups pixels into categories of like signatures, and then the user identifies what cover types those categories represent. With supervised classification, we identify examples of the information classes (i.e., land cover type) of interest in the image. These are called *"training sites"*. The image processing software system is then used to develop a statistical characterization of the reflectance for each information class. This stage is often called "*signature analysis"* and may involve developing a characterization as simple as the mean or the range of reflectances on each band, or as complex as detailed analyses of the mean, variances and covariance over all bands. Once a statistical characterization has been achieved for each information class, the image is then classified by examining the reflectance for each pixel and making a decision about which of the signatures it resembles most.

Land use classification was first done for Solan Forest Division's whole area (recorded forest area + non-forest area, Fig. 26) and then from these classified images, the forest compartments (recorded forest area) were extracted, to assess the land use change in the forests of the Division (Fig. 27). Table 3 gives the area estimated from the classification.

Table 3. Estimated area of Solan forest division (whole area) and forest compartments

Study area	Area (ha)
Solan Forest Division (recorded forest area + non-forest area)	**56,320**
Forest compartments (recorded forest area)	**13,067**

Land use classification for each date was performed in three steps i.e.

(a) Delineation of training areas

(b) Classification and

(c) Accuracy Assessment

(a) Delineation of Training Areas

Training sites are sets of pixels that represent what is recognized as a discernable pattern, or potential land cover class. Homogeneous training areas to represent the variety of land use types within the study area were delineated with the aid of a False Colour Composite (FCC) image. The FCC image for the year of 1998 and 2010 was created by displaying NIR in red band, RED in green band, and GREEN in blue band, respectively (Fig. 8 and Fig. 9). The training area delineation technique utilized in this study was a traditional approach whereby training area polygons were digitized on the image display device. The training areas were selected with criteria that they represent the area of each class throughout the image. The number of training samples for each class were chosen in proportion to the area covered by the respective classes on the ground.

(b) Classification

A supervised signature extraction with the maximum likelihood algorithm was employed to classify the images. Wide ranges of supervised classifiers are available but they share a common objective to allocate each pixel of unknown class membership to a pre-defined class on the basis of its spectral properties. Maximum likelihood classifier (MLC) has been found to be the most accurate and commonly used classifier, when data distributional assumptions are met. In MLC the distribution of reflectance values in a training site is described by a probability density function, developed on the basis of Bayesian statistics. The classifier then evaluates the probability that a given pixel will belong to a category and classifies the pixel to the category with the highest probability of membership. This classifier is based on the decision rule that the pixels of unknown class membership are allocated to those classes with which they have the highest likelihood of membership (Foody *et al*., 1992).

Both statistical and graphical analyses of feature selection were conducted, and bands 2 (green), 3 (red), and 4 (near infrared) were found to be most effective in discriminating each class and thus used for classification. In the final step the images of 1998 and 2010 were superimposed over each other to detect the changes from one period to the other. This process finally gave the land use / land cover change pattern of Solan Forest Division.

(c) Accuracy Assessment of Classification

Accuracy assessment of classification is an essential component of the classification process. Therefore, a complete accuracy assessment was performed on classified images of two dates generated during this study. An error matrix was established to evaluate the accuracy of the classification. An error matrix is a square array of numbers laid out in rows and columns that expresses the number of sample units assigned to a particular category relative to the actual category as verified in the field. It is the most common and a very effective way to represent the accuracy of the classification results, as the accuracy of each category is clearly described (Fan *et al.,* 2007). The ground truth data (reference data) used were collected from field surveys and existing stock map that had been field-checked. Overall accuracy, user's and producer's accuracies and the Kappa statistics, were derived from the error matrices. The overall accuracy is computed by dividing the total correct pixels (sum of the major diagonal) by the total number of pixels in the error matrix. The user's accuracy, calculated by dividing the number of correctly classified pixels in a class by the total number of pixels assigned to that class, is the probability that the mapped class (for example, agricultural land) correctly represents its ground distribution. The producer's accuracy, calculated by dividing the total number of correctly classified pixels in a class by the total number of reference measurements of that class, is the probability that a class identified from the reference data is correctly classified on the map. The Khat statistics (an estimate of Kappa), which provides a measure of how many more pixels were correctly classified than expected by chance (Congalton and Green, 1999) was also calculated. The Kappa statistic is computed as the summation of the diagonal multiplied by the summation of each row multiplied by the summation of each column divided by the summation of each row multiplied by the summation of each column.

A sample of ground truth points distributed randomly on the classified image was made using the SAMPLE command in IDRISI. Total 450 points were overlaid over the classified image to assign to each point an identifier of the land cover type. The sample points vector file (450 ground truth points) was then rasterised using the POINTRAS module and thereafter, each sample point was assigned an identifier by visiting the reference data to create a “ground truthing image”. This served as reference image for testing the accuracy of all six-land use classes in the classification. The ERRMAT module in IDRISI was run on the reference data points and the final classified images. This generated an error matrix between the reference data points and the classified image.

Land use change Analysis

Land use change was estimated using the Land Change Modeler in IDRISI TAIGA

EXPERIMENT No. 2

3.3 Temporal change in carbon stock of forest stands

Site selection

The present investigation focuses on the temporal change in carbon stock of the Chil Working Circle, in two ranges of Solan Forest Division, Solan and Dharampur. Chir pine (*Pinus roxburghii* Sarg.) is a common tree in lower elevation forests (450-2300 m a.s.l.) in the outer ranges and foothills of the Himalayas extending from Pakistan to Arunachal Pradesh in India (Sahni, 1990). Chir pine generally occurs at lower elevations than the other pines in the Himalayas, often forming the first low elevation forests above dry deciduous woodlands and shrublands.

Chir pine forests in Solan Forest Division of Himachal Pradesh are being managed under the Indian Irregular Shelterwood system. Out of a total of 161 compartments in the Chil Working Circle, 33 compartments in Solan and Dharampur Forest Ranges (Fig. 10) were selected for the analysis of the temporal

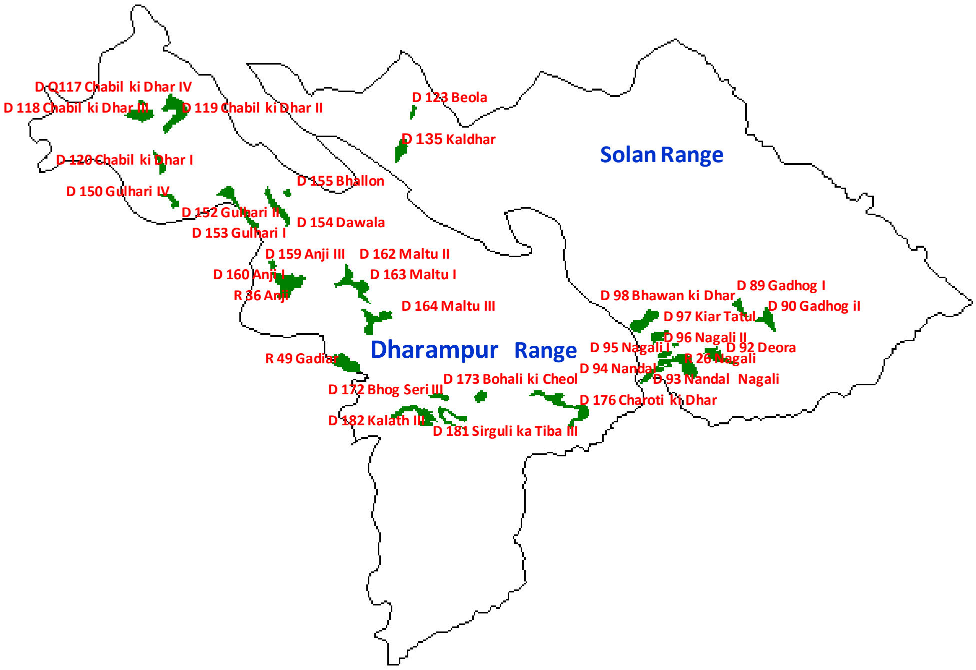


Fig. 10. Selected sample plots (compartments) in Solan and Dharampur Forest Ranges

Fig. 11. Enumeration of chir pine forests

change in carbon stock (Appendix III). The basis for the selection of study sites was the area of the compartments and only those compartments were selected whose area in hectares was constant over the entire period under study i.e. 1956-57, 1984-85, 2002-03 and 2011-2012. Visits to the forests offices in the forest sites were made in order to carry out enumeration of forest growing stock. First hand knowledge regarding history of the forest operations, area maps and growing stocks was collected from the respective range forest offices. Forest inventories that are designed for monitoring of forest resources at national scales provide a firm basis for large-scale carbon assessments. The inventory data given in the working plans of Solan Forest Division for 1956-57, 1983-84 to 1997-98 and 2002-03 to 2016-17 were used in the present study, which includes: Name of the Forest, Species, Number of trees in each diameter class, Compartment and the Area of each forest in hectares.

Source of Basic Data

(i) Forest inventory measurements

For the year 2011 the number of trees in each diameter class were determined through the enumeration of the 33 compartments (Fig. 11). The diameter at breast height was determined with the help of tree calliper. Vegetation analysis was done in the rainy season (August to October) and all trees above 10 cm diameter at breast height were included in the enumeration.

Nested plot design was adopted for the collection of understorey biomass data. Biomass of shrubs was estimated by laying down 5m x 5m quadrates and for herbaceous vegetation 1m x 1m quadrates were laid down. The fresh weight (g) of the harvested understorey vegetation was measured and brought to the laboratory for measuring oven dried weight.

(ii) Soil sampling

In each forest stand soil samples were collected from humus layer, 0–20 cm, 20-40 cm, 40-100 cm layer, in three replications. To reduce variability, soil samples were collected and mixed together to form a composite soil sample. The samples were packed in bags and brought to the laboratory for organic C estimation. For organic C determination, the soil samples were first air dried in shade on ground, then ground with a mortar and pestle and finally passed through a 2 mm sieve and then thoroughly mixed. Soil bulk density was calculated as:

Soil Bulk density (gm/cm3) = Soil weight (gm) ÷ volume of cylinder (cm3)

Analysis of the sampled parameters

(i) Analysis of upper storey vegetation

The most accurate method for calculating the carbon stocks in tree is by measuring the total biomass. For this purpose first volume over bark (VOB ha^{-1}) and then biomass was calculated (Brown *et al*., 1989; Brown and Iverson, 1992; Brown and Lugo, 1992; Gillespie *et al*., 1992).

(ii) Volume calculations

Non destructive method for biomass estimation was adopted for trees whereas harvest method was used to determine the biomass of understorey vegetation i.e. herbs and shrubs. The volume of each forest was determined from volume factors of Chir Pine for each diameter class, which were obtained from the inventory report of the Working Plan (Table 4). The number of trees of each diameter class was multiplied by the corresponding volume factor for the determination of the total volume of each compartment.

Table 4. Volume factors of chir pine

Diameter Class (cms)	Volume (m^3)
10-20 V	0.0504
20-30 IV	0.2499
30-40 III	0.6846
40-50 IIA	1.3544
50-60 IIB	2.2593
60-70 IA	3.3994
70-80 IB	4.7746
80-90 IC	6.3849
>90 ID	8.2303

(iii) Stem wood biomass calculations

By the use of calculated volume of the stem (m^3), total stem biomass (kg) was measured with the help of wood density (Kg m^{-3}). For the present study wood density values were sourced from technical reports, websites and were confirmed from parallel studies conducted on the sites for determining wood densities of the species present in these forest sites.

Biomass (kg) = Volume (m^3) × Specific Gravity (g cm^{-3})

For *Pinus roxburghii* the specific gravity used for calculations was 0.491 g cm^{-3} (Rana *et al*., 1989; Sheikh *et al*., 2009)

(iv) Branch, leaves and roots biomass (BLRB) calculations

The branch, leaves and root biomass of *Pinus roxburghii* was calculated by using biomass expansion factors (BEF). (Rana and Singh, 1989). Table 5 gives the Biomass expansion factors (BEF) of chir pine in sub tropical forests

Table 5. Biomass expansion factors (BEF) of chir pine in sub tropical forests

Sr. No.	**Forest Type**	**Species**	**Biomass Percentage Per Tree (%)**					**Total**
			Stem	**Branches**	**Leaves**	**Fruit**	**Roots**	**(%)**
1	**Sub Tropical Pine**	***Pinus roxburghii***	63.23	14.95	3.21	-	18.61	100

(v) Analysis of under storey vegetation

In the present study under storey vegetation was harvested from each quadrat. Shoot biomass of all the shrubs and herbs in each quadrat was harvested at ground level and root biomass was sampled using 25cm x 25cm x 40cm monolith. All the harvested material was put into the labeled bags for further analysis. The monoliths were washed with a fine jet of water on 2.0 and 0.5 mm mesh screens. The shoot and root samples were oven dried at 65 ± 5^0C to a constant weight and weighed for further calculations (Woomer, 1999). The biomass was calculated by the following formula:

Biomass (g) = dry weight (g)

(vi) Detritus

(a) Standing dead tree

Standing dead tree biomass was estimated using (31.62m x 31.62m) quadrates. Standing dead trees falling in the quadrate were enumerated. The diameter at breast height (dbh) was measured with a calliper. The rest of the methodology for calculating the standing dead tree volume was same as that for stem volume. In order to calculate the biomass of standing dead trees, such trees are assumed to fall under decay class "0" as using Harmon *et al*. (1996) and Yan *et al*. (2006). Then mass of the individual was calculated as follows:

Mass = Volume x Density

(b) Fallen trees

Fallen trees biomass was estimated using (31.62m x 31.62m) quadrates. Fallen trees falling in the quadrate were enumerated. The diameter at 1.3 m from the large end was measured with a calliper. The rest of the methodology for calculating the fallen tree volume was same as that for stem volume. In order to calculate the biomass of fallen trees, such trees are categorized in decay class 1-5 as given by Harmon *et al*. (1996) and Yan *et al*. (2006). Thus density of particular decay class is used to calculate mass of the individual fallen tree. Then mass of the individual was calculated as follows:

Mass = Volume x Density

(c) Surface litter

Surface litter was collected within a 1m x 1m quadrate. Collected samples were weighed, sub sampled and oven dried at 65±5 5^0C to a constant weight, ground and ashed. Ash corrected dry weight was assumed to contain 45% carbon.

(d) Detritus carbon content

Detritus carbon content was calculated as the product of dry mass and an assumed C concentration of 50%. Standing dead trees, fallen trees and forest floor carbon stock were separately calculated and summed to estimate detritus carbon content of whole plot.

(vii) Soil analysis

Details of methods and instruments used for soil physical and chemical analysis are presented in the following table.

Table 6. Soil physico-chemical analysis: methods and instruments used

Sr. No.	Parameters	Methods employed	Instrument/apparatus used
1	**pH**	1:2 soil water suspension (Jackson, 1973)	pH meter
2	**Electrical Conductivity (EC)**	1:2 soil water suspension (Jackson, 1973)	Electrical Conductivity Meter
3	**Organic Carbon**	Rapid Titration Method (Walkley and Black, 1934)	---
4	**Bulk Density**	Method for disturbed soils	Pycnometer

(a) Soil organic carbon

To estimate the amount of carbon in the forest soil, samples of soils were brought into the laboratory from the field for further analysis. For determining the carbon concentration in the soil, the method of oxidizable organic carbon given by Walkley and Black, (1934) and outlined in Rayment and Higginson, 1992; Anderson and Ingram, 1993, was used because of available resources.

In this method following reagents were used: Potassium dichromate solution (0.167 M), Sulphuric Acid (Conc.), Ortho phosphoric Acid (Conc.), Ferrous Ammonium Sulphate solution, 0.5 M (approx.) and Diphenylamine Indicator.

Following procedure was adopted for analysis of each sample: 1 gm of soil sample was put in 500ml flask and shaked with 10ml of Potassium dichromate. Then 20ml of concentrated sulphuric acid (conc.H2SO4) was added rapidly and shaked for 30 minutes. After this 200ml of water and 10ml of phosphoric acid was added with 10-15 drops of Diphenylamine and titration was done against Ferrous ammonium sulphate {Fe(NH4)2(SO4)} solution. A blank titration was also made (without soil) to standardize the solution. The total organic carbon was determined by formulae:

$$\text{Carbon Conc.} = \frac{\text{(B)Blank titration – (S)Actual titration x 12 x M (}Fe(NH4)2(SO4)}{\text{weight of oven dried soil in gm x 4000}}$$

B = mL of (Fe(NH4)2(SO4) solution used to titrate blank
S = mL of (Fe(NH4)2(SO4) solution used to titrate sample
12/4000 = milliequivalent weight of C in g.

The conversion of oxidizable organic C to total C was done by multiplying with 1.30 correction factor given by Walkley–Black. The C Concentration (mg C gm^{-1} of soil) was further multiplied with calculated bulk density (gm cm^{-3}) to estimate total carbon stocks (t ha^{-1}) in soils of these forests. Bulk density (gm cm^{-3}) of soils of each forests site was also determined and used for C stock assessment.

(b) Bulk Density

Bulk density is a measure of the weight of the soil per unit volume (g cm^{-3}), usually given on an oven-dry (110° C) basis. Variation in bulk density is attributable to the relative proportion and specific gravity of solid organic and inorganic particles and to the porosity of the soil. Bulk density was determined by Pycnometer method. The mass of the oven dry soil which fills the container of a known volume is determined by weighing. This volume of the packed soil will be equal to the capacity of the container. Bulk density is then calculated as the ratio of the mass of the soil to its volume. Soil bulk density was calculated as:

$$\text{Soil Bulk density (gm/cm3)} = \frac{W2 - W1}{V_t}$$

Where,
W_1 = Weight of empty Pycnometer (g)
W_2 = Weight of Pycnometer + soil (g)
V_t = Volume of soil/water needed to fill the pycnometer (cm^3)

(viii) Total carbon stocks in upperstorey vegetation

The total carbon stock in upper storey vegetation of the forests was determined by multiplication of the total plant biomass by convertible factor which is representative of the average carbon content in plant biomass. This convertible factor (0.50) shows 50 % of total plant biomass is equal to C. This factor is used worldwide (Roy *et al*., 2001; Koach, 1989; Brown and Lugo, 1982;

Malhi *et al*., 2004), thus it has been applied in this study for the calculation of total carbon in upper storey vegetation of sub tropical Chir pine forests of Solan Forest Division.

(ix) Total carbon stocks in under storey vegetation

The calculations of the carbon stock in under storey vegetation was carried out by multiplying the total weight (oven dried t ha^{-1}) with 0.50 conversion factor (Roy *et al*., 2001; Brown and Lugo, 1982; Malhi *et al*., 2004).

(x) Total carbon stocks in forest soils

Total organic carbon was measured from the soils of forests to have an idea of the total carbon stocks at three levels (upper and understorey vegetation and soils). For this purpose the total carbon sequestered by the soils of these forests was determined by estimating C concentration and bulk density at varying (humus, 0-20, 20-40 and 40-100 cm) layers in each forest site.

C estimation

Carbon Stock = Biomass x 0.5 (IPCC default value)

Carbon Density = Carbon in t ha^{-1}

3.4 Carbon mapping and carbon change analysis

Vegetation Index Transformations

A Normalized Difference Vegetation Index (NDVI), invented by Rouse *et al*., (1974), was calculated for each image from band 3 (RED) and band 4 (NIR) of the satellite data using the equation given in Table 7. NDVI expresses vegetated ground and the vegetation condition and is closely related to leaf area index (LAI). The land use changes between different years can be studied by NDVI ratios.

Table 7. Formulae used for deriving vegetation index.

Vegetation	indexFormula
Normalized Difference Vegetation Index	**NDVI =** $\dfrac{NIR - RED}{NIR + RED}$

where,

NIR is the DN in the near infrared band

RED is the DN in the red band

A linear regression model was fitted to study the relationship between carbon per pixel as dependant and NDVI as independent variables. Carbon maps of Solan Forest Division were then prepared and carbon change analysis between 1998 and 2010 was done (Fig. 12).

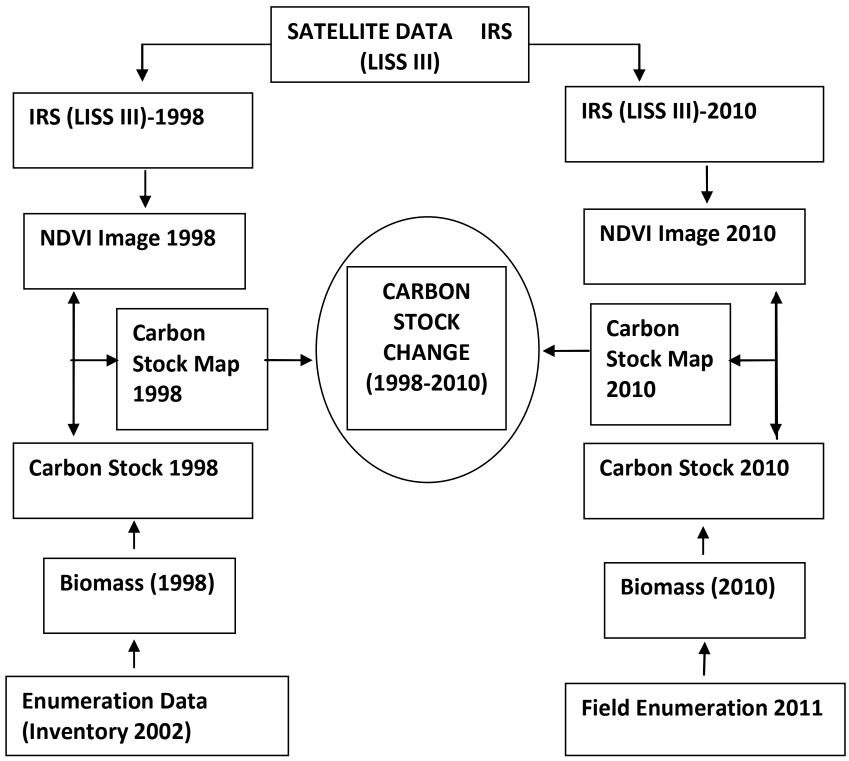


Fig. 12. Flowchart showing steps involved in Carbon mapping and carbon change analysis

EXPERIMENT No. 3

3.5 Impact of climate change on forest growth

Study site and sample collection

Site selection

There are different stages of the dendrochronological analysis that start with an appropriate site and trees selection. It is crucial where we sample since it can interfere in the results obtained depending on the purpose of our study. For example, in order to obtain the better climatic signal, it is recommended to chose the open site (no competency and alterations in the tree growth) from one side, with no anthropological activities nearby that can affect the tree growth as well from the other side, and, finally, the site with the most limiting factors related to climate (very dry site for example). All these 3 factors were taken into consideration in carrying out the investigation. The disc samples were collected from a private forest in Majhgaon, in District Solan, Himachal Pradesh. The site description has been given in Table 8.

Table 8. Description of the study site

Site	Elevation	Slope	Rock	Soil	Density	Site Quality
Majhgaon	1470 m	Steep	Sandstone	Sandy loam of fair depth	0.2	III

Source of data

Sample collection

There are two primary types of samples that are used for studying tree growth. The first type of sample is a core that is bored out of a tree with an increment borer. The second type of specimen is a cross section of a tree that is called a cookie or a disc. Each sampling method has its advantages and disadvantages. A core is a sub section of a disc, so any method that analyses a core is applicable to a disc. A disc contains more information than can be adequately sampled by a single core, and the number of cores per tree needed to yield accurate estimations of area remains a matter of speculation, particularly when rings are highly eccentric (Yanosky and Robinove, 1986). With a core the choice of radius is limited to the width of the core but with a disc the choice of radius is infinite. A total of 21 stump-discs (i.e. cross-sections) were sawed (Fig. 13) from the stumps of chir pine (*Pinus roxburghii*) with a stump height of 0.6 m (Fig. 15). I took the approach of examining all diameter classes, rather than just studying the dominant individuals where sample biases may exist. The diameter classes were 30-40, 40-50, 50-60, 60-70, 70 and over (Fig.16). Stump-discs thus obtained were taken to the Wood Workshop (Fig. 14), Department of Forest Products, U.H.F., Nauni, for further processing, before being subjected to dendrochronological techniques.

Climatic data

Minimum and maximum monthly temperature (Vincent & Gullet, 1999) and total monthly precipitation (Mekis and Hogg, 1999) were obtained from the agrometeorology department of Dr. Y.S. Parmar University of Horticulture and Forestry, Nauni, Solan, for the period of 1983–2010.

Sensitive and complacent trees

Trees that respond to yearly fluctuations in limiting factors by producing larger or smaller rings are termed “sensitive”. When growth is not limited by any factor that fluctuates annually, trees consistently produce rings of smaller width, such trees are termed “complacent”. Seasonal and yearly fluctuations in precipitation and temperature are the most common factors limiting growth in sensitive trees. To obtain climatic information from tree ring series dendrochronologists select sites with trees that are most sensitive to climatic fluctuations in the region of interest. Usually these trees grow on steep slopes, in well drained soils and at the upper or lower elevational limits for the species. Conversely trees in poorly drained soils and near springs, rivers or other water sources are usually climatically complacent. (LaMarche *et al*., 1984).Out of a total of 21 stump discs 6 were rejected as they were complacent and could not be successfully crossdated. (Fig.17). The flowchart showing steps involved in assessing impact of climate change on tree growth is given below (Fig.18).

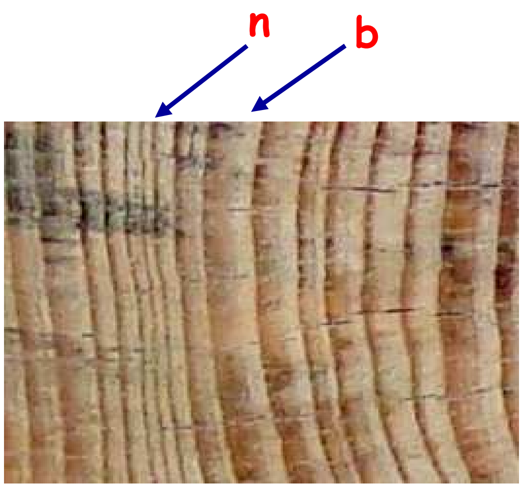
Fig. 13. Sawing the disc samples

Fig. 14. Wood Workshop

Fig. 15. Measuring the stump height

Fig. 16. Measuring the stump diameter

a) Complacent Ring Series



b) Sensitive Ring Series

Fig. 17. Complacent and sensitive ring series

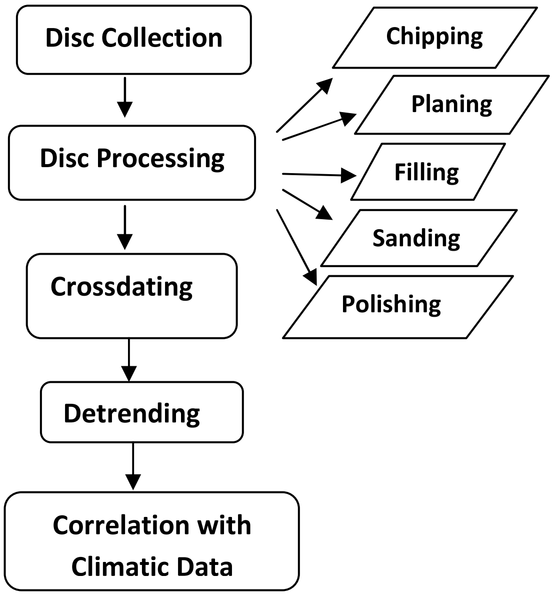


Fig. 18. Flowchart showing steps involved in assessing impact of climate change on tree growth

Processing the discs

(i) Chipping and planing

The stump discs were first air-dried. The discs were then chipped and leveled in a wood working machine. (Fig. 19, 20)

(ii) Sanding

Subsequently, repeated sanding was done with progressively finer grains of sandpaper (60, 180, 240, 400, 800 grit). For hand sanding the sandpaper was wrapped around sanding blocks (Fig. 21). A finely sanded surface is crucial to the cross dating of ring series. Ring boundaries, microrings and diagnostic characteristics such as frost damage, false rings and injuries are often discernible only when the surface is smooth.

(iii) Filling

The cracks and cavities on the surface of the discs were filled with wood filler and then sanded again on drying to increase the smoothness of the discs (Fig. 22).

(iv) Polishing

The surface of the discs was polished to increase the visibility of the rings (Fig. 23). Figure 24 shows the finished discs.

Dendrochronological Analysis

(i) Cross-dating

Each tree ring was assigned the calendar year of its formation by means of crossdating (Fritts, 1976). Cross dating is the comparison of ring width patterns in different trees and the selection of the exact place of correspondence between them (Douglass, 1919). Cross-dating between trees is possible because the same environmental conditions limit tree growth throughout a region, and the year to year fluctuations in growth limiting factors produce synchronous variations in ring width. Cross dating is critical to developing an accurate tree-ring chronology because it ensures 1) that every visible ring is placed in its proper time sequence, 2) prevents false rings from being incorporated into a chronology, and 3) facilitates the identification of absent rings. The cores were crossdated by hand using skeleton plotting to check for missing and false rings using the identification of signature years (Stokes and Smiley, 1968).

A skeleton plot evaluates the tree-ring width in relation to the rest of the rings of each tree in a stand. Signature years are consistently small or large rings indicative of extreme climatic or disturbance events that allow for the crossdating of trees. Skeleton plots, which are a graphical means of representing tree ring widths, are very useful in crossdating; this conceptually simple technique requires only a pencil, graph paper and experience.

In skeleton plotting each vertical line of the graph paper represents one ring. The skeleton plot does not include a drawn line for every ring. The narrower a ring, the longer the drawn line used to represent that ring on the skeleton plot. The maximum value assigned to a drawn line on a skeleton plot is 10 (10 squares on the graph paper) and usually a 10 represents an extremely small or microring. The value or length of the drawn line to be assigned to a particular ring is decided by judging its width relative to that of three to five neighboring rings. This means

Fig.19. Chipping the disc samples

Fig. 20. Wood Working Machine

Fig. 21. Sanding the disc samples

Fig. 22. Filling cracks and cavities

Fig. 23. Polishing the disc surface

Fig. 24. Finished discs

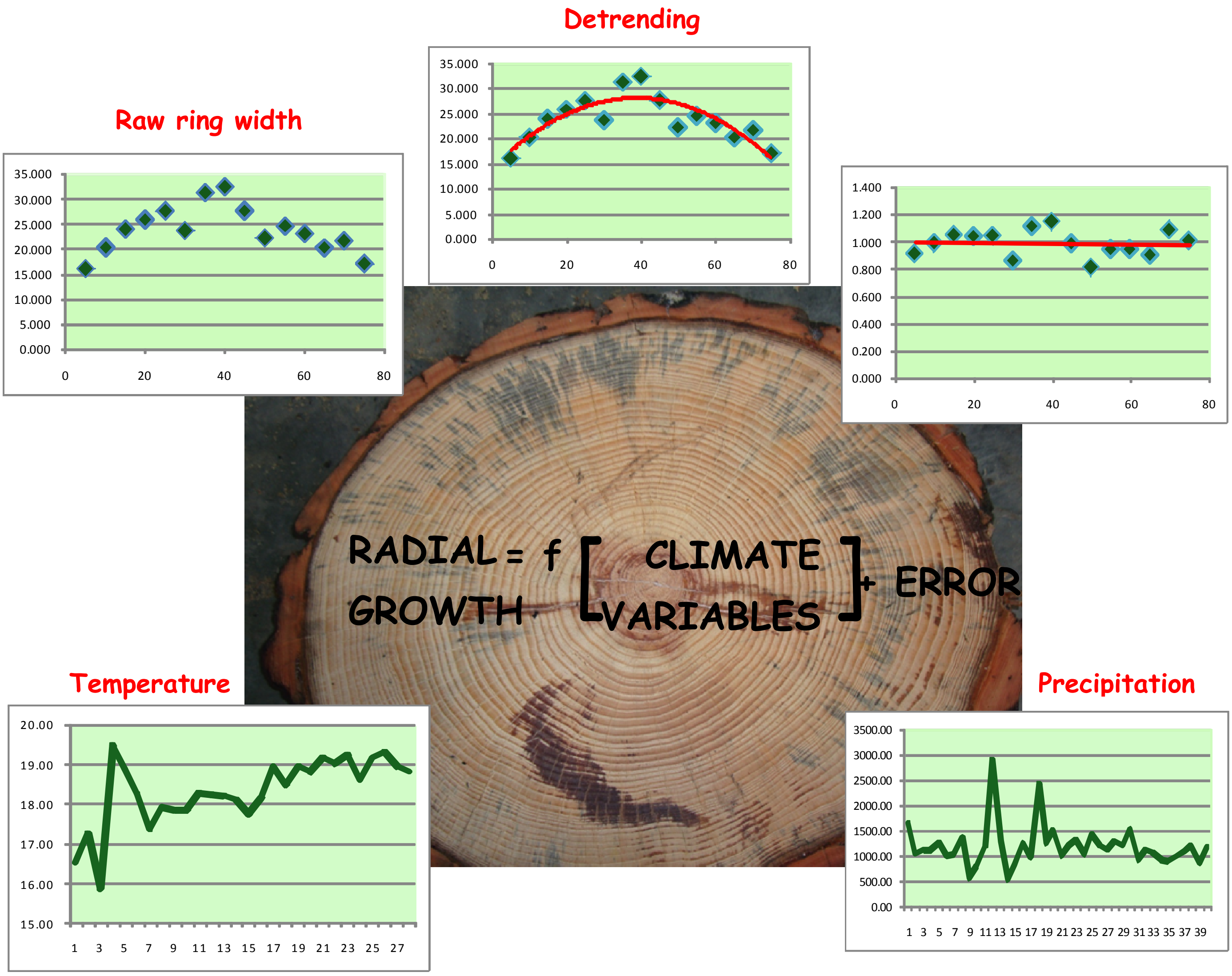


Fig. 25. Principle used for assessing the impact of climate change on forest growth

that the relative width of a ring rather than its actual width, is the important feature in skeleton plotting a sequence of ring widths.

Skeleton plotting of a ring sequence is started at the innermost ring, using an arbitrary numbering sequence starting with zero. The decades are recorded by putting a single pencil dot on each 10^{th} ring, two dots on each 50^{th} ring and three dots on each 100^{th} ring. After individual samples have been plotted, several plots may be compared at one time. The position of the plots may be adjusted so that areas of similar ring patterns are aligned. When this is done correctly, the rings represented by each vertical line may be assumed to have occurred during the same year. If one of the samples contains actual date information, it may then be used to determine dates for the other samples.

Composite skeleton plots were made by visually averaging the skeleton plots of each diameter class. A master skeleton plot for the site was then prepared by visually averaging the length of the drawn lines for each year from all the composite plots for the entire site collection and thus represents the pattern of wide and narrow rings common to all discs from the site. “Signature years” in the chronology – years where most or all trees showed very marked low or high growth, were noted. Actual calendar dates were then assigned to the ring sequences on the skeleton plots.

Once the calendar dates were determined the pencil marks were removed from the discs. The actual dates were recorded on the wood using pinpricks, again putting a single pinprick in each decade ring, two in each half-century ring and three in each century ring. Since false rings and missing rings are common, cross dating is crucial to determining actual calendar dates for every tree ring series in a collection. When a tree is stressed during a growing season, cambial growth may not occur in all parts of the tree, causing the growth ring for a particular year to be missing from the ring width series in the sampled portion of the bole. False rings occur when conditions change during a growing season, causing the tree to form latewood cells before the end of the growing season. Then, when conditions improve, the tree resumes forming earlywood cells, leaving a band of latewood cells with an indistinct boundary within the annual ring. This band of latewood cells can be mistaken for the boundary of the annual ring. This is rectified by crossing out the false ring in the skeleton plot. Similarly, if skeleton plots are compared among many trees, the most likely date for a ring to be locally absent can be determined, that is the year when most trees grew a markedly narrow ring. The plot for that particular tree can then be corrected by inserting the locally absent ring or missing ring. The crossdating accuracy was then checked by the determination of the inter series correlation coefficient. Trees exhibiting correlation values below 0.4 were excluded.

Crossdating assures chronological accuracy and is based on co-variability which guarantees the presence of climate information. The use of many samples averages out the many extraneous factors that are not shared as climate is and gives an accurate picture of the climatic conditions that all the trees shared. Thus, skeleton plotting captures the extremes in variations of the samples ring widths. These may be thought of as the samples features, which are likely due to significant variations in the dominant environmental factor.

(ii) Measurement of ring widths

The ring widths were measured with a vernier calliper (0.01 mm) and a magnifying lens.

(iii) Detrending

After a common short-lived increase in radial growth following germination, the growth increment curve of open-grown trees reaches a maximum and then declines monotonically with increasing age to a relatively constant growth rate. This negative growth trend is partly related to the geometric constraint of adding an approximately equal volume of wood each year to a stem of increasing radius. Other factors contributing to this trend are declining apical dominance, increasing transport distances for food, hormones and water, and limitations on exploitable· site resources for growth. The result is a growth increment curve that decays with time due to factors which are relatively independent of yearly fluctuations of climate. Because this curve is clearly associated with increasing tree age, it will be defined here as the trend of a tree-ring series. Being non-climatic, the age trend must be approximated and removed from a tree-ring series before the series can be used to study variations of past climate. In dendrochronology, this operation of modelling and removing such non-climatic variance is known as *standardization or detrending* (Douglass, 1919; Fritts, 1976). When ring width series are standardized the mean and variance of the inner part of each series is made comparable to the outer part. Thus, the rapid vigorous growth of youth and the slower, steadier growth of old age are scaled to about the same mean and variance. Because all indexed tree ring series will have a mean of about 1.0, index series from trees of different ages can be averaged together to form site chronologies. If ring width series from trees of different ages were averaged together before being transformed into indices, the resulting series would have peaks of higher variance and larger ring widths wherever the younger trees entered the series. (Fritts, 1976).

Trend in a time series is a slow, gradual change in some property of the series over the whole interval under investigation. Trend is sometimes loosely defined as a long term change in the mean but can also refer to change in other statistical properties. For example, tree-ring series of measured ring width frequently have a trend in variance as well as mean. *Detrending* is the statistical or mathematical operation of removing trend from the series. Detrending is often applied to remove a feature thought to distort or obscure the relationships of interest. The expected growth of a tree without environmental variation is approximated by fitting a curve to the ring width series. Each ring width value is then divided by the value of the curve for that year, producing an index of tree growth as a function of variation in environmental factors. Ring Width Index (RWI) is typically used in dendroclimatological studies to standardize ring widths into indices to highlight above- or below-average periods of growth through time in relation to climate (Esper *et al*., 2008). This process of detrending and transforming ring widths into dimensionless indices is known as 'standardization' because it tends to equalize the growth variations between cross-dated tree ring series over time regardless of tree age or size (Fritts, 1976). In turn, this allows the cross-dated series from m individual trees to be properly averaged into a mean-value function, which more reliably reflects the high-frequency variations in growth presumably not related to the biological growth trends that were removed. Many deterministic (few stochastic) models are known and applied to growth trend estimation and to removing non-climatic variance from ring series. The models belong to the family of linear, exponential, polynomial, or more complex growth functions, as comprehensively summarized for example by Vys-kot *et al*., 1971, Smelko *et al*., 1992 and most recently by Pretzsch, 2009.

Theoretically, the standardization curve represents the amount of radial growth produced each year if all climatically-related growth influences in the tree's environment were held constant through time. In this sense, the standardization curve is a time series of expected values of radial growth, and the ring-width indices, or scaled variations, about the curve are the departures from expected growth due to climatic fluctuations. In the case where the expected growth series evolves through time as a simple age trend, this curve can be adequately approximated by a mathematical function of relatively simple form. In the present study there was a common polynomial trend in all the tree ring samples. Therefore, a polynomial equation of the 2^{nd} order was fitted to the ring width data. The model was selected by comparing the R^2 of the candidate models. The one with higher R^2 value was selected for detrending the ring width series. Also the resemblance of the ring width series to one of the several mathematical functions was observed and it was found that the data corresponded to a polynomial form. Bosela *et al*. 2011 studied the detrending ability of several regression equations in tree-ring research, based on tree-ring data of Norway spruce (*Picea abies*) and from all examined/applied equations, polynomial of degree 5 was found to be the most universal and suitable for detrending of all examined ring width curves, along with smoothing spline and Smelko-Burgan functions. Besides removing age trends, standardization reduces each ringwidth series to a series of dimensionless indices with a mean of 1.0 and a homoscedastic variance (Matalas, 1962). This allows several standardized tree-ring series from a stand to be averaged together for improving the signal-to-noise ratio of the series (DeWitt and Ames, 1978). Once a growth curve has been estimated from the data, the standardized tree-ring indices are computed by dividing the actual values by the predicted values as follows:

$\mathbf{z_t = r_t/g_t}$

where, z_t is the ring width index (RWI)

r_t is the observed ringwidth,

g_t is the estimated growth curve for year t.

The division of r_t by g_t is meant to stabilize the variance because the local variance of a ring width series is proportional to its local mean. The “ratio” option is attractive for some kinds of data because the ratio is dimensionless, and the ratio operation tends to remove trend in variance that might accompany trend in mean. Tree-ring width is one such data type: variance of ring width tends to be high when mean ring width is high, and low when mean ring width is low. This process of detrending and transforming ring widths into dimensionless indices is known as ’standardization’ because it tends to equalize the growth variations between cross-dated tree ring series over time regardless of tree age or size (Fritts, 1976). In turn, this allows the cross-dated series from m individual trees to be properly averaged into a mean-value function, which more reliably reflects the high-frequency variations in growth presumably not related to the biological growth trends that were removed. Figure 25 shows the principle used in assessing the impact of climate change on forest growth.

(iv) Relationship between Ring Width Index (RWI) and climatic variables

The statistical characteristics of the resulting master chronology are examined and the relationship between the ring-width indices and climate is then modeled. This is followed by verification from independent data sources: historical documentation, available meteorological data, or other climate indicators (Fritts, 1976). Once a set of tree-rings has been accurately cross-dated, the chronology must then be verified as a sufficient proxy for climate reconstruction. This step is referred to as calibration which correlates a composite chronology of tree-ring width with various climatic parameters. Calibration can be accomplished by comparing a tree ring chronology with local weather station data.

Analytical Framework

All analysis was done with the help of the software package known as Statistical Package for Social Sciences (SPSS 16.0).

(i) Correlation Analysis

Correlation studies the degree of relationship between two or more variables. Karl Pearson’s correlation coefficient between tree ring data and climatic variables i.e. temperature and rainfall was worked out to separately analyse the importance of these factors in influencing forest growth.

(ii) Step-wise multiple linear regression analysis

Step-wise multiple linear regression is used to test the effect of n independent (Predictor) variables on a single dependant (Criterion) variable. Step-wise multiple linear regression analysis is used to find out the contribution of different factors to forest growth. In the present study climatic variables i.e. temperature and rainfall were taken as independent variables and ring width index (RWI) was taken as dependant variable.

Chapter-4

EXPERIMENTAL RESULTS

Chapter-4

EXPERIMENTAL RESULTS

The results emerging out of the present investigation entitled "Evaluation of Forest Carbon Stock and Land use of Solan Forest Division" conducted in Solan (H.P.) during 2009-2012 have been presented under following experiments:

EXPERIMENT NO. 1

4.1 Land use change of Solan Forest Division

EXPERIMENT NO. 2

4.2 Temporal change in carbon stock of forest stands

- **4.2.1 Temporal status of carbon in forest trees of Solan and Dharampur Ranges of Solan Forest Division**
- **4.2.2 Carbon status of Solan and Dharampur Ranges of Solan Forest Division in 2011**
- **4.2.3 Carbon mapping and carbon change analysis**

EXPERIMENT NO. 3

4.3 Impact of climate change on forest growth

- **4.3.1 Climate trend (1983-2020)**
- **4.3.2 Dendrochronological Analysis**
- **4.3.3 Relationship between Ring Width Index (RWI) and climatic variables**

EXPERIMENT NO. 1

4.1 Land use change of Solan Forest Division

The results of land use change for Solan Forest Division between the year 1998 and 2010 are presented under the following headings:

(A) Land use classification

(B) Accuracy Assesment

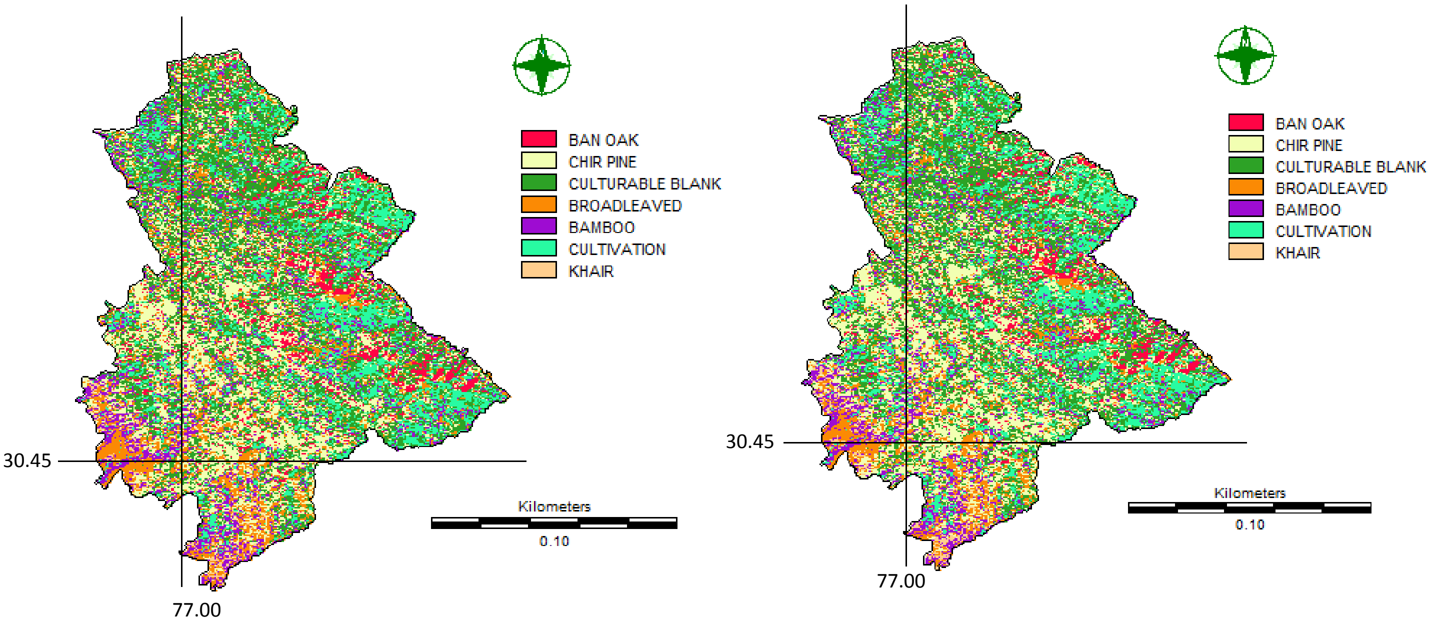
A maximum likelihood (MAXLIKE) classification was run including three bands i.e. Green, Red and Near-infrared each for date 1998 and 2010 as a first step in studying land use change of the study area. Of the three hard supervised classifiers, MINDIST (Minimum Distance to Means Classifier), PIPED (Parallelepiped) and MAXLIKE (Maximum Likelihood Classifier), MAXLIKE is clearly the most powerful. With high quality (homogenous) training sites, it is capable of producing excellent results. Using the information from a set of training sites, MAXLIKE uses the mean and variance/covariance data of the signatures to estimate the posterior probability that a pixel belongs to each class. In many ways, MAXLIKE procedure is similar to MINDIST with the standardized distance option. The difference is that MAXLIKE accounts for intercorrelation between bands. By incorporating information about the covariance between bands as well as their inherent variance, MAXLIKE produces what can be conceptualized as an elliptical zone of characterization of the signature. In actuality, it calculates the posterior probability of belonging to each class, where the probability is highest at the mean position of the class and falls off in an elliptical pattern away from the mean.

(A) Land use classification

The classification resulted in total geographical area of 56,320 ha in Solan Forest Division (recorded forest area + non-forest area) covered under different land use categories as shown in Table 9. The results revealed that in 1998, Culturable Blank, Chir pine, Cultivation, Broadleaved, Bamboo, Ban oak and Khair land use categories covered 17278 ha, 13036 ha, 8239 ha, 7448 ha, 6290 ha, 3266 ha, and 763 ha area which accounted for 30.68%, 23.15%, 14.63%, 13.22%, 11.17%, 5.80%, and 1.35% of the total area, respectively (Fig. 26).

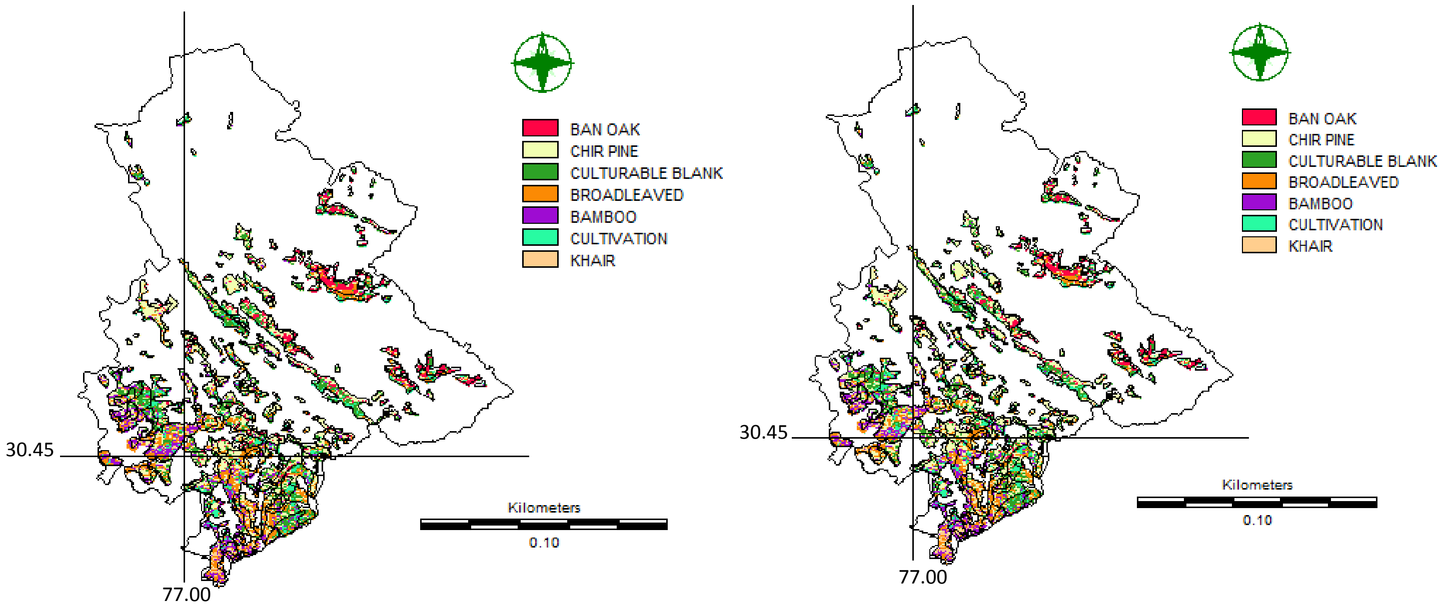
On the other hand classification based on 2010 images revealed that the distribution of area under various land uses i.e. Culturable Blank, Chir pine, Cultivation, Broadleaved, Bamboo, Ban oak and Khair land use categories was 17158 ha, 13735 ha, 8805 ha, 6901 ha, 6252 ha, 2614 ha and 855 ha which accounted for 30.47%, 24.39%, 15.63%, 12.25%, 11.10% 4.65% and 1.52% of the total area, respectively.

Among all the land uses, Chir pine, Cultivation and Khair reported an increase in area of 699 ha (5.36%), 566 ha (6.87%) and 92 ha (12.06%),



a) 1998 **b) 2010**

Fig. 26. Land use classification based on Maximum Likelihood Classifier for Solan Forest Division a) 1998 and b) 2010



a) 1998 **b) 2010**

Fig.27. Land use classification based on Maximum Likelihood Classifier for forest compartments extracted from Solan Forest Division a) 1998 and b) 2010

respectively from 1998 to 2010, whereas Ban oak, Broadleaved, Culturable Blank and Bamboo reported a decrease in area of 652 ha (19.96%), 547 ha (7.34%), 120 ha (0.70%) and 38 ha (0.60%), respectively from 1998 to 2010.

The territorial (compartment wise) classification resulted in total geographical area of 13,067 ha (recorded forest area) in Solan Forest Division covered under different land use categories as shown in Table 10. The results revealed that in 1998, Chir pine, Culturable Blank, Broadleaved, Bamboo, Ban oak, Cultivation and Khair land use categories covered 4200 ha, 2608 ha, 2413 ha, 1491 ha, 1092 ha, 934 ha and 329 ha area which accounted for 32.14%, 19.96%, 18.47%, 11.41%, 8.36%, 7.15%, and 2.52% of the total area, respectively (Fig. 27).

On the other hand classification based on 2010 images revealed that the distribution of area under various land uses i.e. Chir pine, Culturable Blank, Broadleaved, Bamboo, Cultivation, Ban oak and Khair land use categories was 4391 ha, 2537 ha, 2261 ha, 1498 ha, 1063 ha, 911 ha and 406 ha and which accounted for 33.60%, 19.42%, 17.30%, 11.46%, 8.13%, 6.97% and 3.11% of the total area, respectively.

Among all the land uses, Chir pine, Cultivation and Khair reported an increase in area of 191 ha (4.55%), 129 ha (13.81%) and 77 ha (23.40%), while Ban oak, Broadleaved, Culturable Blank and Bamboo reported a decrease in area of 181 ha (16.58%), 152 ha (6.30%), 71 ha (2.72%) and 7 ha (0.47%), respectively from 1998 to 2010.

(B) Accuracy Assessment

The error matrices between reference data and classified data for 1998 and 2010 classifications are presented in Table 11 and Table 12, respectively. The results revealed that the producer’s accuracy for different category types ranged from 79% to 96% and 86% to 92% as a result of 1998 and 2010 land use classification, respectively, whereas, user’s accuracy was reported to range from 74% to 93% and 85% to 92% for the corresponding land use classification dates. Among all the land uses, Cultivation land use category reported the highest User’s accuracy of 93 per cent as per 1998 land use classification, whereas as per 2010 land use classification, Khair land use category reported the highest User’s accuracy of 92 per cent.

Table 9. Land use change in Solan Forest Division

Category	Area under Land Use (ha)		Percent Change in Land use Area
	1998	2010	
Cultivation	8239 (14.63)	8805 (15.63)	566 (+) (6.87)
Culturable Blank	17278 (30.68)	17158 (30.47)	120 (-) (0.70)
Forest Land use			
Chir Pine	13036 (23.15)	13735 (24.39)	699 (+) (5.36)
Ban oak	3266 (5.80)	2614 (4.65)	652 (-) (19.96)
Broadleaved	7448 (13.22)	6901 (12.25)	547 (-) (7.34)
Khair	763 (1.35)	855 (1.52)	92 (+) (12.06)
Bamboo	6290 (11.17)	6252 (11.10)	38 (-) (0.60)
Total	56,320	56,320	

*Figures in parenthesis is in percent

Table 10. Territorial (compartment wise) Land use change in Solan Forest Division

Category	Area under Land Use (ha)		Percent Change in Land use Area
	1998	2010	
Cultivation	934 (7.15)	1063 (8.13)	129 (+) (13.81)
Culturable Blank	2608 (19.96)	2537 (19.42)	71(-) (2.72)
Forest Land use			
Chir Pine	4200 (32.14)	4391 (33.6)	191 (+) (4.55)
Ban oak	1092 (8.36)	911 (6.97)	181 (-) (16.58)
Broad Leaved	2413 (18.47)	2261 (17.30)	152 (-) (6.30)
Khair	329 (2.52)	406 (3.11)	77 (+) (23.40)
Bamboo	1491 (11.41)	1498 (11.46)	7 (-) (0.47)
Total	13,067	13,067	

****Figures in parenthesis is in percent***

On the other hand, however, Bamboo reported the highest producer's accuracy of 96 per cent and 92 per cent in 1998 and 2010 land use classification respectively. The 2010 classification resulted in higher overall accuracy of 89 per cent followed by 1998 classification with an accuracy of 87 per cent. However, KHAT accuracy was 85 per cent and 87 per cent for 1998 and 2010 land use classification, respectively (Table 13).

Table 11. Error matrix as a result of land use classification for 1998

	Reference data								
Classified data	**Ban oak**	**Chir pine**	**Culturable Blank**	**Broadleaved**	**Bamboo**	**Cultivation**	**Khair**	**Total**	**User's accuracy**
Ban oak	46	3	1	0	0	1	0	51	**90**
Chir pine	1	64	2	4	0	0	0	71	**90**
Culturable Blank	1	6	65	0	0	3	0	75	**87**
Broadleaved	1	0	3	59	2	0	3	68	**87**
Bamboo	1	0	0	9	48	5	2	65	**74**
Cultivation	0	1	4	0	0	66	0	71	**93**
Khair	0	1	0	3	0	0	45	49	**92**
Total	50	75	75	75	50	75	50	450	
Producer's accuracy	**92**	**85**	**87**	**79**	**96**	**88**	**90**		**87**

Table 12. Error matrix as a result of land use classification for 2010

	Reference data								
Classified data	**Ban oak**	**Chir pine**	**Culturabl e Blank**	**Broadleaved**	**Bambo o**	**Cultivation**	**Khair**	**Total**	**User's accuracy**
Ban oak	43	3	1	0	0	0	0	47	**91**
Chir pine	4	67	1	3	0	1	0	76	**88**
Culturable Blank	0	1	68	3	0	3	0	75	**91**
Broadleaved	1	2	1	65	2	1	2	74	**88**
Bamboo	0	1	0	3	46	1	3	54	**85**
Cultivation	2	1	4	0	0	68	0	75	**91**
Khair	0	0	0	1	2	1	45	49	**92**
Total	50	75	75	75	50	75	50	450	
Producer's accuracy	**86**	**89**	**91**	**87**	**92**	**91**	**90**		**89**

Table 13. Comparison of two classification accuracy measures for two dates

CLASSIFICATION	OVERALL ACCURACY (%)	KHAT ACCURACY (%)
1998	87	85
2010	89	87

EXPERIMENT NO. 2

4.2 Temporal change in carbon stock of forest stands

The results pertaining to the temporal distribution of biomass and carbon stock in 33 compartments of Solan and Dharampur Forest Ranges for the years 1956, 1984, 2002 and 2011 are described below. The data for 1956, 1984 and 2002 were obtained from the records in the working plan of the division. For the estimation of the forest carbon stock of the year 2011, the complete enumeration of 33 compartments - 12 in Solan and 21 in Dharampur Forest Range, was carried out in July-October, 2011. The results show a decrease in the biomass and carbon stock between 1956 and 1984. However there was an increase in the biomass and carbon stock in 2002 with a further increase in the same in the year 2011.

4.2.1 Temporal status of carbon in forest trees of Solan and Dharampur Ranges of Solan Forest Division

(A) Biomass

(i) Aboveground Biomass (t)

The volume of Solan Forest Division for the years 1956, 1984, 2002 and 2011 was determined (Appendix IV). Thereafter, the biomass was estimated for the years 1956, 1984, 2002 and 2011 (Table 14, Appendix V). In the year 1956 R-49 Gadiar had the maximum aboveground biomass of 3182.90 t and the minimum aboveground biomass was recorded in D-153 Gulhari I at 246.81 t. In 1984 D-176 Charoti ki Dhar had the maximum aboveground biomass of 2133.34 t and D-172 Bhog Seri III had the minimum aboveground biomass of 100.52 t. In

2002 a maximum aboveground biomass of 3306.34 t was found in D-119 Chabil ki Dhar II and a minimum aboveground biomass of 82.58 t in D-153 Gulhari I. In the year 2011 D-119 Chabil ki Dhar II had the maximum aboveground biomass of 3442.02 t and D-97 Kiar Tatul had the minimum aboveground biomass of 129.68 t. The total aboveground biomass in 1956 was 34141.98 t, which reduced to 19648.48 t in 1984, increased to 29774.72 t in 2002 and further increased to 33616.25 t in 2011. The temporal distribution of aboveground biomass over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 14493.50 t, an increasing trend over 1984-2002 period by 10126.24 t and over 2002-2011 period there was a further increase by 3841.53 t.

(ii) Aboveground Biomass Density (AGBD) (t ha^{-1})

It was found that in the year 1956 maximum aboveground biomass density of 265.79 t ha^{-1} was present in D-117 Chabil ki Dhar IV and minimum aboveground biomass density of 28.61 t ha^{-1}was present in D-92 Deora. In 1984 the maximum aboveground biomass density of 207.27 t ha^{-1}was recorded in D-96 Nagali II and the minimum aboveground biomass density of 16.31 t ha^{1} was recorded in D-162 Maltu II. In 2002 the maximum aboveground biomass density of 262.26 t ha was found in D-118 Chabil Ki Dhar III and the minimum aboveground biomass density of 15.88 t ha^{-1}was found in D-153 Gulhari I. In 2011, D-118 Chabil Ki Dhar III recorded the maximum aboveground biomass density of 289.88 t ha^{-1} while D-97 Kiar Tatul recorded the minimum aboveground biomass density of 29.47 t ha^{-1}. The total aboveground biomass density in 1956 was 78.45 t ha^{-1}, which reduced to 45.15 t ha^{-1} in 1984, increased to 68.42 t ha^{-1}in 2002 and further increased to 77.24 t ha^{-1} in 2011. The temporal distribution of aboveground biomass density in Solan Forest Range over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 33.30 t ha^{-1}, an increasing trend over 1984-2002 period by 23.27 t ha^{-1}and over 2002-2011 period there was a further increase by 8.82 t ha^{-1} (Table 14).

(iii) Belowground Biomass (t)

In the year 1956 R-49 Gadiar had the maximum belowground biomass of 715.54 t and the minimum belowground biomass was recorded in in D-153 Gulhari I at 55.49 t. In 1984 D-176 Charoti ki Dhar had the maximum belowground biomass of 479.59 t and D-172 Bhog Seri III had the minimum belowground biomass of 22.60 t. In 2002 a maximum belowground biomass of 743.29 t was found in D-119 Chabil ki Dhar II and a minimum belowground biomass of 18.57 t in D-153 Gulhari I. In the year 2011 D-119 Chabil ki Dhar II had the maximum belowground biomass of 773.79 t and D-97 Kiar Tatul had the minimum belowground biomass of 29.15 t. The total belowground biomass in 1956 was 7675.33 t, which reduced to 4417.10 t in 1984, increased to 6693.54 t in 2002 and further increased to 7557.14 t in 2011. The temporal distribution of belowground biomass over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 3258.23 t, an increasing trend over 1984-2002 period by 2276.44 t and over 2002-2011 period there was a further increase by 863.60 t (Table 14).

(iv) Belowground Biomass Density (BGBD) (t ha^{-1})

It was found that in the year 1956 maximum belowground biomass density of 59.75 t ha^{-1} was present in D-117 Chabil ki Dhar IV and minimum belowground biomass density of 6.43 t ha^{-1} was present in D-92 Deora. In 1984 the maximum belowground biomass density of 46.60 t ha^{-1} was recorded in D-96 Nagali II and the minimum belowground biomass density of 3.67 t ha^{-1} was recorded in D-162 Maltu II. In 2002 the maximum belowground biomass density of 58.96 t ha^{-1} was found in D-118 Chabil Ki Dhar III and the minimum belowground biomass density of 3.57 t ha^{-1} respectively was found in D-153 Gulhari I. In 2011, D-118 Chabil Ki Dhar III recorded the maximum belowground biomass density of 65.17 t ha^{-1} while D-97 Kiar Tatul recorded the minimum belowground biomass density of 6.63 t ha^{-1}.

The total belowground biomass density in 1956 was 17.64 t ha^{-1}, which reduced to10.15 t ha^{-1} in 1984, increased to 15.38 t ha^{-1} in 2002 and further increased to 17.36 t ha^{-1} in 2011. The temporal distribution of belowground biomass density in Solan Forest Range over the period of 1956 to 2011 showed a declining trend in over 1956-1984 period by 7.49 t ha^{-1}, an increasing trend over 1984-2002 period by 5.23 t ha^{-1} and over 2002-2011 period there was a further increase by 1.98 t ha^{-1} (Table 14).

(v) Total Tree Biomass (above and below) (t)

The total tree biomass (above+below) in 1956 was 41817.31 t, which reduced to 24065.58 t in 1984, increased to 36468.26t in 2002 and further increased to 41173.39t in 2011. The temporal distribution of tree biomass over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 17751.73 t, an increasing trend over 1984-2002 period by 12402.68 t and over 2002-2011 period there was a further increase by 4705.13 t (Table 14).

(vi) Tree Biomass Density (above and below) (t ha^{-1})

The tree biomass (above+below) in 1956 was 96.09 t ha^{-1}, which reduced to 55.30 t ha^{-1} in 1984, increased to 83.80 t ha^{-1} in 2002 and further increased to 94.61 t ha^{-1} in 2011. The temporal distribution of tree biomass over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 40.79 t ha^{-1}, an increasing trend over 1984-2002 period by 28.50 t ha^{-1} and over 2002-2011 period there was a further increase by 10.81 t ha^{-1} (Table 14).

Table 14. Temporal distribution of Biomass in selected compartments of Solan and Dharampur Forest Ranges in Solan Forest Division

S.No	Name of the Forest	Tree Aboveground Biomass (t)				Tree Belowground Biomass (t)				Total Tree Biomass (t)			
		1956	1984	2002	2011	1956	1984	2002	2011	1956	1984	2002	2011
Solan Forest Range													
1	**D-93 Nandal Nagali**	834.08 (67.26)	567.99 (45.81)	498.71 (40.22)	521.53 (42.06)	187.51 (15.12)	127.69 (10.30)	112.11 (9.04)	117.24 (9.46)	1021.59 (82.39)	695.68 (56.10)	610.82 (49.26)	638.77 (51.51)
2	**D-95 Nagali I**	524.80 (145.78)	343.38 (95.38)	265.18 (73.66)	274.07 (76.13)	117.98 (32.77)	77.19 (21.44)	59.61 (16.56)	61.61 (17.11)	642.78 (178.55)	420.57 (116.83)	324.79 (90.22)	335.68 (93.25)
3	**D-96 Nagali II**	498.75 (124.69)	829.09 (207.27)	139.84 (34.96)	153.95 (38.49)	112.12 (28.03)	186.38 (46.60)	31.44 (7.86)	34.61 (8.65)	610.87 (152.72)	1015.47 (253.87)	171.28 (42.82)	188.56 (47.14)
4	**D-97 Kiar Tatul**	631.27 (143.47)	499.99 (113.64)	130.72 (29.71)	129.68 (29.47)	141.91 (32.25)	112.40 (25.55)	29.39 (6.68)	29.15 (6.63)	773.18 (175.72)	612.39 (139.18)	160.11 (36.39)	158.83 (36.10)
5	**D-123 Beola**	437.03 (99.32)	399.21 (90.73)	512.38 (116.45)	384.90 (87.48)	98.25 (22.33)	89.75 (20.40)	115.19 (26.18)	86.53 (19.67)	535.28 (121.65)	488.96 (111.13)	627.57 (142.63)	471.43 (107.1)
6	**D-135 Kaldhar I**	612.28 (109.34)	239.80 (42.82)	181.78 (32.46)	196.55 (35.10)	137.65 (24.58)	53.91 (9.63)	40.87 (7.30)	44.19 (7.89)	749.93 (133.92)	293.71 (52.45)	222.65 (39.76)	240.74 (42.99)
7	**R-26 Nagali**	2373.35 (70.64)	873.93 (26.01)	1682.13 (50.06)	2054.35 (61.14)	533.54 (15.88)	196.46 (5.85)	378.15 (11.25)	461.83 (13.74)	2906.89 (86.51)	1070.39 (31.86)	2060.28 (61.32)	2516.18 (74.89)
8	**D-92 Deora**	732.38 (28.61)	877.83 (34.29)	916.32 (35.79)	1117.05 (43.63)	164.64 (6.43)	197.34 (7.71)	205.99 (8.05)	251.12 (9.81)	897.02 (35.04)	1075.17 (42.00)	1122.31 (43.84)	1368.17 (53.44)
9	**D-94 Nandal**	1062.76 (126.52)	849.29 (101.11)	460.34 (54.80)	477.71 (56.87)	238.92 (28.44)	190.93 (22.73)	103.49 (12.32)	107.39 (12.78)	1301.68 (154.96)	1040.22 (123.84)	563.83 (67.12)	585.1 (69.65)
10	**D-89 Gadhog I**	304.18 (33.06)	204.60 (22.24)	371.28 (40.36)	758.83 (82.48)	68.38 (7.43)	45.99 (5.00)	83.47 (9.07)	170.59 (18.54)	372.56 (40.50)	250.59 (27.24)	454.75 (49.43)	929.42 (101.02)
11	**D-90 Gadhog II**	689.01 (52.20)	768.67 (58.23)	565.32 (42.83)	594.14 (45.01)	154.89 (11.73)	172.80 (13.09)	127.09 (9.63)	133.57 (10.12)	843.9 (63.93)	941.47 (71.32)	692.41 (52.45)	727.71 (55.13)
12	**D-98 Bhawan Ki Dhar**	1346.40 (70.13)	463.09 (24.12)	1414.38 (73.67)	2084.59 (108.57)	302.68 (15.76)	104.11 (5.42)	317.96 (16.56)	468.63 (24.41)	1649.08 (85.89)	567.2 (29.54)	1732.34 (90.23)	2553.22 (132.98)
Dharampur Forest Range													
13	**R-36 Anji**	932.59 (89.67)	571.36 (54.94)	532.21 (51.17)	915.94 (88.07)	209.65 (20.16)	128.45 (12.35)	119.64 (11.50)	205.91 (19.80)	1142.24 (109.83)	699.81 (67.29)	651.85 (62.68)	1121.85 (107.87)
14	**R-49 Gadiar**	3182.90 (102.02)	1305.40 (41.84)	1426.15 (45.71)	1788.88 (57.34)	715.54 (22.93)	293.46 (9.41)	320.61 (10.28)	402.15 (12.89)	3898.44 (124.95)	1598.86 (51.25)	1746.76 (55.99)	2191.03 (70.23)
15	**D-117 Chabil Ki Dhar IV**	637.90 (265.79)	156.01 (65.00)	591.49 (246.45)	580.23 (241.76)	143.40 (59.75)	35.07 (14.61)	132.97 (55.40)	130.44 (54.35)	781.30 (325.54)	191.08 (79.62)	724.46 (301.86)	710.67 (296.11)
16	**D-118 Chabil Ki Dhar III**	916.75 (88.15)	1202.88 (115.66)	2727.52 (262.26)	3014.74 (289.88)	206.09 (19.82)	270.42 (26.00)	613.16 (58.96)	677.73 (65.17)	1122.84 (107.97)	1473.3 (141.66)	3340.68 (321.22)	3692.47 (355.05)

17	**D-164 Maltu III**	918.46 (58.88)	444.49 (28.49)	1030.23 (66.04)	1139.62 (73.05)	206.48 (13.24)	99.92 (6.41)	231.60 (14.85)	256.19 (16.42)	1124.94 (72.11)	544.41 (34.90)	1261.83 (80.89)	1395.81 (89.48)
18	**D-181 Sirguli Ka Tiba III**	2135.13 (84.73)	1289.64 (51.18)	1441.53 (57.20)	1679.93 (66.66)	479.99 (19.05)	289.92 (11.50)	324.07 (12.86)	377.66 (14.99)	2615.12 (103.77)	1579.56 (62.68)	1765.60 (70.06)	2057.59 (81.65)
19	**D-182 Kalath III**	1911.15 (74.65)	736.93 (28.79)	2622.85 (102.46)	2786.69 (108.86)	429.64 (16.78)	165.67 (6.47)	589.63 (23.03)	626.47 (24.47)	2340.79 (91.44)	902.60 (35.26)	3212.48 (125.49)	3413.16 (133.33)
20	**D-172 Bhog Seri III**	456.87 (103.83)	100.52 (22.84)	249.19 (56.63)	450.14 (102.31)	102.71 (23.34)	22.60 (5.14)	56.02 (12.73)	101.20 (23.00)	559.58 (127.18)	123.12 (27.98)	305.21 (69.37)	551.34 (125.30)
21	**D-159 Anji III**	597.89 (166.08)	239.98 (66.66)	193.05 (53.62)	186.00 (51.67)	134.41 (37.34)	53.95 (14.99)	43.40 (12.06)	41.81 (11.62)	732.30 (203.42)	293.93 (81.65)	236.45 (65.68)	227.81 (63.28)
22	**D-160 Anji I**	1062.32 (102.15)	711.13 (68.38)	484.70 (46.61)	488.58 (46.98)	238.82 (22.96)	159.87 (15.37)	108.96 (10.48)	109.84 (10.56)	1301.14 (125.11)	871.00 (83.75)	593.66 (57.08)	598.42 (57.54)
23	**D-120 Chabil Ki Dhar I**	307.47 (85.41)	594.50 (165.14)	873.31 (242.59)	728.40 (202.33)	69.12 (19.20)	133.65 (37.12)	196.33 (54.54)	163.75 (45.49)	376.59 (104.61)	728.15 (202.26)	1069.64 (297.12)	892.15 (247.82)
24	**D-150 Gulhari IV**	330.43 (75.10)	118.02 (26.82)	207.33 (47.12)	222.88 (50.65)	74.28 (16.88)	26.53 (6.03)	46.61 (10.59)	50.10 (11.39)	404.71 (91.98)	144.55 (32.85)	253.94 (57.71)	272.98 (62.04)
25	**D-152 Gulhari II**	1013.35 (115.15)	193.20 (21.95)	396.91 (45.10)	396.77 (45.09)	227.81 (25.89)	43.43 (4.94)	89.23 (10.14)	89.20 (10.14)	1241.16 (141.04)	236.63 (26.89)	486.14 (55.24)	485.97 (55.22)
26	**D-153 Gulhari I**	246.81 (47.46)	178.15 (34.26)	82.58 (15.88)	158.60 (30.50)	55.49 (10.67)	40.05 (7.70)	18.57 (3.57)	35.65 (6.86)	302.3 (58.13)	218.2 (41.96)	101.15 (19.45)	194.25 (37.36)
27	**D-154 Dawala**	1525.89 (119.21)	393.99 (30.78)	932.21 (72.83)	1284.11 (100.32)	343.03 (26.80)	88.57 (6.92)	209.57 (16.37)	288.68 (22.55)	1868.92 (146.01)	482.56 (37.70)	1141.78 (89.20)	1572.79 (122.87)
28	**D-155 Bhallon**	392.31 (122.60)	208.73 (65.23)	233.90 (73.09)	298.34 (93.23)	88.19 (27.56)	46.92 (14.66)	52.58 (16.43)	67.07 (20.96)	480.50 (150.16)	255.65 (79.89)	286.48 (89.53)	365.41 (114.19)
29	**D-162 Maltu II**	1566.86 (55.17)	463.26 (16.31)	1484.88 (52.28)	1548.04 (54.51)	352.24 (12.40)	104.14 (3.67)	333.81 (11.75)	348.01 (12.25)	1919.10 (67.57)	567.40 (19.98)	1818.69 (64.04)	1896.05 (66.76)
30	**D-163 Maltu I**	631.74 (56.40)	453.64 (40.50)	896.58 (80.05)	959.88 (85.70)	142.02 (12.68)	101.98 (9.11)	201.56 (18.00)	215.79 (19.27)	773.76 (69.09)	555.62 (49.61)	1098.14 (98.05)	1175.67 (104.97)
31	**D-173 Bohali Ki Chali**	756.77 (72.77)	365.63 (35.16)	495.45 (47.64)	535.66 (51.51)	170.13 (16.36)	82.20 (7.90)	111.38 (10.71)	120.42 (11.58)	926.90 (89.12)	447.83 (43.06)	606.83 (58.35)	656.08 (63.09)
32	**D-176 Charoti Ki Dhar I**	2488.34 (65.48)	2133.34 (56.14)	2427.91 (63.89)	2263.44 (59.56)	559.39 (14.72)	479.59 (12.62)	545.81 (14.36)	508.84 (13.39)	3047.73 (80.20)	2612.93 (68.76)	2973.72 (78.26)	2772.28 (72.95)
33	**D-119 Chabil Ki Dhar II**	2083.75 (78.93)	870.80 (32.98)	3306.34 (125.24)	3442.02 (130.38)	468.44 (17.74)	195.76 (7.42)	743.29 (28.15)	773.79 (29.31)	2552.19 (96.67)	1066.56 (40.40)	4049.63 (153.39)	4215.81 (159.69)
Total		**34141.98 (78.45)**	**19648.48 (45.15)**	**29774.72 (68.42)**	**33616.25 (77.24)**	**7675.33 (17.64)**	**4417.10 (10.15)**	**6693.54 (15.38)**	**7557.14 (17.36)**	**41817.31 (96.09)**	**24065.58 (55.30)**	**36468.26 (83.80)**	**41173.39 (94.61)**

* Figures in parenthesis denote biomass density in t ha^{-1}

(B) Carbon Stock

(i) Aboveground Carbon Stock (t)

Data presented in Table 15, Fig. 28 shows the carbon stock of Solan and Dharampur Forest Ranges for 33 compartments for the years 1956, 1984, 2002 and 2011. In the year 1956 R-49 Gadiar had the maximum aboveground carbon stock of 1591.45 t and the minimum aboveground carbon stock was recorded in D-153 Gulhari I at 123.41 t. In 1984 D-176 Charoti ki Dhar had the maximum aboveground carbon stock of 1066.67 t and D-172 Bhog Seri III had the minimum aboveground carbon stock of 50.26 t. In 2002 a maximum aboveground carbon stock of 1653.17 t was found in D-119 Chabil ki Dhar II and a minimum aboveground carbon stock of 41.29 t in D-153 Gulhari I. In the year 2011 D-119 Chabil ki Dhar II had the maximum aboveground carbon stock of 1721.01 t and D-97 Kiar Tatul had the minimum aboveground carbon stock of 64.84 t. The total aboveground carbon stock in 1956 was 17070.99 t, which reduced to 9824.24 t in 1984, increased to 14887.36 t in 2002 and further increased to 16808.12 t in 2011. The temporal distribution of aboveground carbon stock over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 7246.75 t, an increasing trend over 1984-2002 period by 5063.12 t and over 2002-2011 period there was a further increase by 1920.76 t.

(ii) Aboveground Carbon Density (AGCD) (t ha^{-1})

In the year 1956 maximum aboveground carbon density of 132.90 t ha^{-1} was present in D-117 Chabil ki Dhar IV and minimum aboveground carbon density of 14.30 t ha^{-1} was present in D-92 Deora. In 1984 the maximum aboveground carbon density of 103.64 t ha^{-1} was recorded in D-96 Nagali II and the minimum aboveground carbon density of 8.16 t ha^{-1} was recorded in D-162 Maltu II (Table 15).

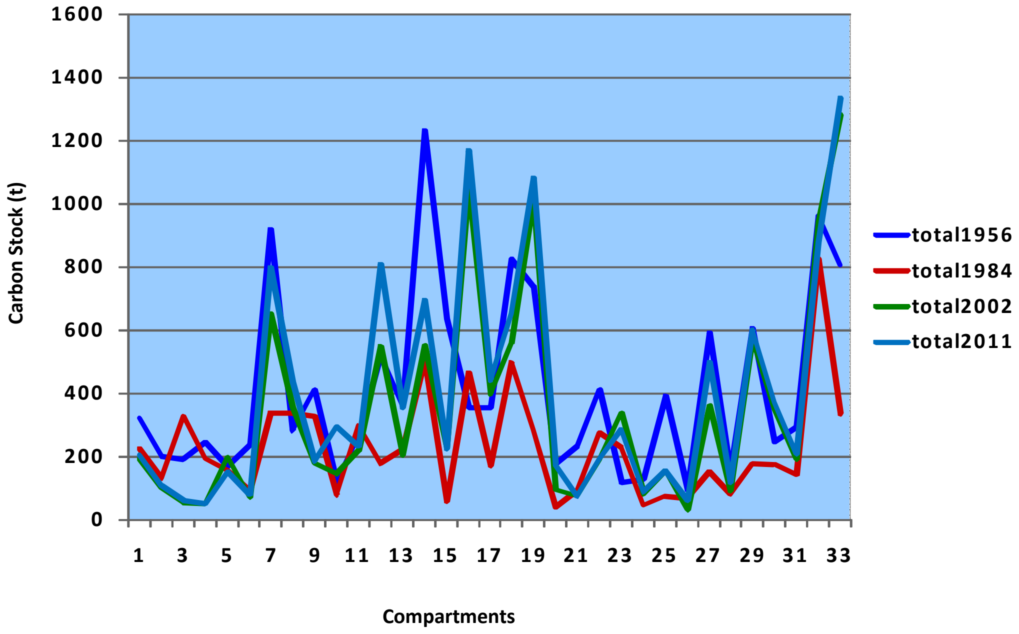


Fig. 28. Temporal distributrion of carbon stock in selected compartments of Solan and Dharampur Ranges of Solan Forest Division

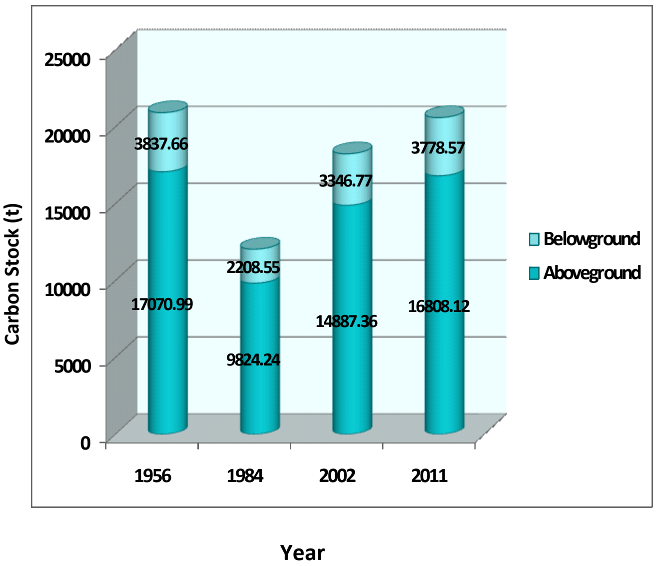


Fig .29. Temporal Distribution of tree aboveground and belowground Carbon stock in selected compartments of Solan Forest Division

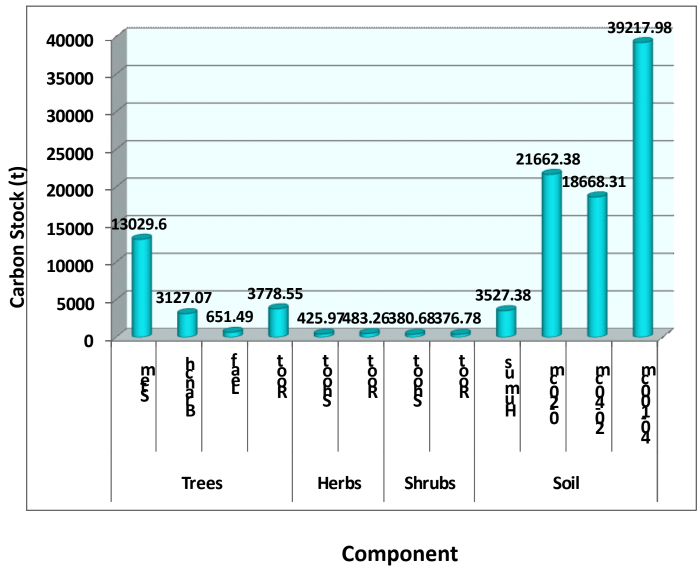


Fig. 30. Carbon status in different components in selected compartments of Solan Forest Division

Table 15. Temporal distribution of Carbon stock in selected compartments of Solan and Dharampur Forest Ranges in Solan Forest Division

S.No.	Name of the Forest	Tree Aboveground Carbon stock (t)				Tree Belowground Carbon stock (t)				Total Tree Carbon Density (t)			
		1956	1984	2002	2011	1956	1984	2002	2011	1956	1984	2002	2011
Solan Forest Range													
1	**D-93 Nandal Nagali**	417.04 (33.63)	284.00 (22.90)	249.36 (20.11)	260.76 (21.03)	93.75 (7.56)	63.84 (5.15)	56.06 (4.52)	58.62 (4.73)	510.79 (41.19)	347.84 (28.05)	305.41 (24.63)	319.39 (25.76)
2	**D-95 Nagali I**	262.40 (72.89)	171.69 (47.69)	132.59 (36.83)	137.04 (38.07)	58.99 (16.39)	38.60 (10.72)	29.81 (8.28)	30.81 (8.56)	321.39 (89.27)	210.29 (58.41)	162.40 (45.11)	167.84 (46.62)
3	**D-96 Nagali II**	249.38 (62.34)	414.54 (103.64)	69.92 (17.48)	76.97 (19.24)	56.06 (14.02)	93.19 (23.30)	15.72 (3.93)	17.30 (4.33)	305.44 (76.36)	507.74 (126.93)	85.64 (21.41)	94.28 (23.57)
4	**D-97 Kiar Tatul**	315.64 (71.74)	250.00 (56.82)	65.36 (14.85)	64.84 (14.74)	70.96 (16.13)	56.20 (12.77)	14.69 (3.34)	14.58 (3.31)	386.59 (87.86	306.20 (69.59)	80.05 (18.19)	79.42 (18.05)
5	**D-123 Beola**	218.51 (49.66)	199.61 (45.37)	256.19 (58.23)	192.45 (43.74)	49.12 (11.16)	44.87 (10.20)	57.59 (13.09)	43.26 (9.83)	267.64 (60.83)	244.48 (55.56)	313.78 (71.31)	235.71 (53.57)
6	**D-135 Kaldhar I**	306.14 (54.67)	119.90 (21.41)	90.89 (16.23)	98.27 (17.55)	68.82 (12.29)	26.95 (4.81)	20.43 (3.65)	22.09 (3.95)	374.96 (66.96)	146.85 (26.22)	111.32 (19.88)	120.37 (21.49)
7	**R-26 Nagali**	1186.67 (35.32)	436.96 (13.00)	841.07 (25.03)	1027.17 (30.57)	266.77 (7.94)	98.23 (2.92)	189.08 (5.63)	230.91 (6.87)	1453.45 (43.26)	535.20 (15.93)	1030.14 (30.66)	1258.09 (37.44)
8	**D-92 Deora**	366.19 (14.30)	438.92 (17.15)	458.16 (17.90)	558.53 (21.82)	82.32 (3.22)	98.67 (3.85)	103.00 (4.02)	125.56 (4.90)	448.51 (17.52)	537.59 (21.00)	561.16 (21.92)	684.09 (26.72)
9	**D-94 Nandal**	531.38 (63.26)	424.64 (50.55)	230.17 (27.40)	238.85 (28.44)	119.46 (14.22)	95.46 (11.36)	51.74 (6.16)	53.70 (6.39)	650.84 (77.48)	520.11 (61.92)	281.91 (33.56)	292.55 (34.83)
10	**D-89 Gadhog I**	152.09 (16.53)	102.30 (11.12)	185.64 (20.18)	379.41 (41.24)	34.19 (3.72)	23.00 (2.50)	41.73 (4.54)	85.29 (9.27)	186.28 (20.25	125.30 (13.62)	227.38 (24.71)	464.71 (50.51)
11	**D-90 Gadhog II**	344.51 (26.10)	384.33 (29.12)	282.66 (21.41)	297.07 (22.51)	77.45 (5.87)	86.40 (6.55)	63.54 (4.81)	66.78 (5.06)	421.95 (31.97)	470.73 (35.66)	346.20 (26.23)	363.85 (27.56)
12	**D-98 Bhawan Ki Dhar**	673.20 (35.06)	231.55 (12.06)	707.19 (36.83)	1042.29 (54.29)	151.34 (7.88)	52.05 (2.71)	158.98 (8.28)	234.31 (12.20)	824.54 (42.94)	283.60 (14.77)	866.17 (45.11)	1276.61 (66.49)
Dharampur Forest Range													
13	**R-36 Anji**	466.30 (44.84)	285.68 (27.47)	266.10 (25.59)	457.97 (44.04)	104.83 (10.08)	64.22 (6.18)	59.82 (5.75)	102.95 (9.90)	571.12 (54.92)	349.90 (33.64)	325.93 (31.34)	560.93 (53.94)
14	**R-49 Gadiar**	1591.45 (51.01)	652.70 (20.92)	713.08 (22.86)	894.44 (28.67)	357.77 (11.47)	146.73 (4.70)	160.30 (5.14)	201.08 (6.44)	1949.22 (62.47)	799.43 (25.62)	873.38 (27.99)	1095.51 (35.11)
15	**D-117 Chabil Ki Dhar IV**	318.95 (132.90)	78.00 (32.50)	295.74 (123.23)	290.12 (120.88)	71.70 (29.88)	17.54 (7.31)	66.48 (27.70)	65.22 (27.17)	390.65 (162.77)	95.54 (39.81)	362.23 (150.93)	355.34 (148.06)
16	**D-118 Chabil Ki Dhar III**	458.38 (44.07)	601.44 (57.83)	1363.76 (131.13)	1507.37 (144.94)	103.05 (9.91)	135.21 (13.00)	306.58 (29.48)	338.87 (32.58)	561.42 (53.98)	736.65 (70.83)	1670.34 (160.61)	1846.24 (177.52)
17	**D-164 Maltu**	459.23	222.25	515.11	569.81	103.24	49.96	115.80	128.10	562.47	272.21	630.91	697.91

	III	(29.44)	(14.25)	(33.02)	(36.53)	(6.62)	(3.20)	(7.42)	(8.21)	(36.06)	(17.45)	(40.44)	(44.74)
18	**D-181 Sirguli Ka Tiba III**	1067.56 (42.36)	644.82 (25.59)	720.77 (28.60)	839.96 (33.33)	239.99 (9.52)	144.96 (5.75)	162.03 (6.43)	188.83 (7.49)	1307.56 (51.89)	789.78 (31.34)	882.80 (35.03)	1028.79 (40.83)
19	**D-182 Kalath III**	955.58 (37.33)	368.46 (14.39)	1311.42 (51.23)	1393.34 (54.43)	214.82 (8.39)	82.83 (3.24)	294.82 (11.52)	313.23 (12.24)	1170.39 (45.72)	451.30 (17.63)	1606.24 (62.74)	1706.58 (66.66)
20	**D-172 Bhog Seri III**	228.43 (51.92)	50.26 (11.42)	124.60 (28.32)	225.07 (51.15)	51.35 (11.67)	11.30 (2.57)	28.01 (6.37)	50.60 (11.50)	279.79 (63.59)	61.56 (13.99)	152.61 (34.68)	275.67 (62.65)
21	**D-159 Anji III**	298.95 (83.04)	119.99 (33.33)	96.52 (26.81)	93.00 (25.83)	67.21 (18.67)	26.97 (7.49)	21.70 (6.03)	20.91 (5.81)	366.15 (101.71)	146.96 (40.82)	118.22 (32.84)	113.91 (31.64)
22	**D-160 Anji I**	531.16 (51.07)	355.56 (34.19)	242.35 (23.30)	244.29 (23.49)	119.41 (11.48)	79.93 (7.69)	54.48 (5.24)	54.92 (5.28)	650.57 (62.55)	435.50 (41.87)	296.83 (28.54)	299.21 (28.77)
23	**D-120 Chabil Ki Dhar I**	153.74 (42.70)	297.25 (82.57)	436.66 (121.29)	364.20 (101.17)	34.56 (9.60)	66.82 (18.56)	98.16 (27.27)	81.87 (22.74)	188.30 (52.30)	364.07 (101.13)	534.82 (148.56)	446.07 (123.91)
24	**D-150 Gulhari IV**	165.22 (37.55)	59.01 (13.41)	103.67 (23.56)	111.44 (25.33)	37.14 (8.44)	13.27 (3.01)	23.31 (5.30)	25.05 (5.69)	202.36 (45.99)	72.28 (16.43)	126.97 (28.86)	136.49 (31.02)
25	**D-152 Gulhari II**	506.67 (57.58)	96.60 (10.98)	198.45 (22.55)	198.39 (22.54)	113.90 (12.94)	21.72 (2.47)	44.61 (5.07)	44.60 (5.07)	620.58 (70.52)	118.32 (13.45)	243.07 (27.62)	242.99 (27.61)
26	**D-153 Gulhari I**	123.41 (23.73)	89.08 (17.13)	41.29 (7.94)	79.30 (15.25)	27.74 (5.34)	20.02 (3.85)	9.28 (1.79)	17.83 (3.43)	151.15 (29.07)	109.10 (20.98)	50.57 (9.73)	97.12 (18.68)
27	**D-154 Dawala**	762.95 (59.61)	197.00 (15.39)	466.11 (36.41)	642.06 (50.16)	171.52 (13.40)	44.29 (3.46)	104.78 (8.19)	144.34 (11.28)	934.46 (73.00)	241.28 (18.85)	570.89 (44.60)	786.40 (61.44)
28	**D-155 Bhallon**	196.15 (61.30)	104.37 (32.61)	116.95 (36.55)	149.17 (46.62)	44.10 (13.78)	23.46 (7.33)	26.29 (8.22)	33.53 (10.48)	240.25 (75.08)	127.83 (39.95)	143.24 (44.76)	182.71 (57.10)
29	**D-162 Maltu II**	783.43 (27.59)	231.63 (8.16)	742.44 (26.14)	774.02 (27.25)	176.12 (6.20)	52.07 (1.83)	166.91 (5.88)	174.00 (6.13)	959.55 (33.79)	283.70 (9.99)	909.35 (32.02)	948.02 (33.38)
30	**D-163 Maltu I**	315.87 (28.20)	226.82 (20.25)	448.29 (40.03)	479.94 (42.85)	71.01 (6.34)	50.99 (4.55)	100.78 (9.00)	107.89 (9.63)	386.88 (34.54)	277.81 (24.80)	549.07 (49.02)	587.84 (52.49)
31	**D-173 Bohali Ki Chali**	378.38 (36.38)	182.82 (17.58)	247.72 (23.82)	267.83 (25.75)	85.06 (8.18)	41.10 (3.95)	55.69 (5.35)	60.21 (5.79)	463.45 (44.56)	223.92 (21.53)	303.41 (29.17)	328.04 (31.54)
32	**D-176 Charoti Ki Dhar I**	1244.17 (32.74)	1066.67 (28.07)	1213.96 (31.95)	1131.72 (29.78)	279.70 (7.36)	239.79 (6.31)	272.90 (7.18)	254.42 (6.70)	1523.86 (40.10)	1306.47 (34.38)	1486.86 (39.13)	1386.14 (36.48)
33	**D-119 Chabil Ki Dhar II**	1041.87 (39.46)	435.40 (16.49)	1653.17 (62.62)	1721.01 (65.19)	234.22 (8.87)	97.88 (3.71)	371.64 (14.08)	386.89 (14.66)	1276.09 (48.34)	533.28 (20.20)	2024.81 (76.70)	2107.90 (79.84)
Total		**17070.99 (39.23)**	**9824.24 (22.57)**	**14887.36 (34.21)**	**16808.12 (38.62)**	**3837.66 (8.82)**	**2208.55 (5.07)**	**3346.77 (7.69)**	**3778.57 (8.68)**	**20908.66 (48.04)**	**12032.79 (27.65)**	**18234.13 (41.90)**	**20586.69 (47.30)**

* Figures in parenthesis denote carbon density in t ha^{-1}

In 2002 the maximum aboveground carbon density of 131.13 t ha^{-1} was found in D-118 Chabil Ki Dhar III and the minimum aboveground carbon density of 7.94 t ha^{-1} was found in D-153 Gulhari I. In 2011, D-118 Chabil Ki Dhar III recorded the maximum aboveground carbon density of 144.94 t ha^{-1} while D-97 Kiar Tatul recorded the minimum aboveground carbon density of 14.74 t ha^{-1}. The total aboveground carbon density in 1956 was 39.23 t ha^{-1}, which reduced to 22.57 t ha^{-1} in 1984, increased to 34.21 t/ha^{-1} in 2002 and further increased to 38.62 t ha^{-1} in 2011. The temporal distribution of aboveground carbon density over the period of 1956 to 2011 showed a declining trend in aboveground and belowground carbon stock over 1956-1984 period by 16.66 t ha^{-1}, an increasing trend over 1984-2002 period by 11.64 t ha^{-1} and over 2002-2011 period there was a further increase by 4.41 t ha^{-1} (Table 15).

(iii) Belowground Carbon stock (t)

In the year 1956 R-49 Gadiar had the maximum belowground carbon stock of 357.77 t and the minimum belowground carbon stock was recorded in in D-153 Gulhari I at 27.74 t. In 1984 D-176 Charoti ki Dhar had the maximum belowground carbon stock of 239.79 t and D-172 Bhog Seri III had the minimum belowground carbon stock of 11.30 t. In 2002 a maximum belowground carbon stock of 371.64 t was found in D-119 Chabil ki Dhar II and a minimum belowground carbon stock of 9.28 t in D-153 Gulhari I. In the year 2011 D-119 Chabil ki Dhar II had the maximum belowground carbon stock of 386.89 t and D-97 Kiar Tatul had the minimum belowground carbon stock of 14.58 t.

The total belowground carbon stock in 1956 was 3837.66 t, which reduced to 2208.55 t in 1984, increased to 3346.77 t in 2002 and further increased to 3778.57 t in 2011. The temporal distribution of aboveground and belowground carbon stock over the period of 1956 to 2011 showed a declining trend in belowground carbon stock over 1956-1984 period by 1629.11 t, an increasing trend over 1984-2002 period by 1138.22 t and over 2002-2011 period there was a further increase by 431.8t (Table 15).

(iv) Belowground Carbon Density (BGCD) (t ha^{-1})

In the year 1956 maximum belowground carbon density of 29.88 t ha^{-1} was present in D-117 Chabil ki Dhar IV and minimum belowground carbon density of 3.22 t $ha^{-1}$was present in D-92 Deora. In 1984 the maximum belowground carbon density of 23.30 t ha^{-1}was recorded in D-96 Nagali II and the minimum belowground carbon density of 1.83 t ha^{-1}was recorded in D- 162 Maltu II. In 2002 the maximum belowground carbon density of 29.48 t ha^{-1}was found in D-118 Chabil Ki Dhar III and the minimum belowground carbon density of 1.79 t ha^{-1}was found in D-153 Gulhari I. In 2011, D-118 Chabil Ki Dhar III recorded the maximum belowground carbon density of 32.58 t ha^{-1} while D-97 Kiar Tatul recorded the minimum belowground carbon density 3.31 t ha^{-1}.

The total belowground carbon density in 1956 was 8.82 t ha^{-1}, which reduced to 5.07 t ha^{-1} in 1984, increased to 7.69 t ha^{-1} in 2002 and further increased to 8.68 t ha^{-1} in 2011. The temporal distribution of belowground carbon density over the period of 1956 to 2011 showed a declining trend by 3.75 t ha^{-1}, an increasing trend over 1984-2002 period by 2.62 t ha^{-1}and over 2002-2011 period there was a further increase by 0.99 t ha^{-1} Table 15.

(v) Tree Carbon (above and below) (t)

The tree carbon (above+below) in 1956 was 20908.66 t (17070.99 t- aboveground , 3837.66 t- belowground), which reduced to 12032.79 t (9824.24 t- aboveground, 2208.55 t- belowground) in 1984, increased to 18234.13 t (14887.36 t- aboveground, 3346.77 t- belowground) in 2002 and further increased to 20586.69 t (16808.12 t- aboveground , 3778.57 t- belowground) in 2011 (Fig. 29). The temporal distribution of tree carbon over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 8875.87 t, an increasing trend over 1984-2002 period by 6201.34 t and over 2002-2011 period there was a further increase by 2352.56 t (Table 15).

(vi) Tree Carbon Density (above and below) (t ha^{-1})

The tree carbon density (above+below) in 1956 was 48.04 t ha^{-1}, which reduced to 27.65 t ha^{-1} in 1984, increased to 41.90 t ha^{-1} in 2002 and further increased to 47.30 t ha^{-1} in 2011. The temporal distribution of tree carbon density over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 20.39 t ha^{-1}, an increasing trend over 1984-2002 period by 14.25 t ha^{-1} and over 2002-2011 period there was a further increase by 5.4 t ha^{-1} (Table 15).

Table 16. Soil pH and Electrical Conductivity (dSm^{-1}) in Solan and Dharampur Forest Range

S.No	Name of the Forest	pH					EC (dSm^{-1})				
		Humus	0-20	20-40	40-100	Mean	Humus	0-20	20-40	40-100	Mean
1	D-93 Nandal Nagali	5.12	5.91	5.97	6.15	**5.94**	0.17	0.15	0.07	0.04	**0.11**
2	D-95 Nagali I	6.01	6.35	6.45	6.69	**6.40**	0.18	0.17	0.09	0.05	**0.13**
3	D-96 Nagali II	5.21	5.81	5.87	5.98	**5.84**	0.16	0.14	0.05	0.04	**0.10**
4	D-97Kiar Tatul	5.34	5.94	6.05	6.19	**6.00**	0.18	0.15	0.07	0.06	**0.11**
5	D-123 Beola	6.09	6.38	6.49	6.67	**6.44**	0.21	0.20	0.10	0.08	**0.15**
6	D-135 Kaldhar I	6.15	6.92	7.01	7.12	**6.97**	0.24	0.21	0.11	0.07	**0.16**
7	R-26 Nagali	5.19	5.97	6.11	6.45	**6.04**	0.18	0.16	0.08	0.04	**0.12**
8	D-92 Deora	6.12	6.64	6.72	6.89	**6.68**	0.23	0.21	0.12	0.09	**0.17**
9	D-94 Nandal	6.02	6.23	6.32	6.56	**6.28**	0.19	0.17	0.07	0.05	**0.12**
10	D-89 Gadhog I	6.67	7.00	7.09	7.26	**7.05**	0.22	0.21	0.11	0.07	**0.16**
11	D-90 Gadhog II	6.11	6.87	7.02	7.11	**6.95**	0.23	0.21	0.13	0.09	**0.18**
12	D-98 Bhawan Ki Dhar	5.89	6.20	6.28	6.35	**6.24**	0.19	0.16	0.07	0.04	**0.12**
13	R-36 Anji	6.05	6.64	6.71	6.92	**6.68**	0.22	0.20	0.11	0.07	**0.16**
14	R-49 Gadiar	5.91	6.21	6.30	6.64	**6.26**	0.19	0.17	0.08	0.05	**0.13**
15	D-117 Chabil Ki Dhar IV	5.22	5.87	5.93	6.13	**5.90**	0.18	0.17	0.11	0.09	**0.14**
16	D-118 Chabil Ki Dhar III	6.05	6.46	6.53	6.72	**6.50**	0.20	0.19	0.09	0.06	**0.14**
17	D-164 Maltoo III	5.87	6.33	6.43	6.68	**6.38**	0.19	0.17	0.08	0.05	**0.13**
18	D-181 Sirguli Ka Tiba III	5.18	5.76	5.81	5.99	**5.79**	0.15	0.13	0.04	0.03	**0.09**
19	D-182 Kalath III	6.09	6.40	6.51	6.72	**6.46**	0.19	0.18	0.09	0.07	**0.14**
20	D-172 Bhog Seri III	5.21	5.78	5.85	6.10	**5.82**	0.16	0.13	0.05	0.04	**0.09**
21	D-159 Anji III	6.13	6.67	6.75	7.02	**6.71**	0.24	0.22	0.12	0.09	**0.17**
22	D-160 Anji I	5.92	6.31	6.39	6.74	**6.35**	0.20	0.18	0.08	0.05	**0.13**
23	D-120 Chabil Ki Dhar I	5.78	6.35	6.44	6.67	**6.40**	0.22	0.18	0.07	0.05	**0.13**
24	D-150 Gulhari IV	6.12	6.79	7.01	7.11	**6.90**	0.23	0.21	0.10	0.09	**0.16**
25	D-152 Gulhari II	6.09	6.75	6.82	7.02	**6.79**	0.22	0.20	0.12	0.08	**0.16**
26	D-153 Gulhari I	6.16	6.72	6.82	6.93	**6.77**	0.23	0.21	0.11	0.08	**0.16**
27	D-154 Dawala	5.91	6.50	6.56	6.81	**6.53**	0.20	0.19	0.10	0.07	**0.15**
28	D-155 Bhallon	6.17	6.43	6.50	6.77	**6.47**	0.19	0.18	0.09	0.06	**0.14**
29	D-162 Maltu II	5.87	6.58	6.65	6.92	**6.62**	0.23	0.20	0.11	0.09	**0.16**
30	D-163 Maltu I	6.21	6.60	6.68	6.79	**6.64**	0.21	0.20	0.10	0.07	**0.15**
31	D-173 Bohali Ki Chali	5.77	6.51	6.62	6.89	**6.57**	0.22	0.19	0.10	0.06	**0.15**
32	D-176 Charoti Ki Dhar I	5.69	6.37	6.47	6.91	**6.42**	0.19	0.18	0.09	0.05	**0.14**
33	D-119 Chabil Ki Dhar II	5.34	5.84	5.90	6.19	**5.87**	0.17	0.15	0.06	0.04	**0.11**

Table 17. Soil Organic Carbon (%) and Bulk Density (gcm^{-3}) in Solan and Dharampur Forest Range

S.No	Name of the Forest	% Organic Carbon					Bulk Density (gcm^{-3})				
		Humus	0-20	20-40	40-100	Mean	Humus	0-20	20-40	40-100	Mean
Solan Forest Range											
1	**D-93 Nandal Nagali**	11.18	2.35	2.12	1.19	**4.21**	0.61	1.14	1.19	1.21	**1.04**
2	**D-95 Nagali I**	11.10	2.24	1.77	1.16	**4.07**	0.66	1.21	1.25	1.27	**1.10**
3	**D-96 Nagali II**	11.37	2.47	2.18	1.22	**4.31**	0.60	1.08	1.13	1.16	**0.99**
4	**D-97Kiar Tatul**	11.25	2.30	2.10	1.20	**4.21**	0.62	1.16	1.20	1.23	**1.05**
5	**D-123 Beola**	11.11	2.22	1.88	1.14	**4.09**	0.67	1.23	1.29	1.32	**1.13**
6	**D-135 Kaldhar I**	10.86	1.30	1.09	1.01	**3.57**	0.81	1.33	1.40	1.44	**1.25**
7	**R-26 Nagali**	11.24	2.28	1.98	1.18	**4.17**	0.64	1.17	1.22	1.26	**1.07**
8	**D-92 Deora**	10.87	1.58	1.21	1.10	**3.69**	0.80	1.31	1.38	1.43	**1.23**
9	**D-94 Nandal**	11.19	2.26	1.88	1.18	**4.13**	0.63	1.19	1.23	1.26	**1.08**
10	**D-89 Gadhog I**	10.77	1.24	1.08	1.04	**3.53**	0.82	1.36	1.42	1.45	**1.26**
11	**D-90 Gadhog II**	10.80	1.30	1.11	1.08	**3.57**	0.81	1.35	1.41	1.44	**1.25**
12	**D-98 Bhawan Ki Dhar**	11.21	2.26	1.87	1.20	**4.14**	0.67	1.20	1.25	1.27	**1.10**
Dharampur Forest Range											
13	**R-36 Anji**	10.91	1.59	1.24	1.11	**3.71**	0.82	1.30	1.36	1.38	**1.22**
14	**R-49 Gadiar**	11.07	2.26	1.93	1.13	**4.10**	0.70	1.21	1.25	1.27	**1.11**
15	**D-117 Chabil Ki Dhar IV**	11.32	2.40	2.13	1.21	**4.27**	0.62	1.11	1.17	1.19	**1.02**
16	**D-118 Chabil Ki Dhar III**	10.87	2.17	1.69	1.17	**3.98**	0.68	1.21	1.27	1.28	**1.11**
17	**D-164 Maltoo III**	11.14	2.23	1.77	1.20	**4.09**	0.69	1.23	1.29	1.33	**1.14**
18	**D-181 Sirguli Ka Tiba III**	11.47	2.49	2.27	1.24	**4.37**	0.62	1.01	1.05	1.10	**0.95**
19	**D-182 Kalath III**	11.04	2.21	1.74	1.19	**4.05**	0.68	1.23	1.31	1.34	**1.14**
20	**D-172 Bhog Seri III**	11.27	2.47	2.13	1.23	**4.28**	0.65	1.07	1.13	1.17	**1.01**
21	**D-159 Anji III**	10.80	1.56	1.20	1.07	**3.66**	0.79	1.30	1.37	1.39	**1.21**
22	**D-160 Anji I**	11.10	2.26	1.80	1.18	**4.09**	0.68	1.22	1.29	1.31	**1.13**
23	**D-120 Chabil Ki Dhar I**	11.21	2.25	1.76	1.16	**4.10**	0.70	1.24	1.31	1.33	**1.15**
24	**D-150 Gulhari IV**	10.79	1.36	1.13	1.05	**3.58**	0.80	1.33	1.38	1.41	**1.23**
25	**D-152 Gulhari II**	10.82	1.43	1.16	1.09	**3.63**	0.81	1.33	1.39	1.41	**1.24**
26	**D-153 Gulhari I**	10.80	1.45	1.18	1.10	**3.63**	0.77	1.30	1.36	1.38	**1.20**
27	**D-154 Dawala**	11.10	2.09	1.67	1.14	**4.00**	0.76	1.27	1.35	1.39	**1.19**
28	**D-155 Bhallon**	11.25	2.23	1.74	1.18	**4.10**	0.73	1.25	1.36	1.41	**1.19**
29	**D-162 Maltu II**	10.89	1.76	1.32	1.11	**3.77**	0.76	1.28	1.35	1.36	**1.19**
30	**D-163 Maltu I**	10.87	1.75	1.29	1.09	**3.75**	0.77	1.27	1.33	1.34	**1.18**
31	**D-173 Bohali Ki Chali**	11.10	2.05	1.61	1.19	**3.99**	0.71	1.23	1.29	1.31	**1.14**
32	**D-176 Charoti Ki Dhar I**	11.31	2.25	1.75	1.17	**4.12**	0.69	1.21	1.26	1.29	**1.11**
33	**D-119 Chabil Ki Dhar II**	11.42	2.44	2.17	1.21	**4.31**	0.67	1.09	1.15	1.18	**1.02**

Table 18. Soil Carbon Stock in Solan and Dharampur Forest Range

S.No	Name of the Forest	Elevation (m)	Area (ha)	Soil Carbon Stock (t)					Total {Humus+Soil (0-100cm)}
				Humus	0-20	20-40	40-100	0-100cm	
Solan Forest Range									
1	**D-93 Nandal Nagali**	1250-1350	12.4	93.87 (7.57)	664.39 (53.58)	625.65 (50.46)	1071.29 (86.39)	2361.33 (190.43)	**2455.20 (198.00)**
2	**D-95 Nagali I**	1350-1420	3.6	26.11 (7.25)	195.15 (54.21)	159.30 (44.25)	318.21 (88.39)	672.66 (186.85)	**698.77 (194.10)**
3	**D-96 Nagali II**	1240-1345	4.0	29.74 (7.44)	213.41 (53.35)	197.07 (49.27)	339.65 (84.91)	750.13 (187.53)	**779.87 (194.97)**
4	**D-97Kiar Tatul**	1260-1350	4.4	33.15 (7.53)	234.78 (53.36)	221.76 (50.40)	389.66 (88.56)	846.21 (192.32)	**879.35 (199.85)**
5	**D-123 Beola**	1350-1420	4.4	36.36 (8.26)	240.29 (54.61)	213.42 (48.50)	397.27 (90.29)	850.98 (193.40)	**887.33 (201.67)**
6	**D-135 Kaldhar I**	1550-1775	5.6	47.78 (8.53)	193.65 (34.58)	170.91 (30.52)	488.68 (87.26)	853.24 (152.36)	**901.02 (160.90)**
7	**R-26 Nagali**	1250-1400	33.6	256.21 (7.63)	1792.63 (53.35)	1623.28 (48.31)	2997.39 (89.21)	6413.30 (190.87)	**6669.51 (198.50)**
8	**D-92 Deora**	1400-1585	25.6	215.94 (8.44)	1059.74 (41.40)	854.94 (33.40)	2416.13 (94.38)	4330.80 (169.17)	**4546.74 (177.61)**
9	**D-94 Nandal**	1280-1380	8.4	63.95 (7.61)	451.82 (53.79)	388.48 (46.25)	749.35 (89.21)	1589.65 (189.24)	**1653.60 (196.86)**
10	**D-89 Gadhog I**	1800-1940	9.2	79.62 (8.65)	310.30 (33.73)	282.18 (30.67)	832.42 (90.48)	1424.90 (154.88)	**1504.52 (163.53)**
11	**D-90 Gadhog II**	1580-1750	13.2	127.02 (9.62)	463.32 (35.10)	413.19 (31.30)	1231.72 (93.31)	2108.22 (159.71)	**2235.25 (169.34)**
12	**D-98 Bhawan Ki Dhar**	1280-1380	19.2	154.30 (8.04)	1041.41 (54.24)	897.60 (46.75)	1755.65 (91.44)	3694.66 (192.43)	**3848.96 (200.47)**
Dharampur Forest Range									
13	**R-36 Anji**	1400-1556	10.40	89.32 (8.59)	429.94 (41.34)	350.77 (33.73)	955.84 (91.91)	1736.55 (166.98)	**1825.87 (175.56)**
14	**R-49 Gadiar**	1200-1450	31.20	251.44 (8.06)	1706.39 (54.69)	1505.40 (48.25)	2686.51 (86.11)	5898.30 (189.05)	**6149.74 (197.11)**
15	**D-117 Chabil Ki Dhar IV**	1250-1338	2.40	18.87 (7.86)	127.87 (53.28)	119.62 (49.84)	207.35 (86.39)	454.84 (189.52)	**473.70 (197.38)**
16	**D-118 Chabil Ki Dhar III**	1270-1530	10.40	69.95 (6.73)	546.15 (52.51)	446.43 (42.93)	934.50 (89.86)	1927.08 (185.30)	**1997.03 (192.02)**
17	**D-164 Maltoo III**	1280-1460	15.60	129.50 (8.30)	855.78 (54.86)	712.39 (45.67)	1493.86 (95.76)	3062.03 (196.28)	**3191.53 (204.59)**
18	**D-181 Sirguli Ka Tiba III**	1170-1290	25.20	198.92 (7.89)	1267.51 (50.30)	1201.28 (47.67)	2062.37 (81.84)	4531.16 (179.81)	**4730.08 (187.70)**
19	**D-182 Kalath III**	1225-1450	25.60	182.58	1391.77	1167.05	2449.31	5008.13	**5190.70**

				(7.13)	(54.37)	(45.59)	(95.68)	(195.63)	**(202.76)**
20	**D-172 Bhog Seri III**	1180-1300	4.40	36.10 (8.20)	232.58 (52.86)	211.81 (48.14)	379.92 (86.35)	824.30 (187.34)	**860.40** **(195.55)**
21	**D-159 Anji III**	1440-1520	3.60	29.18 (8.11)	146.02 (40.56)	118.37 (32.88)	321.26 (89.24)	585.64 (162.68)	**614.82** **(170.78)**
22	**D-160 Anji I**	1280-1420	10.40	85.56 (8.23)	573.50 (55.14)	482.98 (46.44)	964.58 (92.75)	2021.05 (194.33)	**2106.62** **(202.56)**
23	**D-120 Chabil Ki Dhar I**	1300-1420	3.60	30.23 (8.40)	200.88 (55.80)	166.00 (46.11)	333.24 (92.57)	700.13 (194.48)	**730.35** **(202.88)**
24	**D-150 Gulhari IV**	1575-1650	4.40	40.26 (9.15)	159.17 (36.18)	137.23 (31.19)	390.85 (88.83)	687.25 (156.19)	**727.51** **(165.34)**
25	**D-152 Gulhari II**	1500-1600	8.80	70.99 (8.07)	334.73 (38.04)	283.78 (32.25)	811.48 (92.21)	1430.00 (162.50)	**1500.99** **(170.57)**
26	**D-153 Gulhari I**	1450-1600	5.20	47.14 (9.06)	196.04 (37.70)	166.90 (32.10)	473.62 (91.08)	836.56 (160.88)	**883.69** **(169.94)**
27	**D-154 Dawala**	1350-1500	12.80	105.82 (8.27)	679.50 (53.09)	577.15 (45.09)	1216.97 (95.08)	2473.63 (193.25)	**2579.45** **(201.52)**
28	**D-155 Bhallon**	1360-1400	3.20	26.54 (8.29)	178.40 (55.75)	151.45 (47.33)	319.45 (99.83)	649.30 (202.91)	**675.84** **(211.20)**
29	**D-162 Maltu II**	1300-1600	28.40	218.60 (7.70)	1279.59 (45.06)	1012.18 (35.64)	2572.36 (90.58)	4864.12 (171.27)	**5082.72** **(178.97)**
30	**D-163 Maltu I**	1420-1480	11.20	103.12 (9.21)	497.84 (44.45)	384.32 (34.31)	981.52 (87.64)	1863.68 (166.40)	**1966.80** **(175.61)**
31	**D-173 Bohali Ki Chali**	1350-1480	10.40	87.70 (8.43)	524.47 (50.43)	432.00 (41.54)	972.75 (93.53)	1929.22 (185.50)	**2016.92** **(193.93)**
32	**D-176 Charoti Ki Dhar I**	1250-1450	38.00	317.31 (8.35)	2069.10 (54.45)	1675.80 (44.10)	3441.20 (90.56)	7186.10 (189.11)	**7503.41** **(197.46)**
33	**D-119 Chabil Ki Dhar II**	1220-1350	26.40	224.22 (8.49)	1404.27 (53.19)	1317.62 (49.91)	2261.64 (85.67)	4983.53 (188.77)	**5207.74** **(197.26)**
Total				**3527.38** **(8.15)**	**21662.38** **(48.77)**	**18668.31** **(42.14)**	**39217.98** **(90.22)**	**79548.68** **(181.13)**	**83076.05** **(189.29)**

* Figures in parenthesis denote carbon density in t ha^{-1}

4.2.2 Carbon status of Solan and Dharampur Ranges of Solan Forest Division in 2011

(A) Soil Organic Carbon Stock

(i) Soil physico-chemical properties

The general physico-chemical characteristics of the soils recorded during the course of the investigation are presented below.

(a) Soil pH

A perusal of the data presented in Table 16 shows that in the humus layer, the soil pH ranged from 5.12 to 6.67, with the minimum pH at D-93 Nandal Nagali (5.12) and the maximum at D-89 Gadhog I (6.67). At 0-20 cm depth the soil pH ranged from 5.76 to 7.00, with the minimum soil pH at D-181 Sirguli Ka Tiba III (5.76) and the maximum at D-89 Gadhog I (7.00). At 20-40 cm depth the pH ranged from 5.81 to 7.09, with D-181 Sirguli Ka Tiba III having the minimum soil pH (5.81) and the maximum at D-89 Gadhog I (7.09). At 40-100 cm depth the ranged from 5.98 to 7.26, with the minimum at D-96 Nagali II (5.98) and the maximum at D-89 Gadhog I (7.26). The mean soil pH was minimum at D-181 Sirguli Ka Tiba III which was 5.79 and maximum at D-89 Gadhog I which was7.05. In general the soil pH increased with increasing soil depth.

(b) Soil Electrical Conductivity (EC)

The soil EC (Table 16) ranged from 0.15 to 0.24 dSm^{-1} in the humus layer with the minimum at D-181 Sirguli Ka Tiba III (0.15 dSm^{-1}) and the maximum at D-135 Kaldhar I (0.24 dSm^{-1}). At a depth of 0-20 cm the EC ranged from 0.13 to 0.22 with the minimum at D-172 Bhog Seri III (0.13) and the maximum at D-159 Anji III (0.22). At 20-40 cm depth the soil EC ranged from 0.04 to 0.13 dSm^{-1} with the minimum at D-181 Sirguli Ka Tiba III (0.04 dSm^{-1}) and the maximum at D-90 Gadhog II (0.13 dSm^{-1}) while at a depth of 40-100 cm the EC ranged from 0.03 to 0.10 $dSm^{-1}$with the minimum at D-181 Sirguli Ka Tiba III and maximum at D-90 Gadhog II (0.10 dSm^{-1}). The mean soil EC was minimum at D-181 Sirguli Ka Tiba III (0.09 dSm^{-1}) and the maximum at D-90 Gadhog II (0.18 dSm^{-1}). In general the soil EC decreased with increasing depth.

(c) Soil Organic Carbon (%)

The soil organic carbon (%) (Table 17) ranged from 10.79 % to 11.47 % in the humus layer with the minimum at D-150 Gulhari IV (10.79 %) and the maximum at D-181 Sirguli Ka Tiba III (11.47 %). At a depth of 0 to 20 cm the soil organic carbon (%) ranged from 1.24 % to 2.47 % with the minimum at D-89 Gadhog I (1.24 %) and maximum at D-96 Nagali II (2.47 %). At 20 to 40 cm soil depth the soil organic carbon (%) ranged from 1.08 % to 2.27 % with the minimum at D-89 Gadhog I (1.08 %) and maximum at D-181 Sirguli Ka Tiba III (2.27 %) while at 40 to 100 cm depth the soil organic carbon (%) had a range from 1.01 % to 1.24 % with D-135 Kaldhar I recording the minimum (1.01 %) and D-181 Sirguli Ka Tiba III recording the maximum soil organic carbon (%) (2.24 %). The mean soil organic carbon (%) was the minimum at D-89 Gadhog I (3.53 %) and the maximum at D-181 Sirguli Ka Tiba III (4.37 %). It was found that the soil organic carbon (%) decreased with increasing soil depth. There was also a decrease in soil organic carbon (%) with an increase in elevation.

(d) Soil Bulk Density

The soil bulk density (Table 17) ranged from 0.60 to 0.82 gcm^{-3}, with the minimum at D-96 Nagali II (0.60 gcm^{-3}) and maximum at D-89 Gadhog I (0.82 gcm^{-3}) in the humus layer while at a depth of 0 to 20 cm it ranged from 1.01 to 1.36 gcm^{-3}, with the minimum at D-181 Sirguli Ka Tiba III (1.01 gcm^{-3}) and the maximum at D-89 Gadhog I (1.36 gcm^{-3}). At a depth of 20 to 40 cm it ranged from 1.05 to 1.42 gcm^{-3} with the minimum at D-181 Sirguli Ka Tiba III (1.05 gcm^{-3}) and maximum at D-89 Gadhog I (1.42 gcm^{-3}). At 40 to 100 cm soil depth the soil bulk density ranged from 1.10 to 1.45 gcm^{-3} with the minimum at D-181 Sirguli Ka Tiba III (1.10 gcm^{-3}) and maximum at D-89 Gadhog I (1.45 gcm^{-3}). The mean soil bulk density was the minimum at D-181 Sirguli Ka Tiba III (0.95 gcm^{-3}) and the maximum at D-89 Gadhog I (1.26 gcm^{-3}). It was found that the soil bulk density increased with increasing soil depth.

(ii) Soil Carbon Status

(a) Soil Carbon Stock (t)

The soil carbon stock (Table 18) ranged from 18.87 to 317.31 t in the humus layer, from 127.87 to 2069.10 t at a depth of 0 to 20 cm, from 118.37 to 1675.80 t at 20 to 40 cm depth and from 207.35 to 3441.20 t at 40 to 100 cm soil depth. Minimum carbon stock in the humus layer was reported at D-117 Chabil Ki Dhar IV (18.87 t) and maximum at D-176 Charoti Ki Dhar I (317.31 t). At a depth of 0 to 20 cm minimum carbon stock was present at D-117 Chabil Ki Dhar IV (127.87 t) and maximum was present at D-176 Charoti Ki Dhar I (2069.10 t). At a depth of 20 to 40 cm minimum carbon stock was recorded at D-159 Anji III (118.37 t) and maximum at D-176 Charoti Ki Dhar I (1675.80 t) while at 40 to 100 cm soil depth D-117 Chabil Ki Dhar IV recorded a minimum soil carbon stock of 207.35 t and D-176 Charoti Ki Dhar I again recorded a maximum carbon stock of 3441.20 t. Soil carbon stock in 0 to 100 cm layer was minimum at D-117 Chabil Ki Dhar IV (454.84 t) and the maximum at D-176 Charoti Ki Dhar I (7186.10 t). Total soil carbon stock {Humus + Soil (0-100cm layer)} was minimum at D-117 Chabil Ki Dhar IV (473.70 t) and maximum at D-176 Charoti Ki Dhar I (7503.41 t). Total soil carbon stock was 3527.38 t in humus, 21662.38 t in 0-20 cm layer, 18668.31 t in 20-40 cm layer, 39217.98 t in 40-100 cm layer (Fig. 30) and in 0-100 cm soil depth it was found to be 79548.68 t. in {Humus + Soil (0-100cm layer)}it was reported as 83076.05 t.

(b) Soil Carbon Density (tha^{-1})

Data presented in Table 18 shows that the soil carbon density ranged from 6.73 to 9.62 t ha^{-1} at the humus layer, from 33.73 to 55.80 t ha^{-1} at a depth of 0 to 20 cm, from 30.52 to 50.46 t ha^{-1} at 20 to 40 cm depth and from 81.84 to 99.83 t ha^{-1} at 40 to 100 cm soil depth. Minimum soil carbon density in the humus layer was reported at D-118 Chabil Ki Dhar III (6.73 t ha^{-1}) and maximum at D-90 Gadhog II (9.62 t ha^{-1}). At a depth of 0 to 20 cm minimum soil carbon density was present at D-89 Gadhog I (33.73 t ha^{-1}) and maximum was present at D-120 Chabil Ki Dhar I (55.80 t ha^{-1}). At a depth of 20 to 40 cm minimum soil carbon density was recorded at D-135 Kaldhar I (30.52 t ha^{-1}) and maximum at D-93

Nandal Nagali (50.46 t ha^{-1}) while at 40 to 100 cm soil depth D-181 Sirguli Ka Tiba III recorded a minimum soil carbon density of 81.84 t ha^{-1} and D-155 Bhallon again recorded a maximum soil carbon density of 99.83 t ha^{-1}. Soil carbon density in 0 to 100 cm layer was minimum at D-135 Kaldhar I (152.36 t ha^{-1}) and the maximum at D-164 Maltoo III (196.28 t ha^{-1}). Total soil carbon density {Humus+Soil (0-100cm layer)} was minimum at D-135 Kaldhar I (160.90 t ha^{-1}) and maximum at D-155 Bhallon (211.20 t ha^{-1}). Soil carbon density was 8.15 tha^{-1} in humus, 48.77 t ha^{-1} in 0-20 cm layer, 42.14 t ha^{-1} in 20-40 cm layer, 90.22 t ha^{-1} in 40-100 cm layer, 181.13 t ha^{-1} in 0-100 cm soil depth. In {Humus + Soil (0-100cm layer)} it was reported as 189.29 t ha^{-1} (Table 18).

(B) Standing vegetation Carbon Status

(i) Standing vegetation Carbon Stock (t)

(a) Tree

Table 19, gives the carbon stock of selected sample plots in 2011. The carbon stock of the forest trees was the minimum at D-97 Kiar Tatul (79.42 t) which was distributed in the stem, branches, leaves and root as 50.26, 12.06 , 2.51 and 14.58 t respectively. Maximum tree carbon stock was recorded at D-119 Chabil Ki Dhar II (2107.90 t), distributed in the stem, branches, leaves and root as 1334.12, 320.19, 66.71 and 386.89 t respectively. The total tree carbon stock was 20586.69 t, with 13029.60 t in stem, 3127.07 t in branch, 651.49 t in leaf and 3778.55 t in root (Fig. 30).

(b) Herb

The carbon stock of herbs was the minimum at D-150 Gulhari IV (4.44 t) which was 2.00 and 2.44 t in the aboveground and belowground components respectively while the maximum carbon stock was recorded at R-49 Gadiar (110.76 t), distributed in the aboveground and belowground components as 47.89 and 62.87 t respectively. Total herb carbon stock was 909.22 t with 425.97 t in shoot and 483.26 t in root (Table 19).

Table 19. Total carbon stock of selected sample plots in 2011

S.No	Name of the Forest	Area (ha)	Carbon (t)											
			Trees					Herbs			Shrubs			Vegetation Carbon Stock (t)
			Stem	Branch	Leaf	Root	Total	Shoot	Root	Total	Shoot	Root	Total	
Solan Forest Range														
1	**D-93 Nandal Nagali**	12.4	202.14 (16.30)	48.51 (3.91)	10.11 (0.82)	58.62 (4.73)	**319.39 (25.76)**	14.94 (1.21)	16.37 (1.32)	**31.31 (2.53)**	4.15 (0.34)	6.94 (0.56)	**11.10 (0.90)**	**361.80 (29.18)**
2	**D-95 Nagali I**	3.6	106.23 (29.51)	25.50 (7.08)	5.31 (1.48)	30.81 (8.56)	**167.84 (46.62)**	3.47 (0.97)	3.85 (1.07)	**7.33 (2.04)**	4.99 (1.39)	3.37 (0.94)	**8.35 (2.32)**	**183.52 (50.98)**
3	**D-96 Nagali II**	4.0	59.67 (14.92)	14.32 (3.58)	2.98 (0.75)	17.30 (4.33)	**94.28 (23.57)**	5.36 (1.34)	6.30 (1.58)	**11.66 (2.92)**	2.14 (0.54)	1.84 (0.46)	**3.98 (1.00)**	**109.92 (27.48)**
4	**D-97 Kiar Tatul**	4.4	**50.26** (11.42)	12.06 (2.74)	2.51 (0.57)	14.58 (3.31)	**79.42 (18.05)**	5.68 (1.29)	5.28 (1.20)	**10.96 (2.49)**	2.46 (0.56)	2.73 (0.62)	**5.19 (1.18)**	**95.57 (21.72)**
5	**D-123 Beola**	4.4	149.19 (33.91)	35.80 (8.14)	7.46 (1.70)	43.26 (9.83)	**235.71 (53.57)**	4.16 (0.95)	4.95 (1.13)	**9.11 (2.07)**	5.74 (1.31)	5.35 (1.22)	**11.09 (2.52)**	**255.91 (58.16)**
6	**D-135 Kaldhar I**	5.6	76.18 (13.60)	18.28 (3.26)	3.81 (0.68)	22.09 (3.95)	**120.37 (21.49)**	2.44 (0.44)	2.74 (0.49)	**5.18 (0.93)**	10.89 (1.95)	8.71 (1.56)	**19.60 (3.50)**	**145.15 (25.92)**
7	**R-26 Nagali**	33.6	796.26 (23.70)	191.10 (5.69)	39.81 (1.18)	230.91 (6.87)	**1258.09 (37.44)**	35.45 (1.06)	37.97 (1.13)	**73.42 (2.19)**	14.78 (0.44)	17.14 (0.51)	**31.92 (0.95)**	**1363.43 (40.58)**
8	**D-92 Deora**	25.6	432.97 (16.91)	103.91 (4.06)	21.65 (0.85)	125.56 (4.90)	**684.09 (26.72)**	12.42 (0.49)	20.86 (0.82)	**33.28 (1.30)**	29.70 (1.16)	39.55 (1.55)	**69.25 (2.71)**	**786.62 (30.73)**
9	**D-94 Nandal**	8.4	185.16 (22.04)	44.44 (5.29)	9.26 (1.10)	53.70 (6.39)	**292.55 (34.83)**	10.21 (1.22)	11.13 (1.33)	**21.34 (2.54)**	5.67 (0.68)	7.05 (0.84)	**12.72 (1.51)**	**326.61 (38.88)**
10	**D-89 Gadhog I**	9.2	294.12 (31.97)	70.59 (7.67)	14.71 (1.60)	85.29 (9.27)	**464.71 (50.51)**	2.71 (0.30)	4.65 (0.51)	**7.36 (0.80)**	21.67 (2.36)	13.39 (1.46)	**35.05 (3.81)**	**507.12 (55.12)**
11	**D-90 Gadhog II**	13.2	230.29 (17.45)	55.27 (4.19)	11.51 (0.87)	66.78 (5.06)	**363.85 (27.56)**	4.09 (0.31)	5.81 **(0.44)**	**9.90 (0.75)**	25.54 (1.94)	19.21 (1.46)	**44.75 (3.39)**	**418.5 (31.70)**
12	**D-98 Bhawan Ki Dhar**	19.2	807.98 (42.08)	193.92 (10.10)	40.40 (2.10)	234.31 (12.20)	**1276.61 (66.49)**	22.18 (1.16)	23.71 (1.24)	**45.89 (2.39)**	11.62 (0.61)	13.54 (0.71)	**25.15 (1.31)**	**1347.65 (70.19)**
Dharampur Forest Range														
13	**R-36 Anji**	10.40	355.02 (34.14)	85.20 (8.19)	17.75 (1.71)	102.95 (9.90)	**560.93 (53.94)**	4.58 (0.44)	4.73 (0.46)	**9.31 (0.90)**	16.80 (1.62)	13.31 (1.28)	**30.11 (2.90)**	**600.35 (57.73)**
14	**R-49 Gadiar**	31.20	693.36 (22.22)	166.41 (5.33)	34.67 (1.11)	201.08 (6.44)	**1095.51 (35.11)**	47.89 (1.54)	62.87 (2.02)	**110.76 (3.55)**	12.64 (0.41)	22.62 (0.73)	**35.26 (1.13)**	**1241.53 (39.79)**
15	**D-117 Chabil Ki Dhar IV**	2.40	224.90 (93.71)	53.98 (22.49)	11.24 (4.69)	65.22 (27.17)	**355.34 (148.06)**	3.20 (1.34)	3.76 (1.57)	**6.96 (2.90)**	0.83 (0.35)	1.19 (0.50)	**2.02 (0.84)**	**364.32 (151.80)**
16	**D-118 Chabil Ki Dhar III**	10.40	1168.50 (112.36)	280.44 (26.97)	58.43 (5.62)	338.87 (32.58)	**1846.24 (177.52)**	9.41 (0.91)	10.76 (1.04)	**20.18 (1.94)**	12.43 (1.20)	9.93 (0.96)	**22.36 (2.15)**	**1888.78 (181.61)**
17	**D-164 Maltu III**	15.60	441.71 (28.31)	106.01 (6.80)	22.09 (1.42)	128.10 (8.21)	**697.91 (44.74)**	13.88 (0.89)	16.38 (1.05)	**30.26 (1.94)**	6.79 (0.44)	9.67 (0.62)	**16.46 (1.06)**	**744.63 (47.73)**

18	**D-181 Sirguli Ka Tiba III**	25.20	651.13 (25.84)	156.27 (6.20)	32.56 (1.29)	188.83 (7.49)	**1028.79 (40.83)**	40.45 (1.61)	36.16 (1.44)	**76.61 (3.04)**	6.93 **(0.28)**	9.83 (0.39)	**16.76 (0.67)**	**1122.16 (44.53)**
19	**D 182 Kalath III**	25.60	1080.11 (42.19)	259.23 (10.13)	54.01 (2.11)	313.23 (12.24)	**1706.58 (66.66)**	29.70 (1.16)	32.77 (1.28)	**62.46 (2.44)**	14.72 (0.58)	17.15 (0.67)	**31.87 (1.25)**	**1800.91 (70.35)**
20	**D-172 Bhog Seri III**	4.40	174.47 (39.65)	41.87 (9.52)	8.72 (1.98)	50.60 (11.50)	**275.67 (62.65)**	6.86 (1.56)	7.52 **(1.71)**	**14.39 (3.27)**	2.40 (0.55)	1.47 **(0.34)**	**3.87 (0.88)**	**293.93 (66.80)**
21	**D-159 Anji III**	3.60	72.09 (20.03)	17.30 (4.81)	3.60 (1.00)	20.91 (5.81)	**113.91 (31.64)**	2.11 (0.59)	3.20 (0.89)	**5.31 (1.48)**	5.54 (1.54)	3.94 (1.10)	**9.49 (2.64)**	**128.71 (35.75)**
22	**D-160 Anji I**	10.40	189.37 (18.21)	45.45 (4.37)	9.47 (0.91)	54.92 (5.28)	**299.21 (28.77)**	11.39 (1.10)	12.01 (1.16)	**23.40 (2.25)**	8.11 (0.78)	9.72 (0.94)	**17.84 (1.72)**	**340.45 (32.74)**
23	**D-120 Chabil Ki Dhar I**	3.60	282.33 (78.42)	67.76 (18.82)	14.12 (3.92)	81.87 (22.74)	**446.07 (123.91)**	3.74 (1.04)	3.98 (1.11)	**7.72 (2.15)**	3.08 (0.86)	2.61 (0.73)	**5.69 (1.58)**	**459.48 (127.63)**
24	**D-150 Gulhari IV**	4.40	86.39 (19.63)	20.73 (4.71)	4.32 (0.98)	25.05 (5.69)	**136.49 (31.02)**	**2.00** (0.46)	2.44 (0.56)	**4.44 (1.01)**	9.55 (2.17)	7.06 (1.61)	**16.61 (3.78)**	**157.54 (35.80)**
25	**D-152 Gulhari II**	8.80	153.79 (17.48)	36.91 (4.19)	7.69 (0.87)	44.60 (5.07)	**242.99 (27.61)**	3.83 (0.44)	4.75 (0.54)	**8.58 (0.98)**	12.63 (1.44)	15.18 **(1.73)**	**27.81 (3.16)**	**279.38 (31.75)**
26	**D-153 Gulhari I**	5.20	61.47 (11.82)	14.75 (2.84)	3.07 (0.59)	17.83 (3.43)	**97.12 (18.68)**	2.47 (0.48)	2.89 (0.56)	**5.36 (1.03)**	8.35 (1.61)	6.66 (1.28)	**15.00 (2.89)**	**117.48 (22.59)**
27	**D-154 Dawala**	12.80	497.72 (38.88)	119.45 (9.33)	24.89 (1.94)	144.34 (11.28)	**786.40 (61.44)**	8.00 (0.63)	10.69 (0.84)	**18.69 (1.46)**	12.93 (1.01)	14.14 (1.11)	**27.07 (2.12)**	**832.16 (65.01)**
28	**D-155 Bhallon**	3.20	115.64 (36.14)	27.75 (8.67)	5.78 (1.81)	33.53 (10.48)	**182.71 (57.10)**	3.15 (0.99)	3.46 (1.08)	**6.61 (2.07)**	1.49 (0.47)	2.14 (0.67)	**3.63 (1.14)**	**192.95 (60.30)**
29	**D-162 Maltu II**	28.40	600.01 (21.13)	144.00 (5.07)	30.00 (1.06)	174.00 (6.13)	**948.02 (33.38)**	14.48 (0.51)	16.05 (0.57)	**30.53 (1.08)**	40.75 (1.44)	31.67 (1.12)	**72.42 (2.55)**	**1050.97 (37.01)**
30	**D-163 Maltu I**	11.20	372.05 (33.22)	89.29 (7.97)	18.60 (1.66)	107.89 (9.63)	**587.84 (52.49)**	6.10 (0.55)	6.66 (0.60)	**12.77 (1.14)**	15.57 (1.39)	10.86 (0.97	**26.43 (2.36)**	**627.04 (55.99)**
31	**D-173 Bohali Ki Chali**	10.40	207.62 (19.96)	49.83 (4.79)	10.38 (1.00)	60.21 (5.79)	**328.04 (31.54)**	7.54 (0.73)	5.82 (0.56)	**13.36 (1.29)**	11.39 (1.10)	12.74 (1.23)	**24.13 (2.32)**	**365.53 (35.15)**
32	**D-176 Charoti Ki Dhar I**	38.00	877.30 (23.09)	210.55 (5.54)	43.87 (1.15)	254.42 (6.70)	**1386.14 (36.48)**	41.42 (1.09)	48.64 (1.28)	**90.06 (2.37)**	29.45 (0.78)	24.32 (0.64)	**53.77 (1.42)**	**1529.97 (40.26)**
33	**D-119 Chabil Ki Dhar II**	26.40	**1334.12** (50.53)	320.19 (12.13)	66.71 (2.53)	386.89 (14.66)	**2107.90 (79.84)**	40.66 (1.54)	44.09 (1.67)	**84.74 (3.21)**	8.98 (0.34)	11.75 (0.45)	**20.72 (0.79)**	**2213.36 (83.84)**
	Total		**13029.60 (29.94)**	**3127.07 (7.19)**	**651.49 (1.50)**	**3778.55 (8.68)**	**20586.69 (47.31)**	**425.97 (0.98)**	**483.26 (1.11)**	**909.22 (2.09)**	**380.68 (0.87)**	**376.78 (0.86)**	**757.46 (1.74)**	**22253.43 (51.13)**

* Figures in parenthesis denote carbon density in t ha^{-1}

(c) Shrub

The carbon stock of shrubs was the minimum at D-117 Chabil Ki Dhar IV (2.02 t) which was 0.83 and 1.19 t in the aboveground and belowground components respectively while the maximum carbon stock was recorded at D-162 Maltu II (72.42 t), with the maximum aboveground carbon stock of 40.75 t while the maximum belowground carbon stock 39.55 t at D-92 Deora. Total shrub carbon stock was 757.46 t with 380.68 t in shoot and 376.78 t in root (Table 19).

(d) Total

Vegetation carbon stock (trees + herbs + shrubs) was the minimum at D-97 Kiar Tatul (95.57 t) and the maximum at D-119 Chabil Ki Dhar II (2213.36 t). Total vegetation carbon stock was 22253.43 t (Table 19).

(ii) Standing vegetation Carbon Density (t ha^{-1})

(a)Tree

The carbon density of the forest trees was the minimum at D-97 Kiar Tatul (18.05 t ha^{-1}) which was distributed in the stem, branches, leaves and root as 11.42, 2.74, 0.57 and 3.31 t ha^{-1} respectively. Maximum tree carbon stock was recorded at D-119 Chabil Ki Dhar II (177.52 t ha^{-1}), distributed in the stem, branches, leaves and root as 112.36, 26.97, 5.62 and 32.58 t ha^{-1} respectively. The total tree carbon density was 47.31 t ha^{-1}, with 29.94 t ha^{-1} in stem, 7.19 t ha^{-1} in branch, 1.50 t ha^{-1} in leaf and 8.68 t ha^{-1} in root (Table 19).

(b) Herb

The carbon density of herbs was the minimum at D-90 Gadhog II (0.75 t ha^{-1}) with D-89 Gadhog I recording the minimum aboveground carbon density of 0.30 t ha^{-1} and D-90 Gadhog II recording the minimum belowground carbon density of 0.44 t ha^{-1}. The maximum aboveground carbon density was recorded at D-181 Sirguli Ka Tiba III (1.61 t ha^{-1}) and maximum belowground carbon density at D-172 Bhog Seri III (1.71 t ha^{-1}). Total herb carbon density was 2.09 t with 0.98 t ha^{-1}in shoot and 1.11 t ha^{-1} in root (Table 19).

(c) Shrub

The carbon density of shrubs was the minimum at D-181 Sirguli Ka Tiba III (0.67 t ha^{-1}) which also had the minimum aboveground carbon density of 0.28 t ha^{-1}while the minimum belowground carbon density was recorded at D-172 Bhog Seri III (0.34 t ha^{-1}) and the maximum carbon density was recorded at D-89 Gadhog I (3.81 t ha^{-1}), with the maximum aboveground carbon stock of 2.36 t ha^{-1} and the maximum belowground carbon density was recorded at D-152 Gulhari II (1.73 t ha^{-1}). Total shrub carbon density was 1.74 t with 0.87 t ha^{-1} in shoot and 0.86 t ha^{-1} in root (Table 19).

(d) Total

Vegetation carbon density (trees + herbs + shrubs) was the minimum at D-153 Gulhari I (22.59 t ha^{-1}) while it was the maximum at D-118 Chabil Ki Dhar III (181.61 t ha^{-1}). Total vegetation carbon density was 51.13 t ha^{-1} (Table 19).

(C) Detritus Carbon Status

(i) Detritus Carbon Stock (t)

(a) Standing dead tree (above + below)

Data presented in table 20 shows that the standing dead tree carbon stock was 636.49 t. It was maximum at D-176 Charoti Ki Dhar I (57.76 t) and minimum at D-117 Chabil Ki Dhar IV (3.41 t).

(b) Fallen Tree (above + below)

Fallen tree carbon stock was 295.33 t (Table 20). Maximum fallen tree carbon stock was recorded at D-176 Charoti Ki Dhar I (26.98 t) and minimum at D-117 Chabil Ki Dhar IV (1.61 t).

Table 20. Detritus Carbon Stock of selected sample plots in Solan and Dharampur Forest Ranges in 2011

S.No	Name of the Forest	Standing dead tree (above+below)	Fallen tree (above+below)	Floor Material	Total detritus
Solan Forest Range					
1	**D-93 Nandal Nagali**	17.48 (1.41)	8.31 (0.67)	44.52 (3.59)	70.31 (5.67)
2	**D-95 Nagali I**	5.00 (1.39)	2.27 (0.63)	12.85 (3.57)	20.12 (5.59)
3	**D-96 Nagali II**	5.32 (1.33)	2.40 (0.60)	12.12 (3.03)	19.84 (4.96)
4	**D-97 Kiar Tatul**	5.68 (1.29)	2.42 (0.55)	12.23 (2.78)	20.33 (4.62)
5	**D-123 Beola**	6.25 (1.42)	2.86 (0.65)	15.53 (3.53)	24.64 (5.60)
6	**D-135 Kaldhar I**	7.56 (1.35)	3.42 (0.61)	14.34 (2.56)	25.31 (4.52)
7	**R-26 Nagali**	49.73 (1.48)	23.18 (0.69)	130.37 (3.88)	203.28 (6.05)
8	**D-92 Deora**	37.63 (1.47)	17.15 (0.67)	86.78 (3.39)	141.57 (5.53)
9	**D-94 Nandal**	11.84 (1.41)	5.04 (0.60)	24.78 (2.95)	41.66 (4.96)
10	**D-89 Gadhog I**	13.25 (1.44)	6.26 (0.68)	31.56 (3.43)	51.06 (5.55)
11	**D-90 Gadhog II**	18.74 (1.42)	8.71 (0.66)	50.03 (3.79)	77.48 (5.87)
12	**D-98 Bhawan Ki Dhar**	28.99 (1.51)	14.02 (0.73)	76.99 (4.01)	120.00 (6.25)
Dharampur Forest Range					
13	**R-36 Anji**	14.46 (1.39)	6.34 (0.61)	39.31 (3.78)	60.11 (5.78)
14	**R-49 Gadiar**	47.11 (1.51)	22.15 (0.71)	121.99 (3.91)	191.26 (6.13)
15	**D-117 Chabil Ki Dhar IV**	3.41 (1.42)	1.61 (0.67)	7.73 (3.22)	12.74 (5.31)
16	**D-118 Chabil Ki Dhar III**	15.81 (1.52)	7.80 (0.75)	42.02 (4.04)	65.62 (6.31)
17	**D-164 Maltu III**	22.93 (1.47)	10.92 (0.70)	52.57 (3.37)	86.42 (5.54)
18	**D-181 Sirguli Ka Tiba III**	37.80 (1.50)	18.14 (0.72)	97.52 (3.87)	153.47 (6.09)
19	**D 182 Kalath III**	38.40 (1.50)	18.69 (0.73)	102.40 (4.00)	159.49 (6.23)
20	**D-172 Bhog Seri III**	6.07 (1.38)	2.51 (0.57)	16.19 (3.68)	24.77 (5.63)
21	**D-159 Anji III**	4.75 (1.32)	2.09 (0.58)	11.20 (3.11)	18.04 (5.01)
22	**D-160 Anji I**	14.35 (1.38)	6.34 (0.61)	34.22 (3.29)	54.91 (5.28)
23	**D-120 Chabil Ki Dhar I**	5.11 (1.42)	2.41 (0.67)	13.25 (3.68)	20.77 (5.77)
24	**D-150 Gulhari IV**	5.90	2.51	14.04	22.44

		(1.34)	(0.57)	(3.19)	(5.10)
25	**D-152 Gulhari II**	12.14 (1.38)	5.46 (0.62)	31.24 (3.55)	48.84 (5.55)
26	**D-153 Gulhari I**	6.66 (1.28)	2.91 (0.56)	16.07 (3.09)	25.64 (4.93)
27	**D-154 Dawala**	19.20 (1.50)	8.96 (0.70)	51.07 (3.99)	79.23 (6.19)
28	**D-155 Bhallon**	4.38 (1.37)	1.82 (0.57)	10.62 (3.32)	16.83 (5.26)
29	**D-162 Maltu II**	42.03 (1.48)	18.46 (0.65)	103.66 (3.65)	164.15 (5.78)
30	**D-163 Maltu I**	15.68 (1.40)	7.06 (0.63)	42.67 (3.81)	65.41 (5.84)
31	**D-173 Bohali Ki Chali**	14.66 (1.41)	6.86 (0.66)	38.17 (3.67)	59.70 (5.74)
32	**D-176 Charoti Ki Dhar I**	57.76 (1.52)	26.98 (0.71)	148.96 (3.92)	233.70 (6.15)
33	**D-119 Chabil Ki Dhar II**	40.39 (1.53)	19.27 (0.73)	106.13 (4.02)	165.79 (6.28)
Total		**636.49 (1.46)**	**295.33 (0.68)**	**1613.12 (3.71)**	**2544.94 (5.61)**

* Figures in parenthesis denote carbon density in t ha^{-1}

(c) Floor Material

Carbon stock in floor material was recorded as 1613.12 t (Table 20). It was found to be maximum at D-176 Charoti Ki Dhar I (148.96 t) and minimum at D-117 Chabil Ki Dhar IV (7.73 t).

(d) Total

Total detritus carbon stock was 2544.94 t (Table 20). Maximum detritus carbon stock was at D-176 Charoti Ki Dhar I (233.70 t) and minimum at D-117 Chabil Ki Dhar IV (12.74 t).

(ii) Detritus Carbon Density (t ha^{-1})

(a) Standing dead tree (above + below)

A perusal of the data in table 20 shows that the standing dead tree carbon density was 1.46 t ha^{-1}. It was maximum at D-119 Chabil Ki Dhar II (1.53 t ha^{-1}) and minimum at D-153 Gulhari I (1.28 t ha^{-1}).

(b) Fallen Tree (above + below)

Fallen tree carbon stock was 0.68 t ha^{-1} (Table 20). Maximum fallen tree carbon stock was recorded at D-118 Chabil Ki Dhar III (0.75 t ha^{-1}) and minimum at D-97 Kiar Tatul (0.55 t ha^{-1}).

(c) Floor Material

Carbon stock in floor material was recorded as 3.71 t ha^{-1} (Table 20). It was found to be maximum at D-118 Chabil Ki Dhar III (4.04 t ha^{-1}) and minimum at D-135 Kaldhar I (2.56 t ha^{-1}).

(d) Total

Total detritus carbon stock was 5.61 t ha^{-1} (Table 20). Maximum detritus carbon stock was at D-118 Chabil Ki Dhar III (6.31 t ha^{-1}) and minimum at D-135 Kaldhar I (4.52 t ha^{-1}).

(D) Ecosystem Carbon Status

(i) Carbon Stock (t)

Data presented in Table 21 shows that the vegetation carbon stock (trees + herbs + shrubs) was 22253.43 t and it was the minimum at D-97 Kiar Tatul (95.57 t) and the maximum at D-119 Chabil Ki Dhar II (2213.36 t). Soil carbon stock {Humus + Soil (0-100cm layer)} was 83076.05 t. It was minimum at D-117 Chabil Ki Dhar IV (473.70 t) and maximum at D-176 Charoti Ki Dhar I (7503.41 t). Detritus carbon stock was 2544.94 t. It was minimum at D-117 Chabil Ki Dhar IV (12.74 t) and the maximum at D-176 Charoti Ki Dhar I (233.70 t). The total ecosystem carbon stock (t) was 107874.40 t. The ecosystem carbon stock was minimum at D-159 Anji III (761.57 t) and maximum at D-176 Charoti Ki Dhar I (9267.08 t).

(ii) Carbon Density (t ha^{-1})

Data presented in Table 21 shows that the vegetation carbon density (trees + herbs + shrubs) was 51.13 t ha^{-1} and it was minimum at D-153 Gulhari I (22.59 t ha^{-1}) while it was the maximum at D-118 Chabil Ki Dhar III (181.61 t ha^{-}

^{1}). Soil carbon density {Humus+Soil (0-100cm layer)} was 189.29 t ha^{-1}. It was minimum at D-135 Kaldhar I (160.90 tha^{-1}) and maximum at D-155 Bhallon (211.20 tha^{-1}). Detritus carbon density was 5.61 t ha^{-1}. It was minimum at D-135 Kaldhar I (4.52 t ha^{-1}) and the maximum at D-118 Chabil Ki Dhar III (6.31 t ha^{-1}). The total ecosystem carbon density (t ha^{-1}) was 247.87 t ha^{-1}. The ecosystem carbon density was minimum at D-135 Kaldhar I (191.34 t ha^{-1}) and maximum at D-118 Chabil Ki Dhar III (379.95 t ha^{-1}).

Soil Vegetation Ratio

The highest soil vegetation ratio was reported in D-97 Kiar Tatul (9.20) while it was least in D-118 Chabil Ki Dhar III (1.06). Overall the soil vegetation ratio was 4.41 for the Chir pine forests under study (Table 21).

4.2.3 Carbon mapping and carbon change analysis

With the increasing concern for rising CO2 concentrations, the role of forests as a long-term carbon pool, for assimilation of atmospheric CO2 is being increasingly realized; hence studies are currently afoot for assessing the use of forest biomass sinks to sequester carbon as part of a global mitigation effort. The technique of remote sensing has become common in forest investigation, providing the only realistic and cost effective way of acquiring data over large areas. Hence, the carbon mapping of Solan Forest Division was done in the present study.

(A) Relationships between carbon stock and NDVI

Having the carbon stock of the selected sample plots in Solan and Dharampur Forest Ranges of 1984 and 2011, the next step was to relate these to the NDVI in the corresponding plot pixels in the satellite image of the area. The spectral band values were extracted from the radiometrically and geometrically corrected IRS LISS III images of 1998 and 2010 and NDVI was calculated. Linear models were then fitted to the scatter plot of carbon stock (t) per pixel and the average NDVI value of each sample plot. The scatter plots given alongside show the relationship between NDVI and carbon stock of the selected sample plots.

Table 21. Ecosystem Carbon Stock of selected sample plots in Solan and Dharampur Forest Ranges in 2011

S.No	Name of the Forest	Vegetation Carbon Stock (t)	Soil Carbon Stock (t)	Detritus Carbon Stock (t)	Ecosystem Carbon Stock (t)	Soil:Vegetation Ratio
Solan Forest Range						
1	**D-93 Nandal Nagali**	361.80 (29.18)	2455.20 (198.00)	70.31 (5.67)	2887.31 (232.85)	6.79
2	**D-95 Nagali I**	183.52 (50.98)	698.77 (194.10)	20.12 (5.59)	902.41 (250.67)	3.81
3	**D-96 Nagali II**	109.92 (27.48)	779.87 (194.97)	19.84 (4.96)	909.63 (227.41)	7.09
4	**D-97 Kiar Tatul**	95.57 (21.72)	879.35 (199.85)	20.33 (4.62)	995.25 (226.19)	9.20
5	**D-123 Beola**	255.91 (58.16)	887.33 (201.67)	24.64 (5.60)	1167.88 (265.43)	3.47
6	**D-135 Kaldhar I**	145.15 (25.92)	901.02 (160.90)	25.31 (4.52)	1071.48 (191.34)	6.21
7	**R-26 Nagali**	1363.43 (40.58)	6669.51 (198.50)	203.28 (6.05)	8236.22 (245.13)	4.89
8	**D-92 Deora**	786.62 (30.73)	4546.74 (177.61)	141.57 (5.53)	5474.93 (213.86)	5.78
9	**D-94 Nandal**	326.61 (38.88)	1653.60 (196.86)	41.66 (4.96)	2021.87 (240.70)	5.06
10	**D-89 Gadhog I**	507.12 (55.12)	1504.52 (163.53)	51.06 (5.55)	2062.70 (224.21)	2.97
11	**D-90 Gadhog II**	418.5 (31.70)	2235.25 (169.34)	77.48 (5.87)	2731.23 (206.91)	5.34
12	**D-98 Bhawan Ki Dhar**	1347.65 (70.19)	3848.96 (200.47)	120.00 (6.25)	5316.61 (276.91)	2.86
Dharampur Forest Range						
13	**R-36 Anji**	600.35 (57.73)	1825.87 (175.56)	60.11 (5.78)	2486.33 (239.07)	3.04
14	**R-49 Gadiar**	1241.53 (39.79)	6149.74 (197.11)	191.26 (6.13)	7582.53 (243.03)	4.95
15	**D-117 Chabil Ki Dhar IV**	364.32 (151.80)	473.70 (197.38)	12.74 (5.31)	850.76 (354.49)	1.30
16	**D-118 Chabil Ki Dhar III**	1888.78 (181.61)	1997.03 (192.02)	65.62 (6.31)	3951.43 (379.95)	1.06

17	**D-164 Maltu III**	744.63 (47.73)	3191.53 (204.59)	86.42 (5.54)	4022.58 (257.86)	4.29
18	**D-181 Sirguli Ka Tiba III**	1122.16 (44.53)	4730.08 (187.70)	153.47 (6.09)	6005.71 (238.32)	4.22
19	**D 182 Kalath III**	1800.91 (70.35)	5190.70 (202.76)	159.49 (6.23)	7151.10 (279.34)	2.88
20	**D-172 Bhog Seri III**	293.93 (66.80)	860.40 (195.55)	24.77 (5.63)	1179.10 (267.98)	2.93
21	**D-159 Anji III**	128.71 (35.75)	614.82 (170.78)	18.04 (5.01)	761.57 (211.55)	4.78
22	**D-160 Anji I**	340.45 (32.74)	2106.62 (202.56)	54.91 (5.28)	2501.98 (240.58)	6.19
23	**D-120 Chabil Ki Dhar I**	459.48 (127.63)	730.35 (202.88)	20.77 (5.77)	1210.60 (336.28)	1.59
24	**D-150 Gulhari IV**	157.54 (35.80)	727.51 (165.34)	22.44 (5.10)	907.49 (206.25)	4.62
25	**D-152 Gulhari II**	279.38 (31.75)	1500.99 (170.57)	48.84 (5.55)	1829.21 (207.86)	5.37
26	**D-153 Gulhari I**	117.48 (22.59)	883.69 (169.94)	25.64 (4.93)	1026.81 (197.46)	7.52
27	**D-154 Dawala**	832.16 (65.01)	2579.45 (201.52)	79.23 (6.19)	3490.84 (272.72)	3.10
28	**D-155 Bhallon**	192.95 (60.30)	675.84 (211.20)	16.83 (5.26)	885.62 (276.76)	3.50
29	**D-162 Maltu II**	1050.97 (37.01)	5082.72 (178.97)	164.15 (5.78)	6297.84 (221.76)	4.84
30	**D-163 Maltu I**	627.04 (55.99)	1966.80 (175.61)	65.41 (5.84)	2659.25 (237.43)	3.14
31	**D-173 Bohali Ki Chali**	365.53 (35.15)	2016.92 (193.93)	59.70 (5.74)	2442.15 (234.82)	5.52
32	**D-176 Charoti Ki Dhar I**	1529.97 (40.26)	7503.41 (197.46)	233.70 (6.15)	9267.08 (243.87)	4.90
33	**D-119 Chabil Ki Dhar II**	2213.36 (83.84)	5207.74 (197.26)	165.79 (6.28)	7586.89 (287.38)	2.35
Total		**22253.43 (51.13)**	**83076.05 (189.29)**	**2544.94 (5.61)**	**107874.40 (247.87)**	**4.41**

* Figures in parenthesis denote carbon density in t ha^{-1}

A significant linear relationship was observed between carbon and NDVI (R = 0.741) for 1998 and NDVI (R = 0.663) for 2010 (Table 22, Fig. 31, 32).

Table 22. Statistics for the Carbon-NDVI models

Year	B_0	B_1	R	R Square	Adjusted R Square	Std. Error of the Estimate	t	P value
1998	-0.013 (0.069)	0.586 (0.097)	0.741	0.549	0.534	0.20050	6.048	0.000*
2010	-0.002 (0.081)	0.498 (0.102)	0.663	0.440	0.422	0.21974	4.857	0.000*

*significant at < 0.05

(B) Estimation of carbon stock of Solan Forest Division

Carbon inventory maps for the study area have been given in Fig.33 to 37. The carbon stock (t) ranged from 29.33 t to 13476.68 t as per the 1998 satellite imagery (Fig. 33) and from 31.99 t to 14508.33 t as per the 2010 imagery (Fig. 34), as estimated from the remote sensing based models dependant on NDVI. The carbon density (t ha^{-1}) ranged from < 10.49 t ha^{-1} to 168.03 tha^{-1} as per the 1998 imagery (Fig. 35) and as per the 2010 imagery it ranged from < 11.32 t ha^{-1} to 181.23 t ha^{-1} (Fig. 36). D-233 Datiyar had maximum carbon stock both in 1998 and 2010 at 13476.68 t and 14508.32 t while minimum was carbon stock was at R-34 Mansa Devi which was 29.33 t and 31.99 t respectively. Carbon density was maximum at D-219 Satrol II which was 168.02 tha^{-1} and 181.23 tha^{-1} and minimum was at R-33 Gulhari which was 4.82 tha^{-1} and 5.19 tha^{-1}in 1998 and 2010 respectively. (Appendix VI)

(C) Carbon change analysis

The percent change in carbon stock ranged from < 0.71% to 11.49%. D-174 Bigaur recorded maximum carbon stock change of 11.49% while minimum was at D-95 Nagali I at 4.77% (Fig. 37).

EXPERIMENT NO. 3

4.3 Impact of climate change on forest growth

4.3.1 Climate trend (1983-2020)

4.3.2 Dendrochronological Analysis

4.3.3 Relationship between Ring Width Index (RWI) and climatic variables

4.3.1 Climate trend (1983-2020)

(A) Temperature

(i) Seasonal variation trends in Temperature (^oC)

(ii) Monthly variation trends in Temperature (^oC)

(B) Precipitation

(i) Seasonal variation trends in Precipitation (mm)

(ii) Monthly variation trends in Precipitation (mm)

(iii) Mean annual and total annual Precipitation (mm)

(A) Temperature

(i) Seasonal variation trends in Temperature (^oC)

Past and present climatic trends and variations in temperature were analysed season wise i.e. winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November). Maximum temperature (T_{max}), minimum temperature (T_{min}) and average temperature (T_{av}) for three different periods 1983-1990 (BL), 1991-2000 (P1) and 2001-2010 (P2) for the region were analysed. The period 1983-1990 was taken as the baseline for comparison. The results obtained area described as below.

(a) Mean Maximum Temperature (^oC) (T_{max})

Table 23 shows the seasonal variation trends in Mean Maximum (^0C), Mean Minimum (^0C) and Average Temperature (^0C) for three different periods. T_{max} during the baseline period of 1983-1990 was 15.65 ^oC in winter, 25.79 ^oC in spring, 28.70 ^oC in summer and 24.13 ^oC in autumn. In 1991-2000 period T_{max} was 18.21 ^oC in winter, 26.95 ^oC in spring, 28.90 ^oC in summer and 25.51 ^oC in

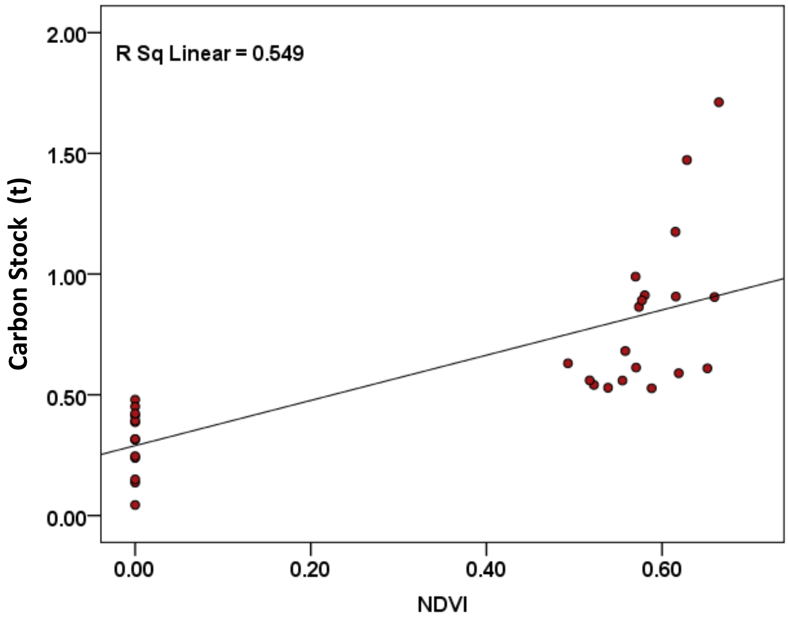


Fig. 31. Relationship between NDVI and Carbon stock (t) (1998)

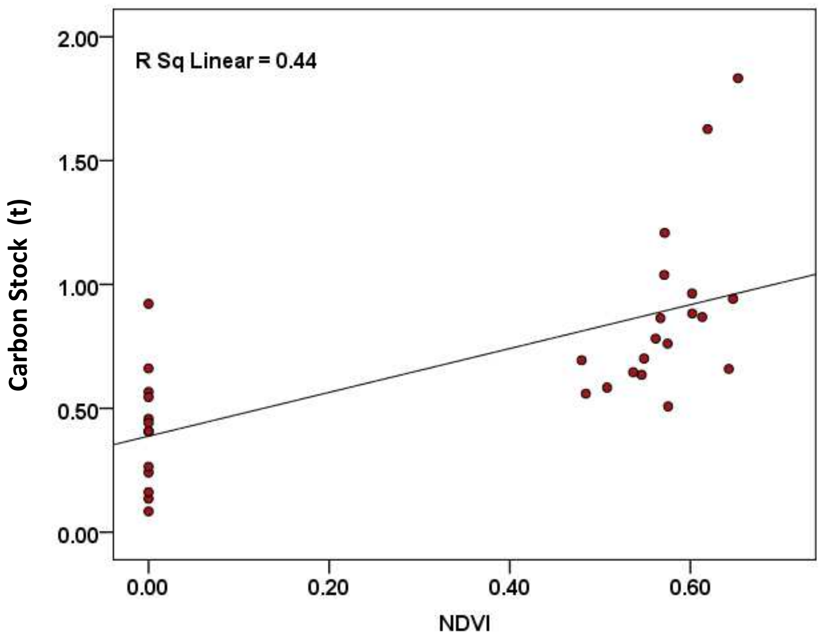


Fig. 32. Relationship between NDVI and Carbon stock (t) (2010)

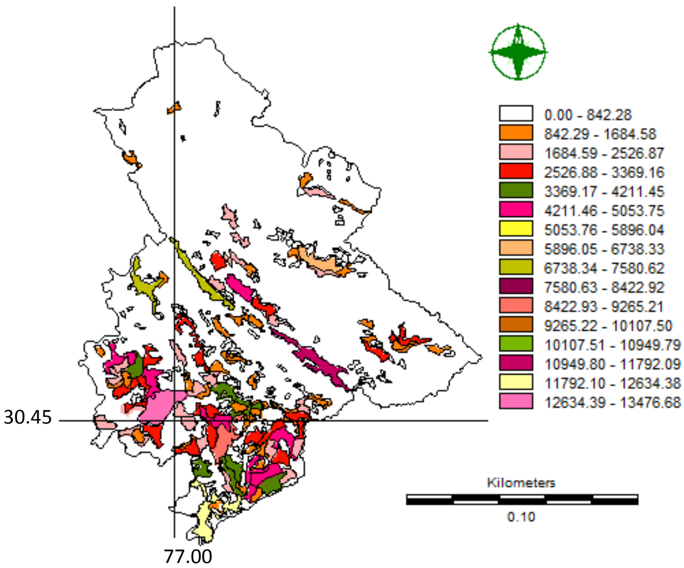


Fig. 33.Total Carbon Stock (t) in Solan Forest Division (1998)

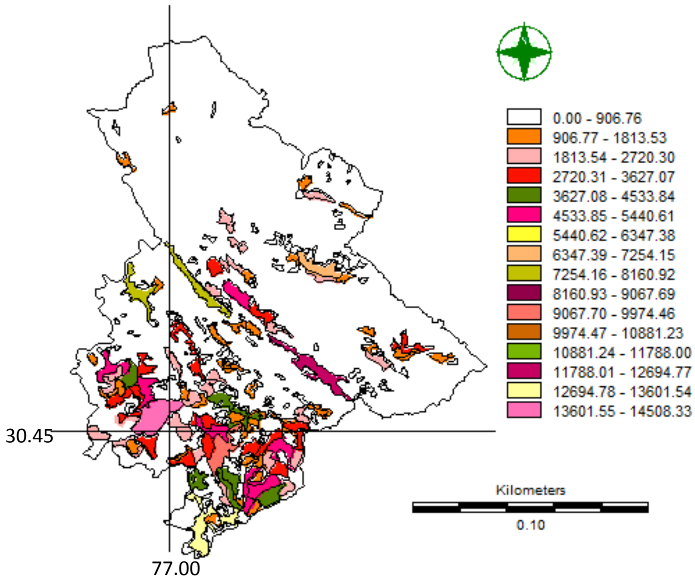


Fig. 34. Total Carbon Stock (t) in Solan Forest Division (2010)

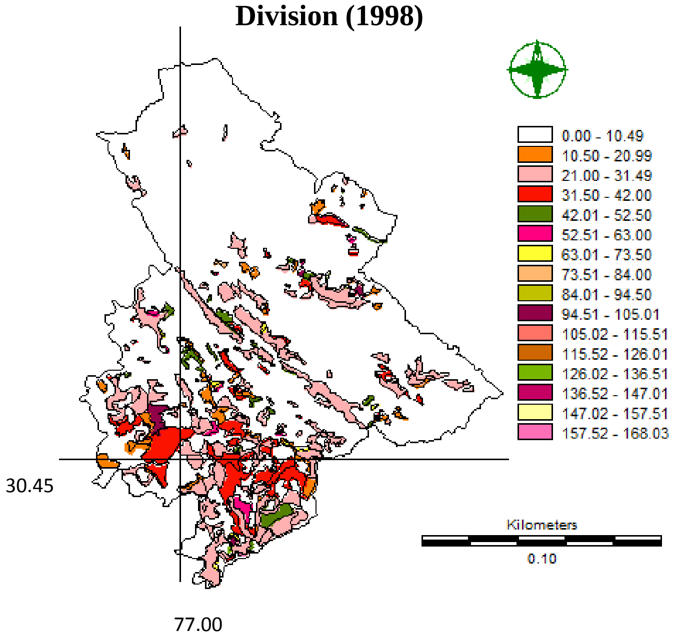


Fig. 35. Carbon Stock (t /ha) in Solan Forest Division (1998)

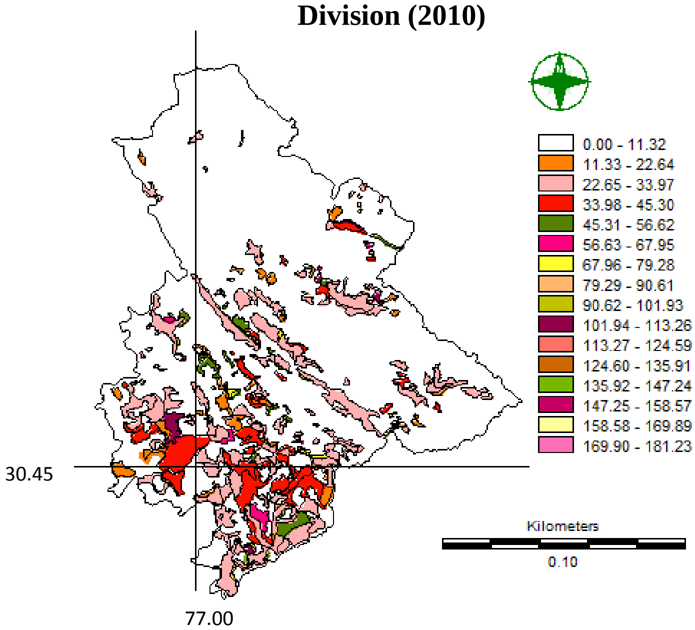


Fig. 36. Carbon Stock (t /ha) in Solan Forest Division (2010)

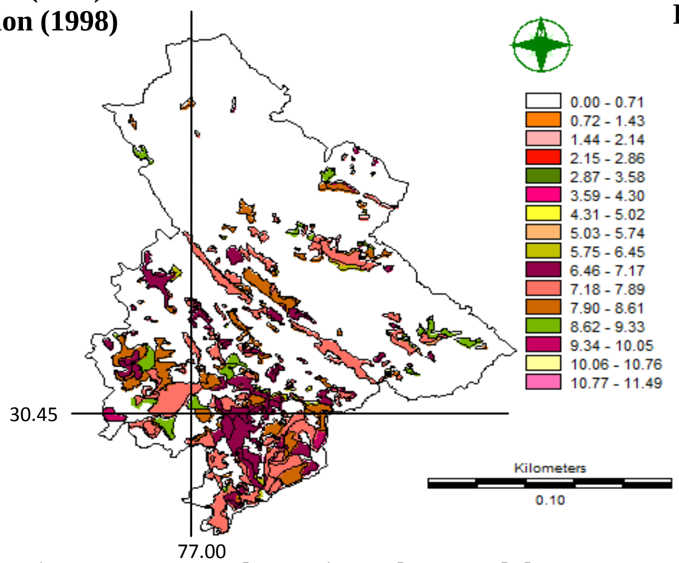


Fig. 37. Per cent change in carbon stock between 1998 and 2010

autumn. In 2001-2010 period T_{max} was 20.67 ^{o}C in winter, 28.91 ^{o}C in spring, 29.61 ^{o}C in summer and 26.56 ^{o}C in autumn. T_{max} during the period 1991-2000 and 2001- 2010 compared over the baseline has shown increase in every season. Winter temperature showed highest increase over the baseline. It increased by 2.56 ^{o}C during 1991-2000 and 5.02 ^{o}C during 2001-2010 period. During spring T_{max} rose by 1.16 ^{o}C over the baseline during 1991-2000 and 3.12 ^{o}C during 2001-2010 period. An increase of 0.20 ^{o}C over the baseline during 1991-2000 and 0.91 ^{o}C during 2001-2010 period in summer occurred. In autumn, it increased by 1.38 ^{o}C during 1991-2000 and 2.43 ^{o}C during 2001-2010 period over the baseline (Fig. 38).

(b) Mean Minimum Temperature (^{o}C) (T_{min})

During the baseline period of 1983-1990 T_{min} was 3.70 ^{o}C in winter, 13.35 ^{o}C in spring, 19.05 ^{o}C in summer and 11.26 ^{o}C in autumn. In 1991-2000 period T_{min} was 3.18 ^{o}C in winter, 11.96 ^{o}C in spring, 19.69 ^{o}C in summer and 11.18 ^{o}C in autumn. During 2001-2010 period T_{min} was 3.25 ^{o}C in winter, 12.68 ^{o}C in spring, 19.55 ^{o}C in summer and 10.89 ^{o}C in autumn. (Table 23). A decrease of 0.52 ^{o}C over the baseline in winter during 1991-2000 and 0.45 ^{o}C during 2001-2010 period occured.

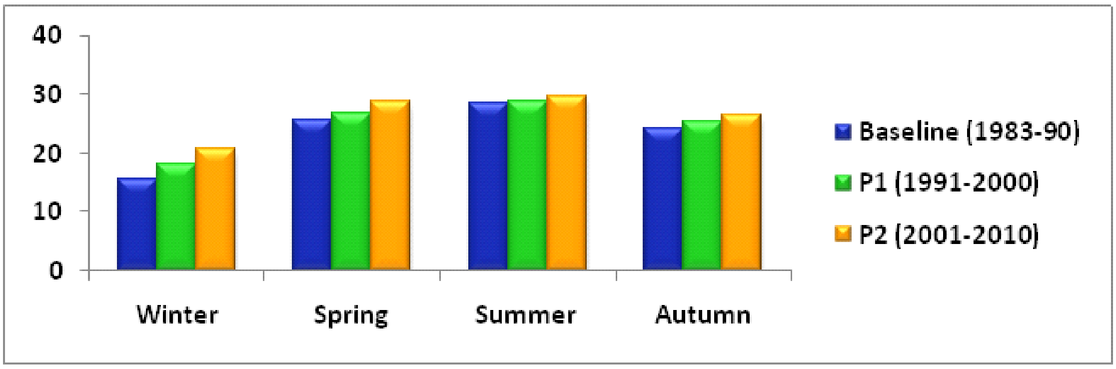
During spring T_{min} decreased by 1.39 ^{o}C over the baseline during 1991-2000 and 0.67 ^{o}C during 2001-2010 period. An increase of 0.64 ^{o}C over the baseline during 1991-2000 and 0.49 ^{o}C during 2001-2010 period in summer occurred, which was the highest increase in T_{min} over the baseline among all seasons. In autumn, it decreased by 0.07 ^{o}C during 1991-2000 and 0.37 ^{o}C during 2001-2010 period over the baseline (Fig. 39).

Table 23. Seasonal variation trends in Mean Maximum (^{0}C), Mean Minimum (^{0}C) and Average Temperature (^{0}C) for three different periods

	Season			
	Winter	**Spring**	**Summer**	**Autumn**
Mean Max.				
1983-90 (BL)	15.65	25.79	28.70	24.13
1991-2000 (P1)	18.21	26.95	28.90	25.51
2001-2010 (P2)	20.67	28.91	29.61	26.56
Increase/decrease over baseline				
P1	2.56	1.16	0.20	1.38
P2	5.02	3.12	0.91	2.43
Mean Min.				
1983-90 (BL)	3.70	13.35	19.05	11.26
1991-2000 (P1)	3.18	11.96	19.69	11.18
2001-2010 (P2)	3.25	12.68	19.55	10.89
Increase/decrease over baseline				
P1	-0.52	-1.39	0.64	-0.07
P2	-0.45	-0.67	0.49	-0.37
Average				
1983-90 (BL)	9.68	19.57	23.88	17.70
1991-2000 (P1)	10.69	19.46	24.29	18.35
2001-2010 (P2)	11.96	20.79	24.58	18.73
Increase/decrease over baseline				
P1	1.02	-0.11	0.42	0.65
P2	2.29	1.22	0.70	1.03

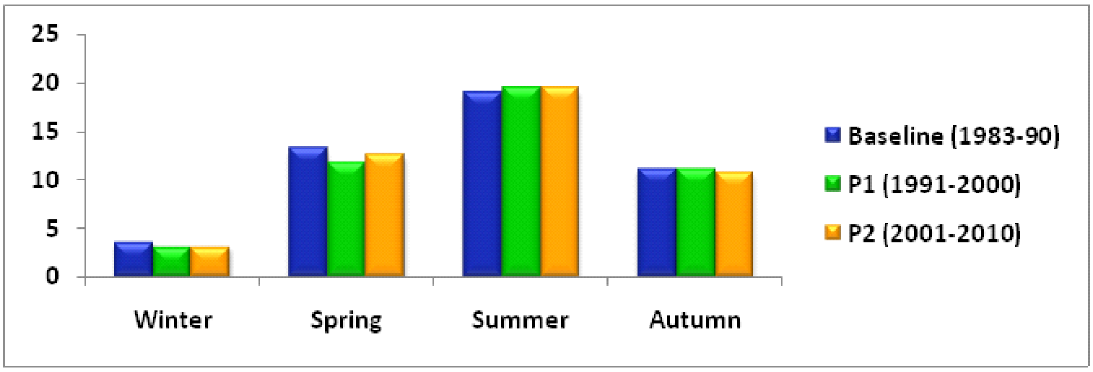
(c) Average Temperature (^{o}C) (T_{av})

Average temperature during the baseline period of 1983-1990 T_{av} was 9.68 ^{o}C in winter, 19.57 ^{o}C in spring, 23.88 ^{o}C in summer and 17.70 ^{o}C in autumn. In 1991-2000 period T_{av} was 10.69 ^{o}C in winter, 19.46 ^{o}C in spring, 24.29 ^{o}C in summer and 18.35 ^{o}C in autumn. During 2001-2010 period T_{av} was 11.96 ^{o}C in winter, 20.79 ^{o}C in spring, 24.58 ^{o}C in summer and 18.73 ^{o}C in autumn. (Table 23). An increase of 1.02 ^{o}C over the baseline during 1991-2000 and 2.29 ^{o}C during 2001-2010 period occured. During spring T_{av} decreased by 0.11 ^{o}C over the baseline during 1991-2000 and 1.22 ^{o}C during 2001-2010 period. An increase of 0.42 ^{o}C during 1991-2000 and 0.70 ^{o}C during 2001-2010 period in summer over the baseline occurred. In autumn, it increased by 0.65 ^{o}C during 1991-2000 and 1.03 ^{o}C during 2001-2010 period over the baseline (Fig. 40).



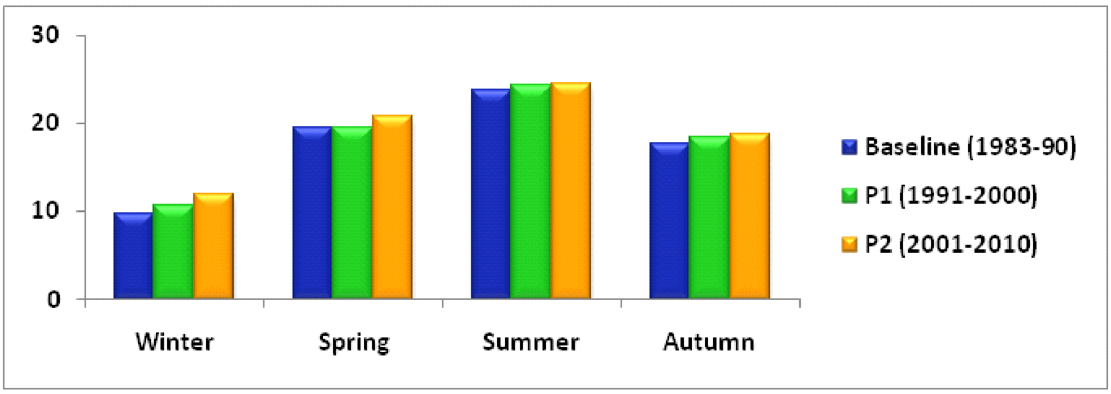
Season

Fig. 38. Seasonal variation trends in Mean Maximum Temperature (^{0}C) for three different periods



Season

Fig. 39. Seasonal variation trends in Mean Minimum Temperature (^{0}C) for three different periods



Season

Fig. 40. Seasonal variation trends in Average Temperature (^{0}C) for three different periods

(ii) Monthly variation trends in Temperature (^oC)

Month wise variation in past and present temperatures: $T_{max,}$ T_{min} and T_{av} were analysed for the similar periods of time. Table 24 shows the monthly variation trends in Mean Maximum (^0C), Mean Maximum (^0C) and Average Temperature (^0C) for three different periods. The variation trends are as below:

Table 24. Monthly variation trends in Mean Maximum (^0C), Mean Maximum (^0C) and Average Temperature (^0C) for three different periods

Time period & Temperature	Month											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Mean Max.												
1983-90 (BL)	14.53	15.93	21.00	26.44	29.94	30.48	28.10	27.51	27.00	24.68	20.73	16.50
1991-2000 (P1)	16.13	18.48	22.10	27.33	31.43	30.89	28.37	27.43	27.47	26.17	22.90	20.01
2001-2010 (P2)	19.40	21.24	25.17	29.52	32.04	32.22	28.21	28.40	28.39	27.15	24.14	21.37
Increase/decrease over baseline												
P1	1.61	2.56	1.10	0.89	1.49	0.42	0.27	-0.08	0.47	1.50	2.18	3.51
P2	4.88	5.32	4.17	3.08	2.10	1.75	0.11	0.89	1.39	2.48	3.42	4.87
Mean Min.												
1983-90 (BL)	3.11	4.86	10.48	12.49	17.08	19.23	19.14	18.80	16.46	11.30	6.01	3.13
1991-2000 (P1)	2.51	4.14	7.99	11.70	16.19	18.64	20.16	20.27	17.10	10.40	6.05	2.89
2001-2010 (P2)	2.21	4.65	8.61	13.20	16.22	18.67	20.24	19.73	16.63	10.31	5.73	2.90
Increase/decrease over baseline												
P1	-0.60	-0.72	-2.49	-0.79	-0.88	-0.58	1.02	1.47	0.64	-0.90	0.04	-0.24
P2	-0.90	-0.21	-1.87	0.71	-0.85	-0.55	1.10	0.93	0.17	-0.99	-0.28	-0.23
Average												
1983-90 (BL)	8.82	10.39	15.74	19.46	23.51	24.85	23.62	23.16	21.73	17.99	13.37	9.81
1991-2000 (P1)	9.32	11.31	15.05	19.52	23.81	24.77	24.27	23.85	22.29	18.29	14.48	11.45
2001-2010 (P2)	10.81	12.95	16.89	21.36	24.13	25.45	24.23	24.07	22.51	18.73	14.94	12.14
Increase/decrease over baseline												
P1	0.50	0.92	-0.69	0.05	0.30	-0.08	0.65	0.69	0.55	0.30	1.11	1.64
P2	1.99	2.55	1.15	1.90	0.62	0.60	0.61	0.91	0.78	0.74	1.57	2.32

(a) Mean monthly Maximum Temperature (^oC) (T_{max})

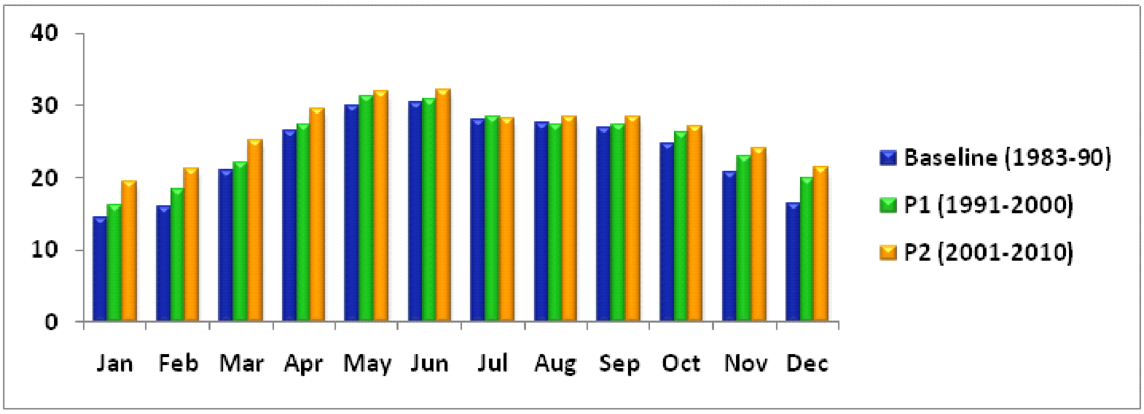
$T_{max,}$ increased in all the months during 1991-2000 and 2000-2010 except August of 1991-2000 period, where it decreased over the baseline. During 1991-2000 T_{max} increased from January to July by 1.61 ^oC, 2.56 ^oC, 1.10 ^oC, 0.89 ^oC, 1.49 ^oC, 0.42 ^oC and 0.27 ^oC respectively, then it decreased in August by 0.08 ^oC and then again increased by 0.47 ^oC, in September, 1.50 ^oC in October, 2.18 ^oC in November and 3.51 ^oC in December, which was maximum in all months over the baseline period. During 2001-2010 T_{max} increased from January to December by 4.88 ^oC, 5.32 ^oC, 4.17 ^oC, 3.08 ^oC, 2.10 ^oC, 1.75 ^oC, 0.11 ^oC, 0.89 ^oC, 1.39 ^oC, 2.48 ^{o}C, 3.42 ^{o}C and 4.87 ^{o}C respectively, while the maximum increase was observed in the month of February (Table 24, Fig. 41).

(b) Mean monthly Minimum Temperature (^{o}C) (T_{min})

Month wise minimum temperature for the three different periods is shown in (Table 24, Fig. 42). T_{min} showed an increasing as well as decreasing trend in the period of 1991-2000 and 2001-2010 over the baseline period. During 1991-2000 T_{min} decreased by 0.60 ^{o}C, 0.72 ^{o}C, 2.49 ^{o}C, 0.79 ^{o}C, 0.88 ^{o}C and 0.58 ^{o}C in the months of January, February, March, April, May and June respectively, then it increased from July to September by 1.02 ^{o}C, 1.47 ^{o}C and 0.64 ^{o}C and then decreased by 0.90 ^{o}C, in October, increased by 0.04 ^{o}C in November and then again decreased by 0.24 ^{o}C in December over the baseline. During 2001-2010 T_{min} decreased from January to March by 0.90 ^{o}C, 0.21 ^{o}C and 1.87 ^{o}C respectively, increased in April by 0.71 ^{o}C, decreased in May and June by 0.85 ^{o}C and 0.55 ^{o}C, increased from July to September by 1.10 ^{o}C, 0.93 ^{o}C and 0.17 ^{o}C and again decreased from October to December by 0.99 ^{o}C, 0.28 ^{o}C and 0.23 ^{o}C respectively.

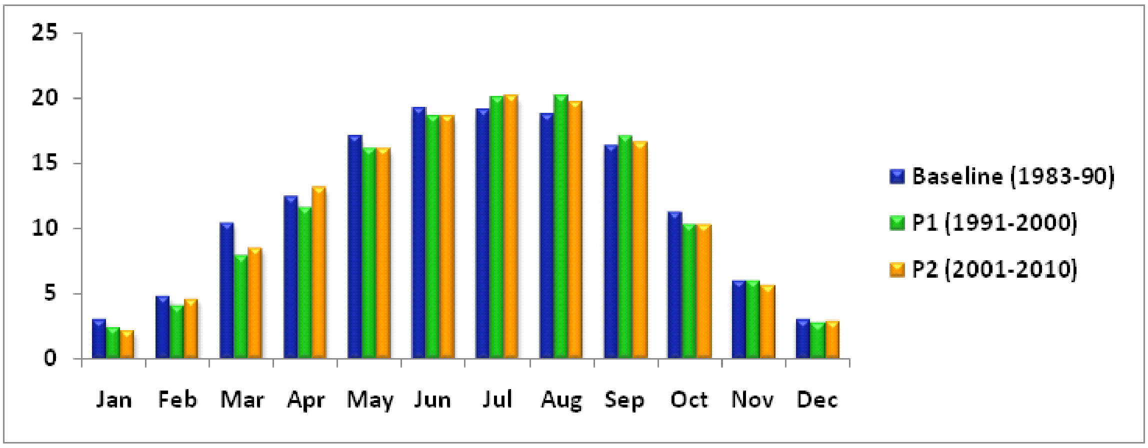
(c) Average monthly Temperature (^{o}C) (T_{av})

Average monthly temperature increased in all the months of 1991-2000 and 2001-2010 except March and June of 1991-2000 period, where it decreased over the baseline. During 1991-2000, T_{av} increased in January and February by 0.50 ^{o}C and 0.92 ^{o}C, then it decreased in March by 0.69 ^{o}C, increased in April and May by 0.05 ^{o}C and 0.30 ^{o}C, then decreased in June by 0.08 ^{o}C and then increased from July to December by 0.65 ^{o}C, 0.69 ^{o}C, 0.55 ^{o}C, 0.30 ^{o}C, 1.11 ^{o}C and 1.64 ^{o}C over the baseline. During 2001-2010 T_{av} increased from January to December by 1.99 ^{o}C, 2.55 ^{o}C, 1.15 ^{o}C, 1.90 ^{o}C, 0.62 ^{o}C, 0.60 ^{o}C, 0.61 ^{o}C, 0.91 ^{o}C, 0.78 ^{o}C, 0.74 ^{o}C, 1.57 ^{o}C and 2.32 ^{o}C respectively over the baseline (Table 24, Fig. 43).



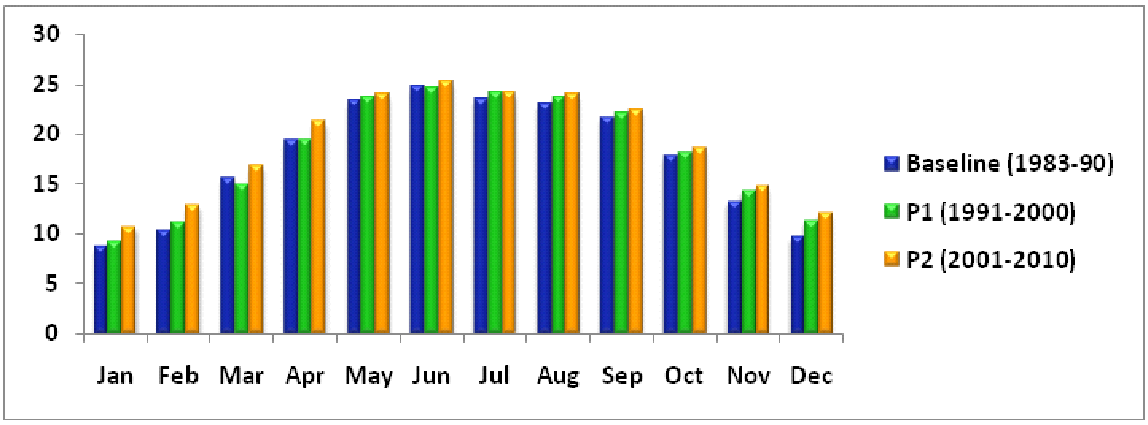
Month

Fig. 41. Mean Monthly Maximum Temperature (^{0}C) for three different periods



Month

Fig. 42. Mean Monthly Minimum Temperature (^{0}C) for three different periods



Month

Fig. 43. Average monthly Temperature (^{0}C) for three different periods

(B) Precipitation

(i) Seasonal variation trends in Precipitation (mm)

Variations in precipitation during past and present climatic trends were analysed season wise i.e. winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November) for the same period of time. The variation trends are as below:

Total rainfall decreased over the years in spring and summer season while there was a small increase in the total rainfall in autumn over the baseline during the period of 1991-2000 as well as 2001-2010. Similar to autumn, slight increase in rainfall during 1991-2000 over the baseline was also observed in winter which later during 2001-2010 showed considerable decrease. In the period 1991-2000 the decline of rainfall was 66.18 mm in spring and 6.4 mm in summer. In winter and autumn it increased by 32.14 mm and 13.33 mm respectively over the baseline. During 2001-2010 total rainfall decreased in winter, spring and summer by 20.57 mm, 88.25 mm and 144.50 mm respectively, with maximum reduction in summer rainfall. In autumn it increased by 45.78 mm over the baseline (Table 25, Fig. 44).

(ii) Monthly variation trends in Precipitation (mm)

Month wise variation in past and present mean and total rainfall were recorded and analysed for the similar period of time. The variation trends are described below:

Table 25. Seasonal variation trends in rainfall (mm) for three different periods

Time period	Season			
	Winter	Spring	Summer	Autumn
1983-90 (BL)	154.46	230.06	710.71	165.76
1991-2000 (P1)	186.60	163.88	704.31	179.09
2001-2010 (P2)	133.89	141.81	566.21	211.54
Increase/decrease over baseline				
P1	32.14	-66.18	-6.40	13.33
P2	-20.57	-88.25	-144.50	45.78

(iii) Mean Monthly Rainfall (mm)

Mean monthly rainfall for 1991-2000 and 2001-2010 period over the baseline did not exhibit any single increasing or decreasing trend (Table 26). In 1991-2000 mean monthly rainfall increased in January, February, June, August, September and November by 29.10 mm, 10.65 mm, 13.28 mm, 18.92 mm, 12.05 mm and 1.70 mm respectively and decreased by 11.72 mm, 3.43 mm, 51.04 mm, 38.60 mm, 0.42mm and 7.61 mm during the months of March, April, May, July, October and December respectively. During 2001-2010 mean rainfall decline was more over the baseline. It decreased by 0.98 mm, 11.97 mm, 15.47 mm, 60.82mm, 14.36 mm, 91.70 mm, 38.45 mm, 13.66 mm, 4.86 mm and 27.84 mm in the months of January, March, April, May, June, July, August, October, November and December respectively. Maximum reduction occurred in the month of July. Mean rainfall increased by 8.25 mm and 64.30 mm in February and September respectively over the baseline (Fig. 45).

(iv) Total Monthly Rainfall (mm)

An increase in total monthly rainfall during 1991-2000 over the baseline was observed except in May, which later during 2001-2010 showed considerable decrease. In the period of 1991-2000 total rainfall increased from January to April by 376.30 mm, 240 mm, 29.80 mm and 61.90 mm, decreased in May by 293.40 mm and then again increased from June to December by 419.70 mm, 235.60 mm, 702.10 mm, 355.90 mm, 69.20 mm, 39.70 mm and 14.00 mm over the baseline respectively. Maximum increase in total rainfall was recorded in August followed by June and the maximum reduction was in May in 1991-2000 over the baseline. During 2001-2010 total rainfall increased from January to March by 75.50 mm, 216 mm and 27.30 mm respectively, whereas in April and May total rainfall declined by 58.50 mm and 391.20 mm, increased in June by 143.40 mm, decreased in July by 295.40 mm, then increased in August and September by 128.40 mm and 878.40 mm and then again decreased from October to December by 63.20 mm, 25.90 mm and 188.30 mm respectively over the baseline. Maximum increase in total rainfall was recorded in September and maximum reduction was in May in 2001-2010 period over the baseline (Table 26, Fig. 46).

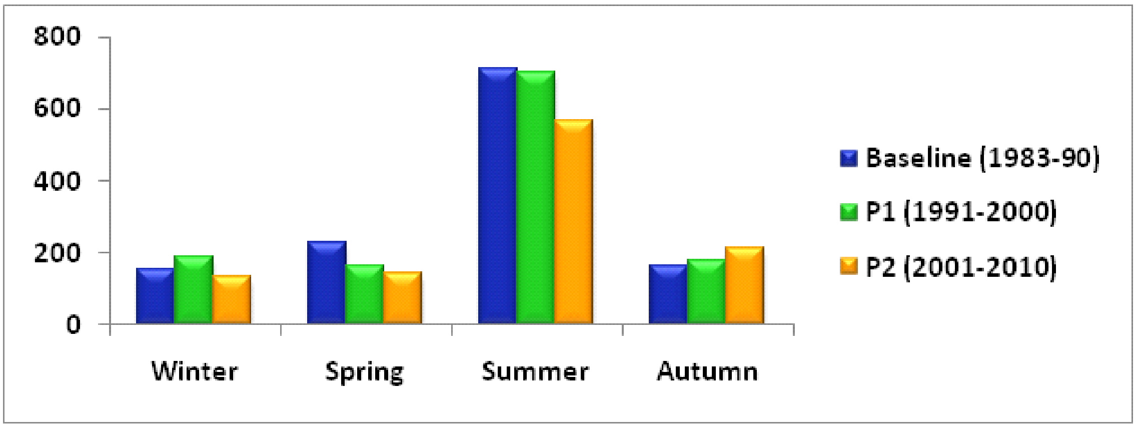


Fig. 44. Seasonal variation trends in rainfall (mm) for three different periods

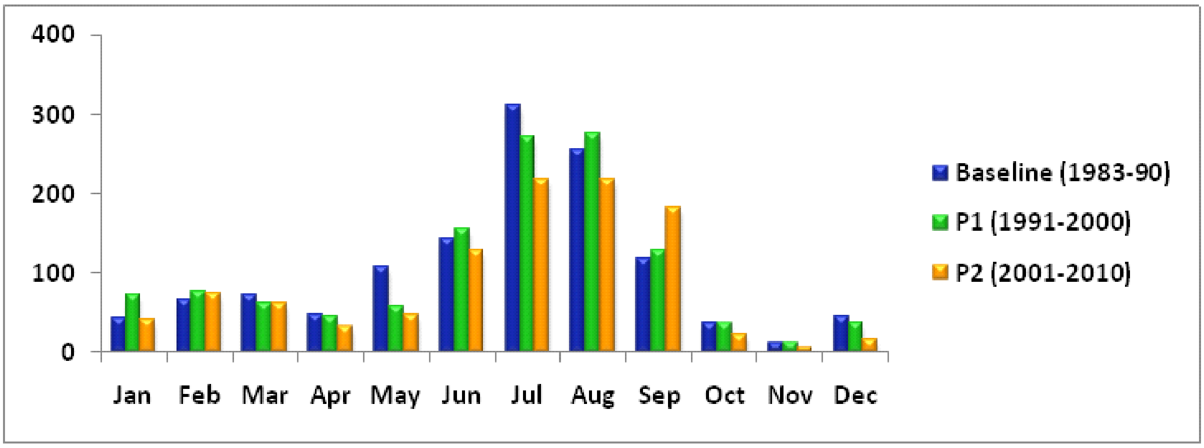


Fig. 45. Mean monthly rainfall for three different periods

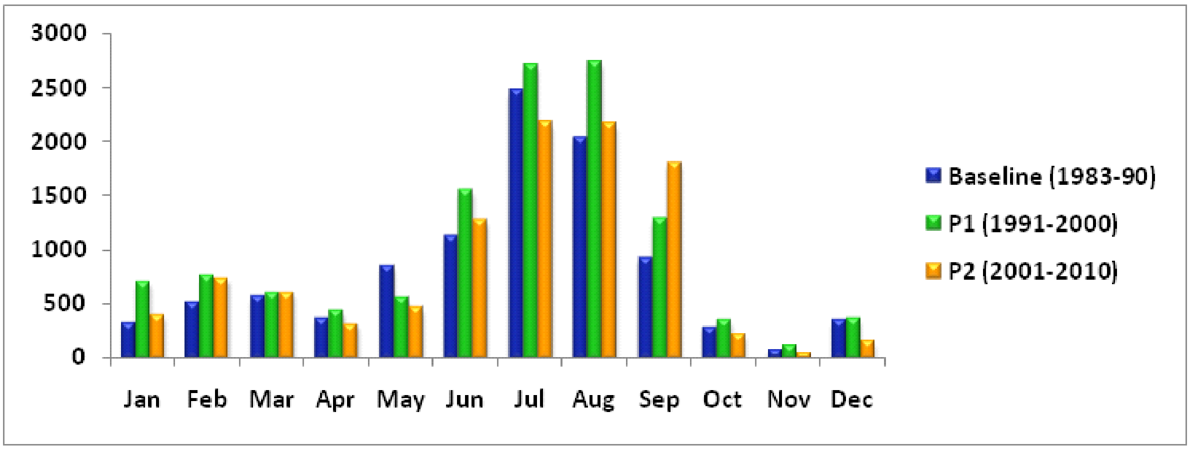


Fig. 46. Total monthly rainfall for three different periods

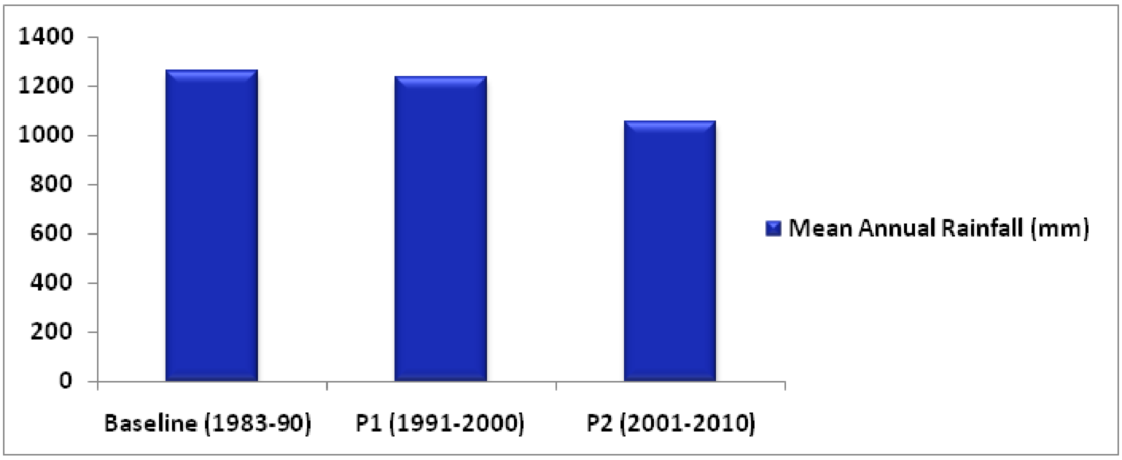


Fig. 47. Mean Annual Rainfall for three different periods

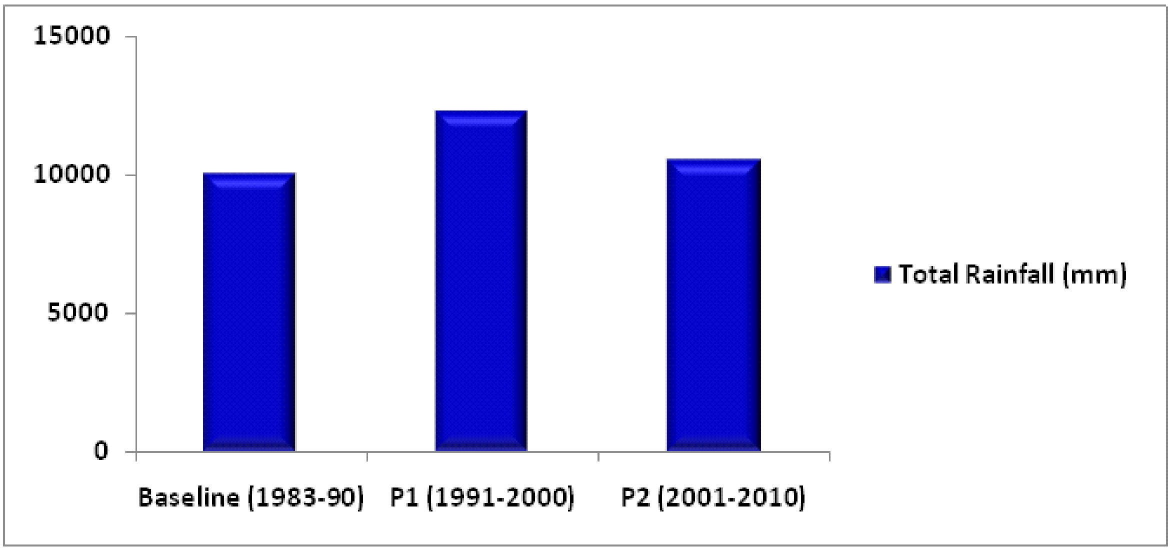


Fig. 48. Total Rainfall for three different periods

Table 26. Monthly variation trends in Mean Rainfall (mm) and Total Rainfall (mm) for the last three decades

Time Period & Precipitation	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Mean Rainfall (mm)												
1983-90 (BL)	42.68	66.74	73.49	48.09	108.49	143.48	310.79	256.45	117.71	36.70	11.35	45.05
1991-2000 (P1)	71.77	77.39	61.77	44.66	57.45	156.75	272.19	275.37	129.76	36.28	13.05	37.44
2001-2010 (P2)	41.69	74.99	61.52	32.62	47.67	129.12	219.09	218	182.01	23.04	6.49	17.21
Increase/decrease over baseline												
P1	29.10	10.65	-11.72	-3.43	-51.04	13.28	-38.60	18.92	12.05	-0.42	1.70	-7.61
P2	-0.98	8.25	-11.97	-15.47	-60.82	-14.36	-91.70	-38.45	64.30	-13.66	-4.86	-27.84
Total Rainfall (mm)												
1983-90 (BL)	341.40	533.90	587.90	384.70	867.90	1147.80	2486.30	2051.60	941.70	293.60	90.80	360.40
1991-2000 (P1)	717.70	773.90	617.70	446.60	574.50	1567.50	2721.90	2753.70	1297.60	362.80	130.50	374.40
2001-2010 (P2)	416.90	749.90	615.20	326.20	476.70	1291.20	2190.90	2180.00	1820.10	230.40	64.90	172.10
Increase/decrease over baseline												
P1	376.30	240.00	29.80	61.90	-293.40	419.70	235.60	702.10	355.90	69.20	39.70	14.00
P2	75.50	216.00	27.30	-58.50	-391.20	143.40	-295.40	128.40	878.40	-63.20	-25.90	-188.30

(v) Mean Annual Rainfall and Total Rainfall (mm)

Mean annual rainfall and total rainfall were recorded and analysed for the similar period of time (Table 27).

Mean annual rainfall followed a declining trend over the years. During the period of 1991-2000, mean annual rainfall decreased by 27.12 mm and in 2001-2010 it decreased by 207.55 mm over the baseline (Fig. 47).

The total rainfall for 1991-2000 as well as 2001-2010 increased over the baseline i.e. 1983-1990 but the total rainfall during 2001-2010 followed a declining trend from 1991-2000. In the period of 1991-2000 it increased by 2250.80 mm and in 2001-2010 by 446.50 mm over the baseline (Table 27, Fig. 48).

Table 27. Annual variation trends in Mean Rainfall (mm) and Total Annual Rainfall (mm) for three different periods

Time period	Mean Annual Rainfall (mm)	Total Annual Rainfall (mm)
1983-90 (BL)	1261.00	10088.00
1991-2000 (P1)	1233.88	12338.80
2001-2010 (P2)	1053.45	10534.50
Increase/decrease over baseline		
P1	-27.12	2250.80
P2	-207.55	446.50

4.3.2 Dendrochronological Analysis

(A) Crossdating

Out of a total of 21 disc samples only 15 were found to be sensitive enough to be crossdated, the remaining 6 were rejected because of a complacent ring series. These 15 tree ring samples were then classified on the basis of diameter overbark into 5 diameter classes: D1-30 to 40 cm, D2: 40 to 50 cm, D3: 50 to 60 cm, D4: 60-70 cm and D5: > 70 cm. Crossdating was simplified by the presence of very few missing rings. Composite plots for each diameter class were constructed and then all the 5 composite plots were used to develop the master chronology.

It was found that all the composite plots agreed from 1979 to 1999, when there was similar response to climate in all the trees in the site, while for the rest of the period the composite plots did not agree with each other (Fig. 49). The chronology of narrow and broad rings is given below weighted in direct proportion to the relative narrowness or broadness:

1937-7 Δ	1953-1 □	1972-4 Δ	1983-6 Δ	1997-6 Δ
1940- 3 □	1954-8 Δ	1975-2 □	1984-5 Δ	1999-2 □
1941-7 Δ	1961-5 Δ	1976-3 □	1985-7 Δ	2002-4 Δ
1942-7 Δ	1965-3 □	1978-1 □	1986-1 □	2003-2 □
1946-2 □	1967-5 Δ	1979-8 Δ	1989-5 Δ	2005-1 □
1947-3 □	1969-4 Δ	1980-7 Δ	1992-5 Δ	2006-7 Δ
1952-2 □	1971-3 □	1982-1 □	1993-1 □	2008-3 □

Δ narrow rings

(B) Detrending

The raw ring width (RRW) of each tree was plotted against age and then a trendline was fitted to each depending on the significance of the correlation coefficient. It was found that polynomial equations provided the best fit for the data. Each of the RRW series was detrended by fitting a polynomial equation of the 2nd order to the series (Table 28), and then dividing the actual values (measured ring width) and the predicted values (from the curve or line). If the

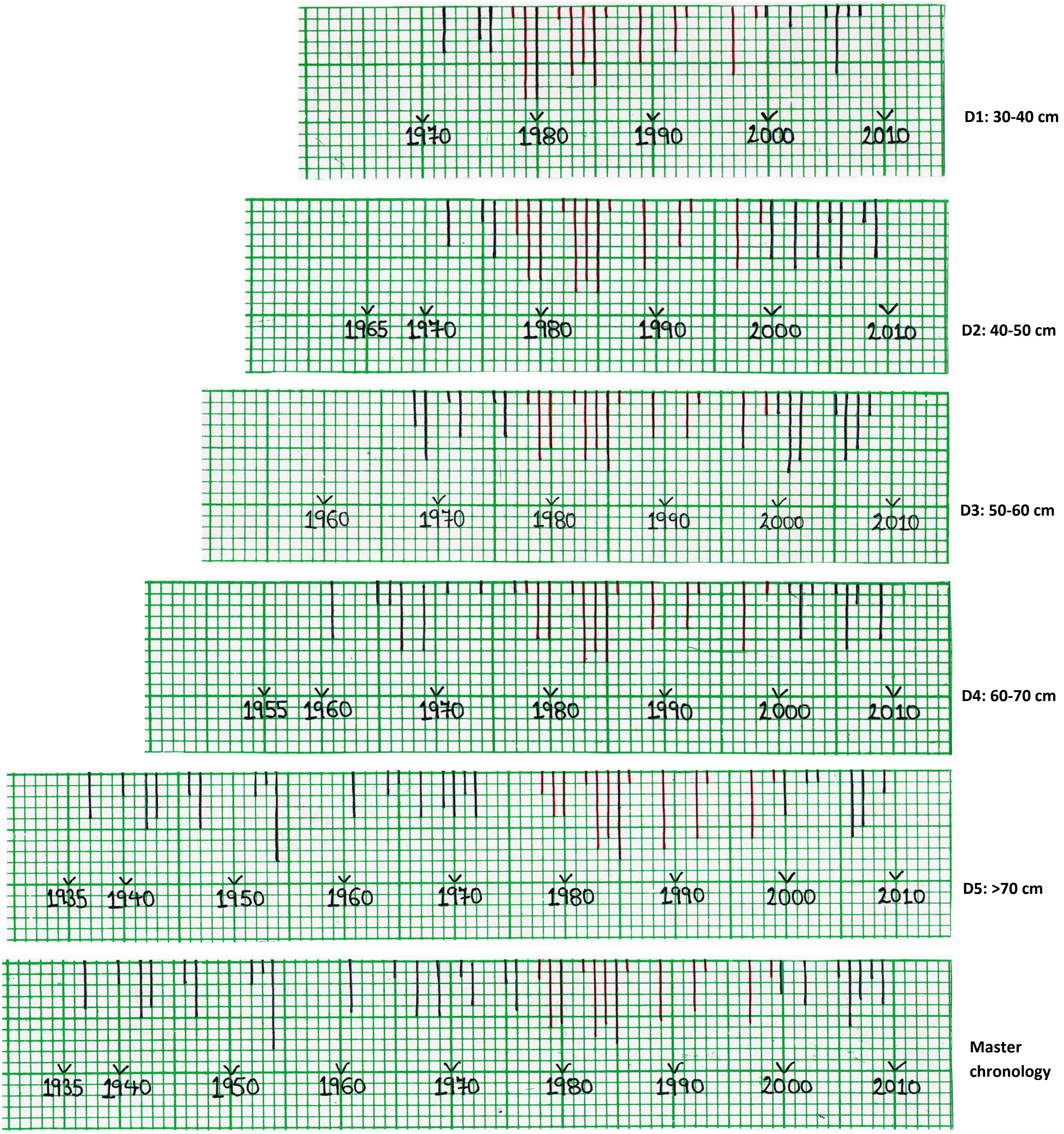


Fig. 49. Composite skeleton plots of the tree ring samples and the master chronology

actual ring width is equal to the predicted value an index value of 1.0 is obtained. If the actual ring width is greater than the predicted an index value greater than 1.0 is obtained and if actual is less than the predicted an index less than 1 is obtained. A simple way to think of it is that an index value of 0.5 means that growth during that year was 50 % of normal. This means that since the standardization procedures produce a series of indices varying around 1.0, a growth trend would be visible as a series of indices greater or less than 1.0. Figures 51 to 55 show the relationship between ring width (mm) and age in different diameter classes before and after detrending.

Climatic records were procured from the Deparment of Environmental Sciences, U.H.F., Nauni, to relate the detrended tree ring data with climatic variables. Histograms were plotted to visually compare the class frequencies of indices between different diameter classes (Fig. 50). The histograms show that the overall distribution of indices is approximately normal in all diameter classes and the mean index values for all diameter classes are the expected values for well-standardized chronologies (about 1.0) and the standard deviations are within the norm compared to the values presented by Fritts and Shatz (1975) for 21 ponderosa pine chronologies. Table 29 gives the Ring Width Index (RWI) of all diameter classes. All the tree ring samples showed narrow rings in 1979 and 1980, with index values of 0.64958 and 0.71642 respectively. The year 1982 was another signature year for growth where a broad ring was common to all the tree ring samples and an index value of 1.26723 was obtained. Thereafter three narrow rings were common to all composite plots in 1983, 1984 and 1985, with index values of 0.66764, 0.71328 and 0.58897 respectively. In 1986, a broad ring was recorded in all the composite plots with an index value of 1.23517. Thereafter, narrow rings were recorded in 1989 and 1992, with low index values of 0.70584 and 0.85841. Next a broad ring with an index value of 1.17021 in 1993 was common to all plots. 1997 was also a marker year where a narrow ring was recorded with an index value of 0.63978 and a broad ring thereafter in 1999 with an index value of 1.13145.

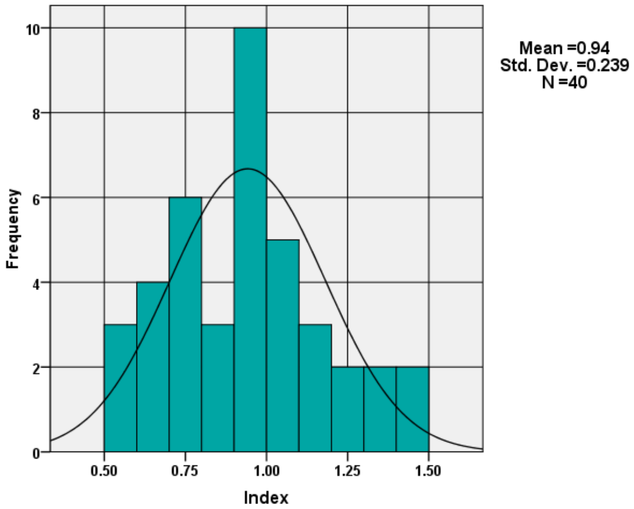
Table 28. Polynomial equations used for detrending the raw ring widths

Diameter Class		a	b	c	R	R square
D1 (30-40 cm)	Tree1	2.873	0.275	-0.005	0.653**	0.426
	Tree 2	2.306	0.272	-0.005	0.538**	0.289
	Tree 3	2.281	0.300	-0.006	0.557**	0.310
D2 (40-50 cm)	Tree 4	2.057	0.262	-0.005	0.602**	0.362
	Tree 5	1.971	0.230	-0.004	0.514**	0.264
	Tree 6	1.545	0.243	-0.004	0.657**	0.432
D3 (50-60 cm)	Tree 7	2.642	0.236	-0.004	0.612**	0.375
	Tree 8	2.128	0.248	-0.004	0.600**	0.359
	Tree 9	2.028	0.195	-0.003	0.624**	0.390
D4 (60-70 cm)	Tree 10	2.371	0.248	-0.004	0.668**	0.446
	Tree 11	2.441	0.217	-0.003	0.595**	0.354
	Tree 12	2.465	0.174	-0.002	0.535**	0.286
D5 (70-80 cm)	Tree 13	2.547	0.185	-0.002	0.646**	0.417
	Tree 14	2.570	0.162	-0.002	0.590**	0.348
	Tree 15	2.223	0.172	-0.002	0.579**	0.335

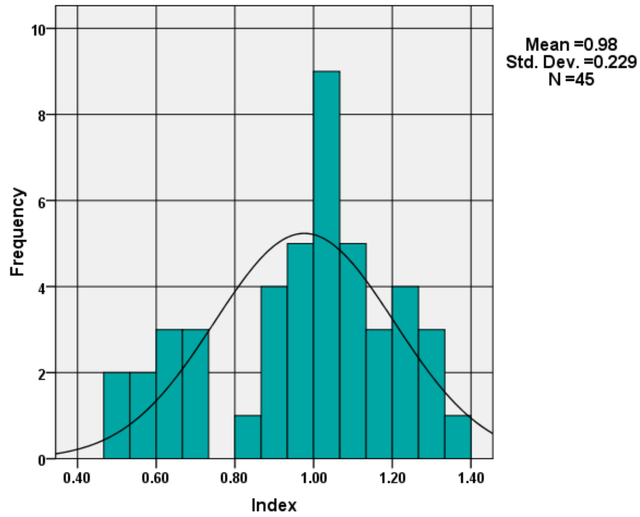
** (Significant at both 1% and 5% level of significance)

Table 29. Ring Width Index (RWI) of all diameter classes

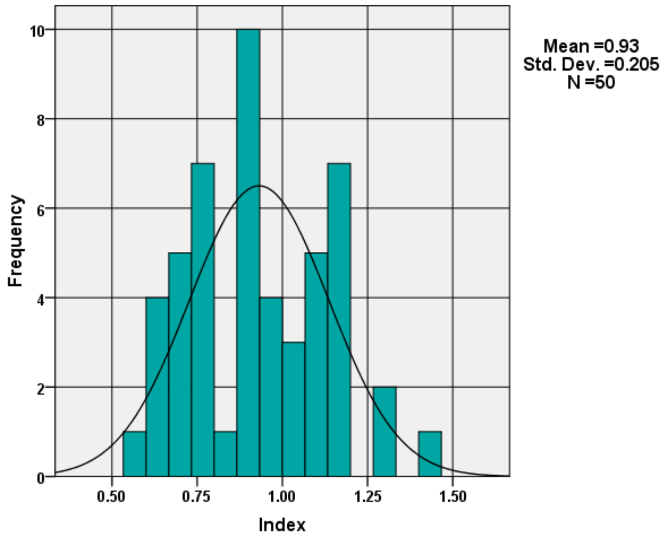
Age	D1 (30-40 cm)	D2 (40-50 cm)	D3 (50-60 cm)	D4 (60-70 cm)	D5 (> 70 cm)	Average Site index
1					0.90152	0.90152
2					0.71710	0.71710
3					0.73815	0.73815
4					0.88312	0.88312
5					1.07558	1.07558
6					0.87968	0.87968
7					0.59584	0.59584
8					0.70239	0.70239
9					1.01326	1.01326
10					1.03937	1.03937
11					1.20036	1.20036
12					0.74541	0.74541
13					0.98214	0.98214
14					1.12570	1.12570
15					1.21695	1.21695
16					1.38146	1.38146
17					1.42096	1.42096
18					1.43301	1.43301
19					0.47787	0.47787
20					0.88800	0.88800
21				0.84422	1.05390	0.94906
22				0.92930	1.18949	1.05939
23				0.98689	1.09750	1.04219
24				1.04779	0.98047	1.01413
25				1.09411	1.12342	1.10877
26			0.68335	0.83357	0.89829	0.80507
27			0.73869	0.96524	1.01374	0.90589
28			0.88561	1.00402	1.08966	0.99310
29			0.77105	1.17221	1.18365	1.04230
30			0.88079	1.21296	1.20060	1.09812
31		0.99696	0.88326	1.27010	1.14417	1.07362
32		0.96991	0.88994	0.75399	0.77052	0.84609
33		0.97920	1.08677	1.05090	1.04474	1.04040
34		1.05696	0.91768	0.74861	0.92009	0.91084
35		1.11798	1.12867	1.13462	0.82320	1.05112
36	0.76418	1.24229	1.42359	1.37208	1.11864	1.18415



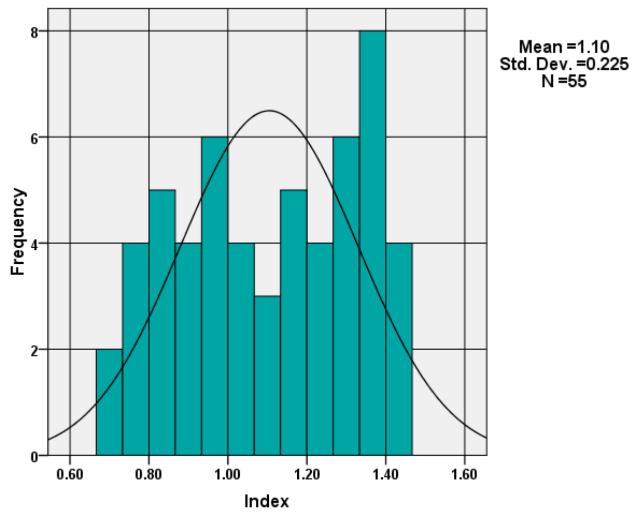
D1 (30-40 cm)



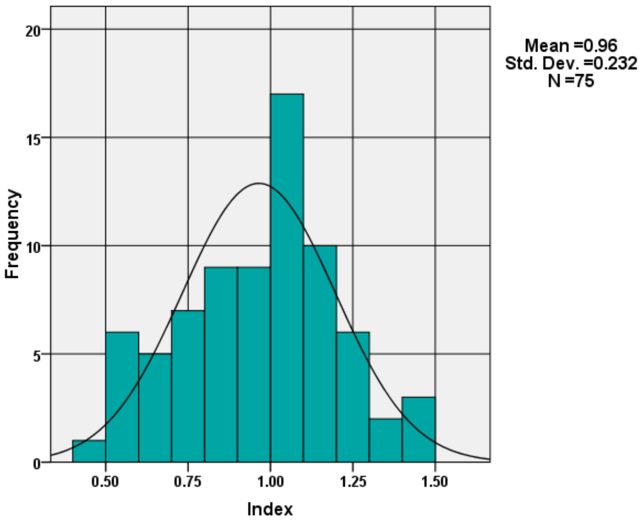
D2 (40-50 cm)



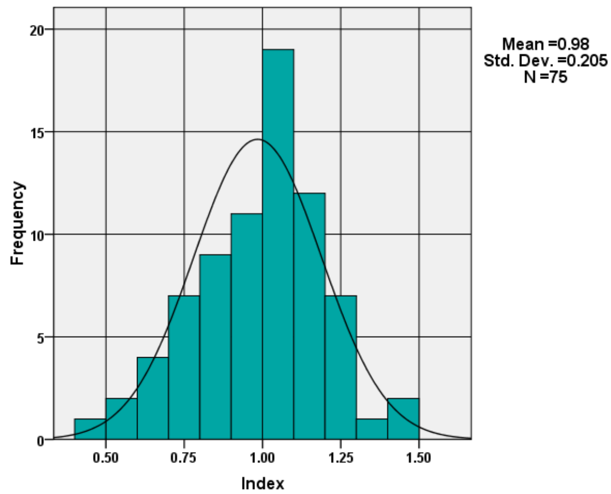
D3 (50-60 cm)



D4 (60-70 cm)



D5 (> 70 cm)



Master chronology

Fig. 50. Histograms showing the distribution of indices in different diameter classes

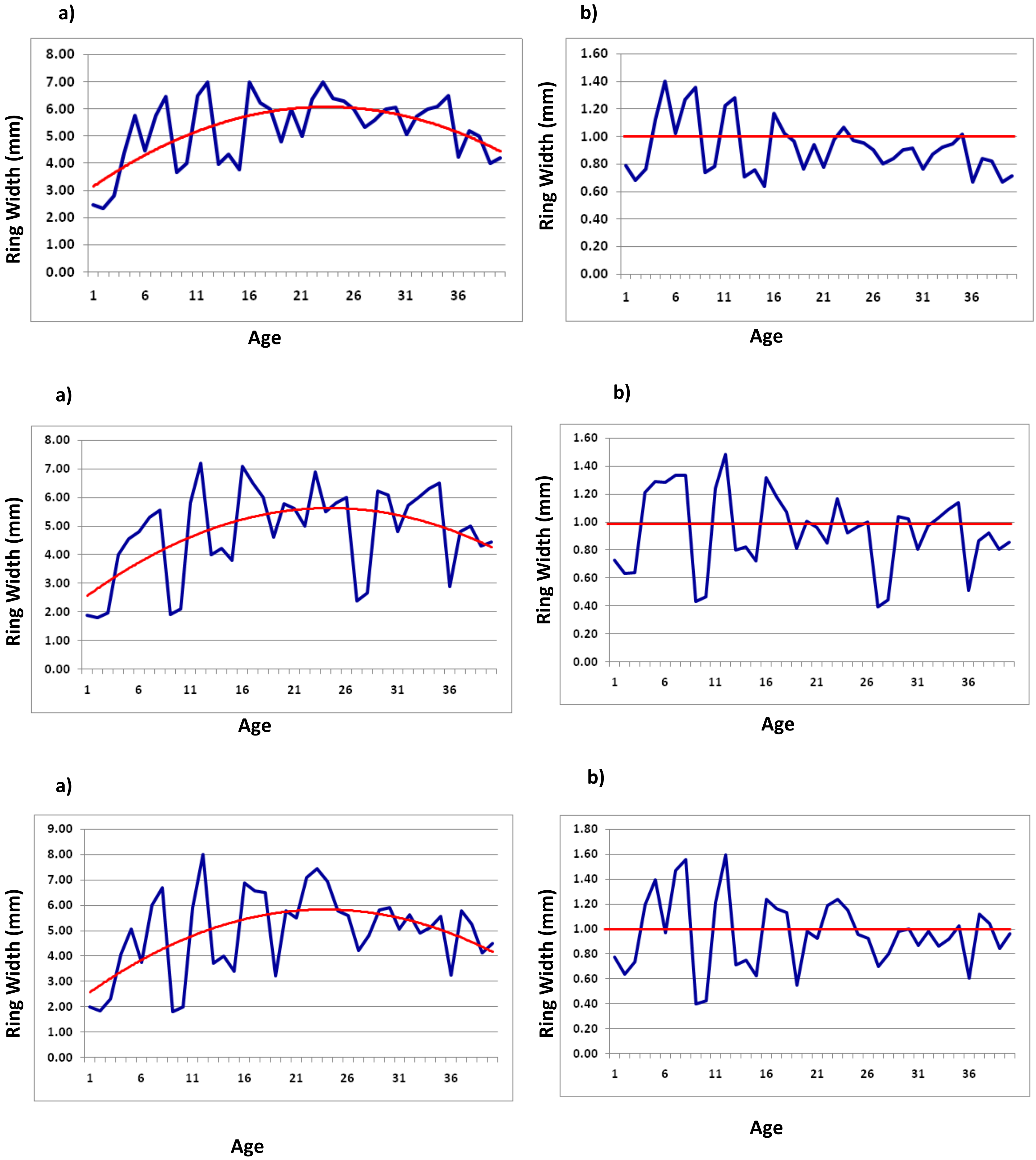


Fig 51. D1: 30-40 cm, a) Before Detrending b) After Detrending

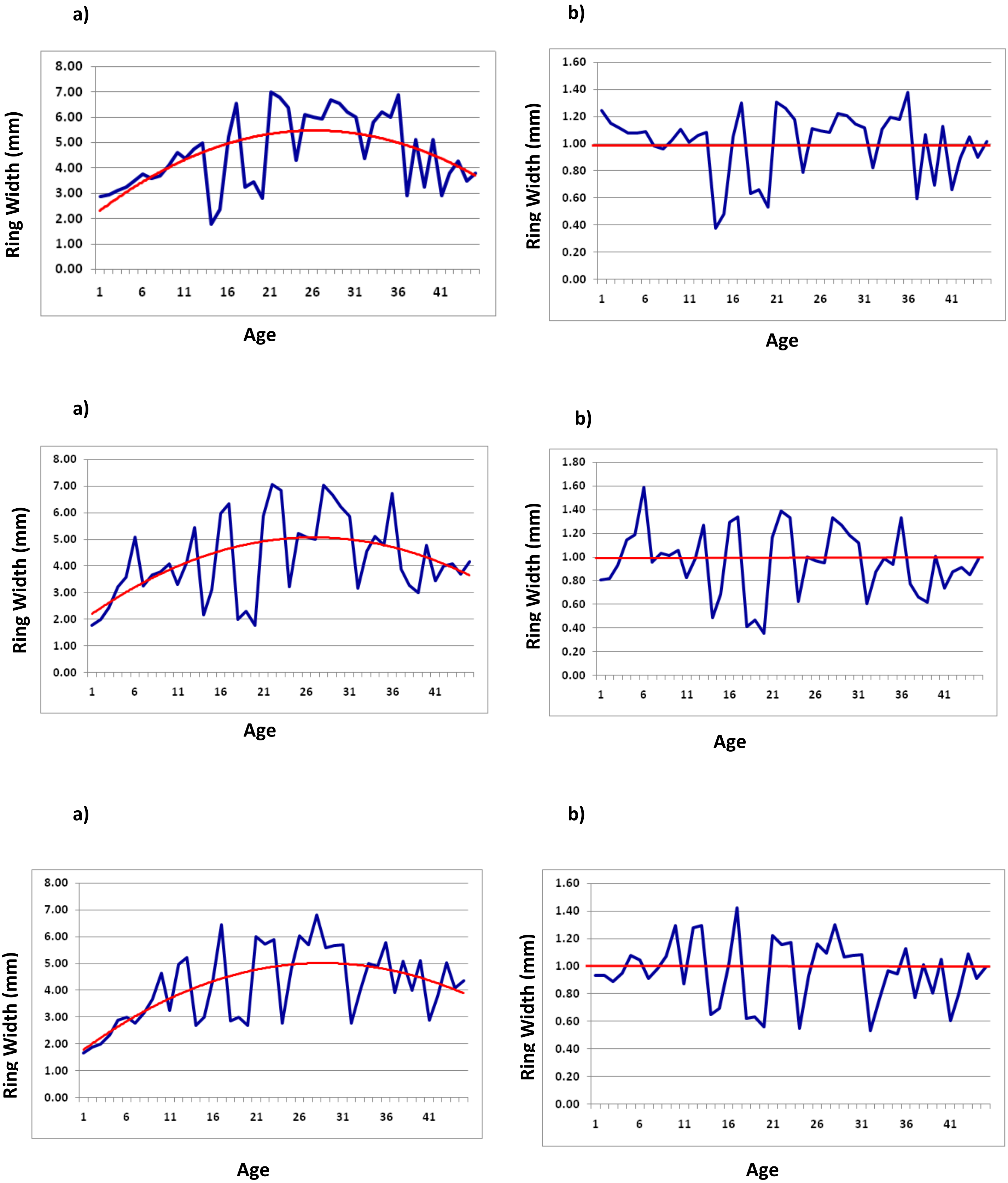


Fig. 52. D2: 40-50 cm, a) Before Detrending b) After Detrending

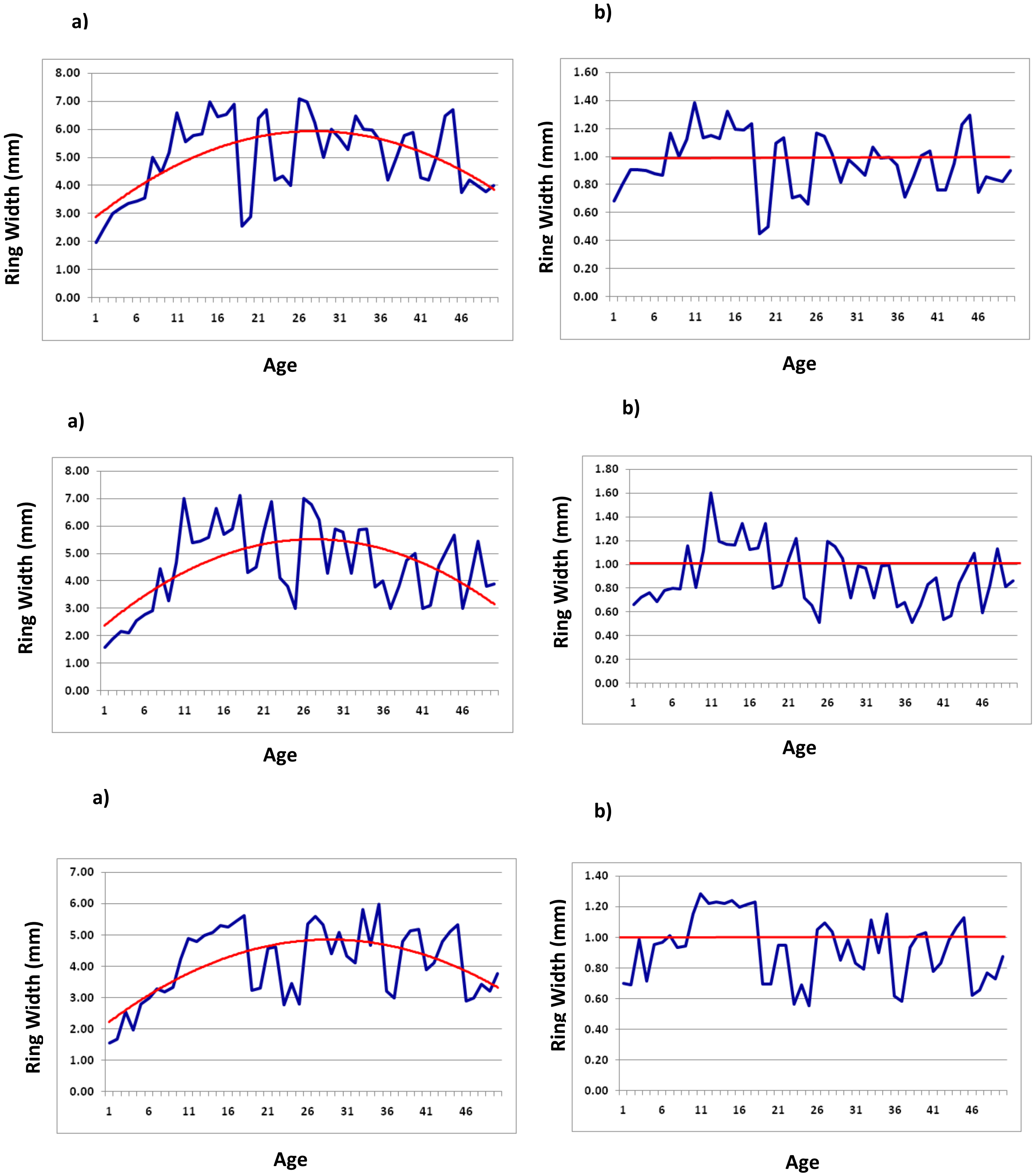


Fig. 53. D3: 50-60 cm, a) Before Detrending b) After Detrending

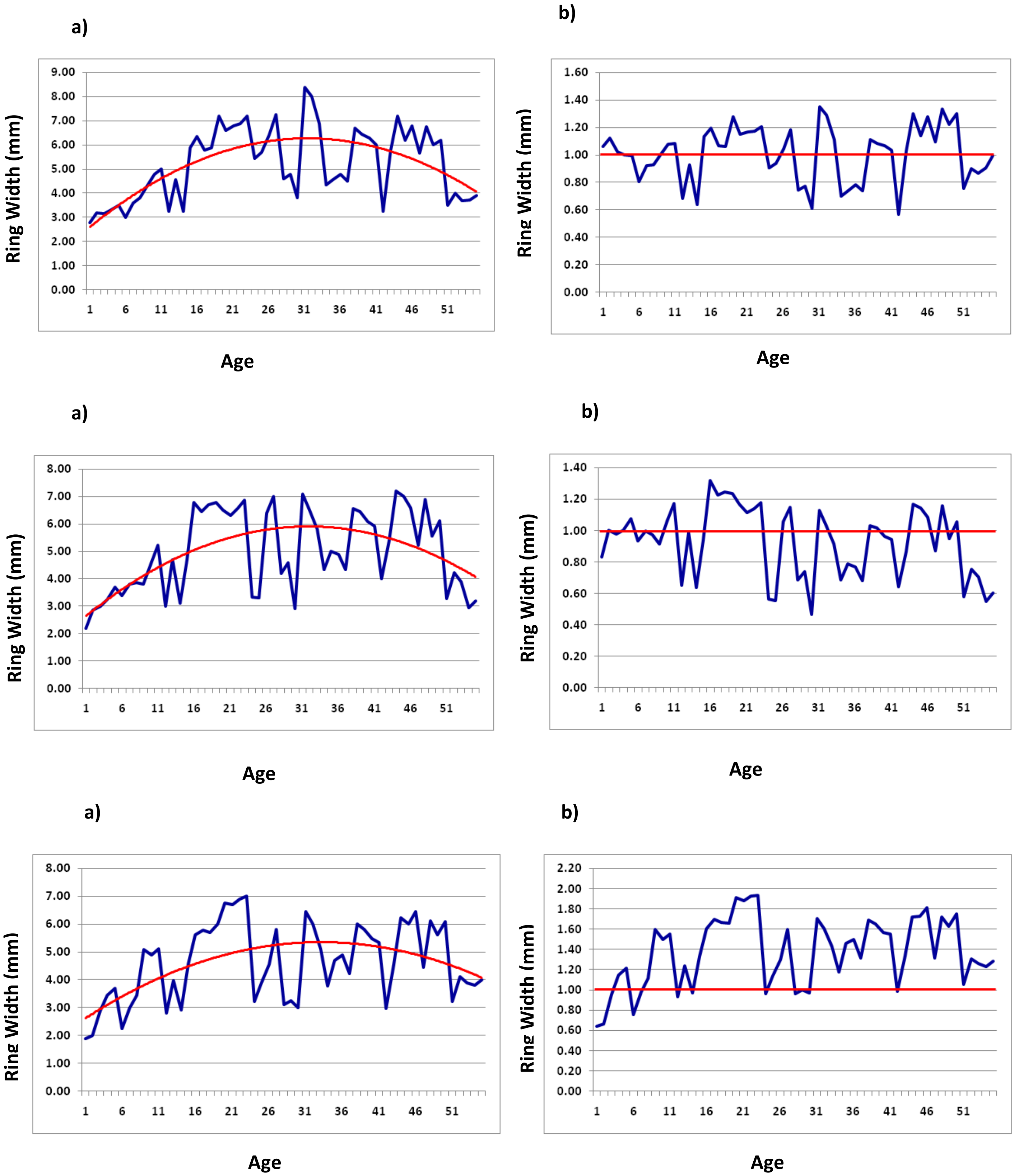


Fig. 54. D4: 60-70 cm, a) Before Detrending b) After Detrending

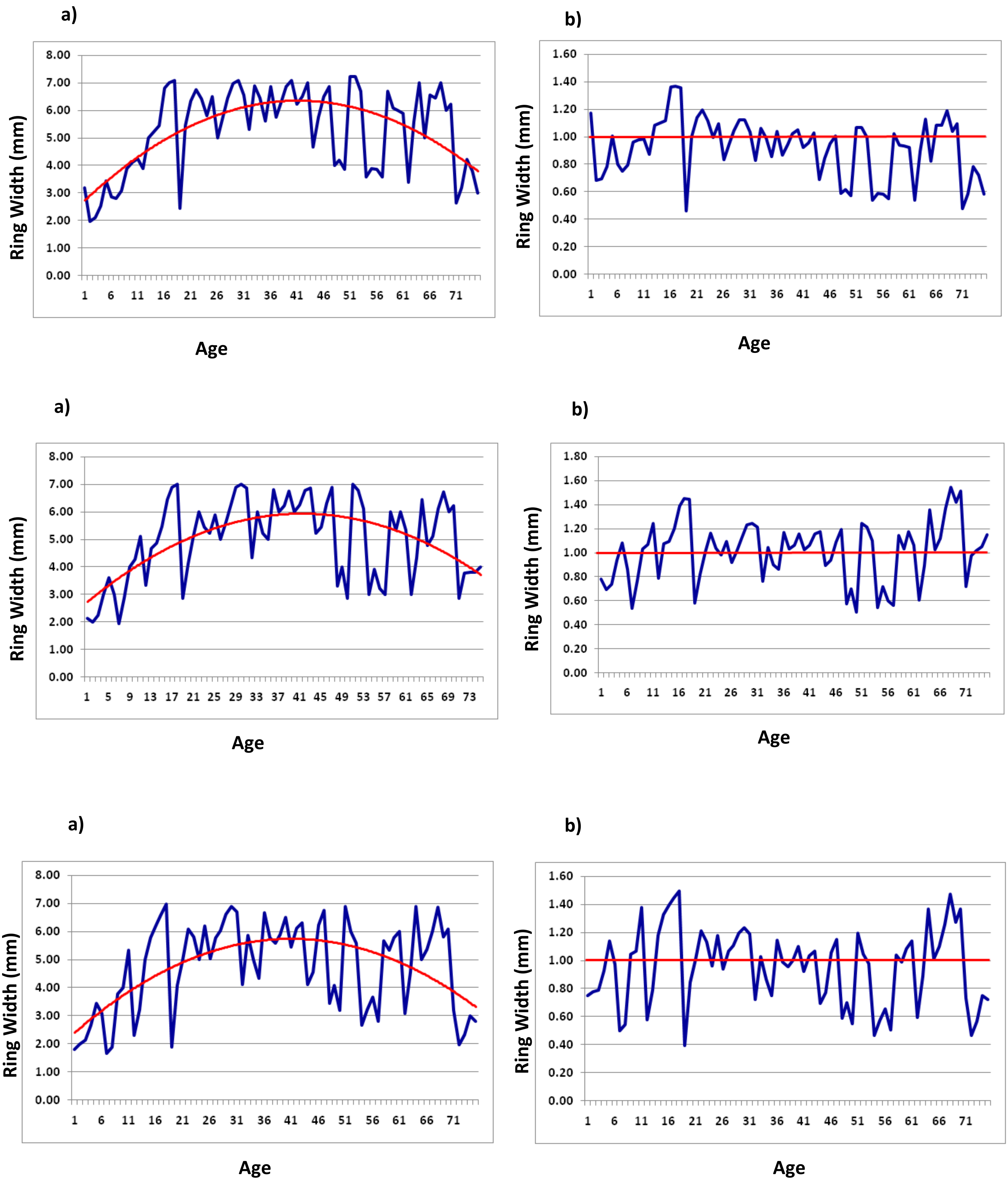


Fig. 55. D 5: >70 cm, a) Before Detrending b) After Detrending

37	0.65259	0.95109	1.18242	1.33001	0.96231	1.01568
38	0.71317	0.99295	1.18337	1.32544	0.98796	1.04058
39	1.17719	1.03876	1.17079	1.39133	1.06011	1.16763
40	1.36199	1.15530	1.30271	1.40922	1.05970	1.25778
41	1.09249	0.90339	1.17198	1.38852	0.97003	1.10528
42	1.35890	1.11115	1.18142	1.41347	1.04982	1.22295
43	1.41739	1.21767	1.26884	1.44073	1.09148	1.28722
44	0.52660	0.50541	0.64807	0.80988	0.75796	0.64958
45	0.55811	0.62200	0.67435	0.87652	0.85111	0.71642
46	1.22710	1.11885	1.02991	1.13589	1.03196	1.10874
47	1.45427	1.35522	1.10109	1.30911	1.11644	1.26723
48	0.74170	0.55359	0.66235	0.79742	0.58313	0.66764
49	0.77725	0.58837	0.69181	0.83606	0.67291	0.71328
50	0.66167	0.48219	0.57675	0.68197	0.54227	0.58897
51	1.24175	1.23377	1.13809	1.39471	1.16751	1.23517
52	1.12251	1.26834	1.13075	1.30889	1.10793	1.18769
53	1.05780	1.22932	1.03542	1.15422	1.02509	1.10037
54	0.70816	0.65251	0.79601	0.85573	0.51678	0.70584
55	0.97674	1.01602	0.98269	0.99615	0.62662	0.91964
56	0.88926	1.07732	0.91084	1.01700	0.61280	0.90144
57	1.00590	1.04296	0.79251	0.91142	0.53926	0.85841
58	1.15819	1.28838	1.05622	1.27994	1.06830	1.17021
59	1.01484	1.18150	0.96226	1.25107	0.98582	1.07910
60	0.95978	1.13653	0.93034	1.20077	1.06375	1.05823
61	0.94323	1.10864	0.74730	1.17531	1.04117	1.00313
62	0.63272	0.65486	0.60251	0.72979	0.57902	0.63978
63	0.69655	0.91510	0.81703	1.07762	0.89246	0.87975
64	0.97413	1.05109	0.95039	1.39618	1.28544	1.13145
65	0.98123	1.02095	0.98521	1.33799	0.95176	1.05543
66	0.81556	1.28034	0.69301	1.39178	1.10349	1.05684
67	0.94121	0.71437	0.72037	1.09193	1.23796	0.94117
68	0.93884	0.91539	0.92553	1.40410	1.40346	1.11747
69	0.98595	0.70717	1.08732	1.26537	1.24313	1.05779
70	1.06128	1.06233	1.17273	1.37002	1.32539	1.19835
71	0.59848	0.66794	0.65402	0.79700	0.64255	0.67200
72	0.94191	0.85841	0.78105	0.98694	0.67559	0.84878
73	0.92796	1.01829	0.91386	0.94415	0.78962	0.91878
74	0.77465	0.88666	0.78821	0.89490	0.84100	0.83708
75	0.84485	1.00130	0.87950	0.96190	0.81858	0.90123

(C) Relationship between ring width index and climatic variables

(i) Correlation between RWI vs average annual temperature (^{0}C)

Regression analysis of climate with the standardized chronology measures the statistical significance of the correlations found above. It quantifies the degree to which tree growth is controlled by any particular parameter, as well as the amount of variance in ring width explained by that parameter. The R-value is a correlation coefficient of linear dependence of the ring widths on the climate data in question. R^2 is a coefficient of determination that determines the “goodness of fit” and the amount of variance explained by the climatic parameter in question. The p-value represents the statistical significance of correlation between the two parameters, and n is the number of observations in the data set.

Table 30 shows the correlation between ring width indices (dependant variable) and average annual temperature (average of maximum and minimum temperature, independent variable). For D1 a significant linear relationship was observed between RWI and average annual temperature (^{0}C) (R=0.514, P < 0.05, Fig. 56). Incase of D2 also a significant linear relationship was found between the RWI and average temperature (^{0}C) (R=0.536, P < 0.05, Fig. 58). D3 showed significant correlation between RWI and temperature (^{0}C) (R=0.558, P < 0.05, Fig. 60). A significant relationship between RWI and temperature (^{0}C) was found incase of D4 (R=0.648, P < 0.05, Fig. 62) and D5 (R=0.662, P < 0.05, Fig. 64). The master chronology was found to have a significant relationship with the average annual temperature (^{0}C) (R=0.681, P < 0.05, Fig. 66). It was observed that the correlation coefficient (R) and the p value increased with an increase in the diameter class indicating stronger temperature related growth responses in mature trees. ANOVA showing the regression between ring width index and temperature is given in Appendix VII.

(ii) Correlation between RWI vs total annual rainfall (mm)

The correlation between RWI (dependant variable) and total annual rainfall (mm, independent variable) is depicted in Table 31. A significant linear relationship existed between RWI and the total annual rainfall (mm) incase of D1 (R=0.475, P < 0.05, Fig. 57). D2 had a significant relationship between RWI and rainfall (R=0.530, P < 0.05, Fig. 59). Although poor, a significant linear relationship was also found in D3 (R=0.334, P < 0.05, Fig. 61). However, D4 and D5 exhibited non significant relationship between RWI and rainfall (Fig. 63, 65). The master chronology for the site showed significant linear relationship with rainfall (R= 0.413, P < 0.05, Fig. 67). ANOVA showing the regression between ring width index and rainfall is given in Appendix VIII.

(iii) Multiple regression between RWI & temperature and RWI & precipitation

Step wise multiple linear regression analysis depicts the contribution of temperature and precipitation to the radial growth of Chir pine (Table 32). The combined effect of temperature and precipitation on ring width was significant in all diameter classes D1 (R= 0.591), D2 (R=0.646), D3 (R= 0.631), D4 (0.662) and D5 (R= 0.663), and the master chronology was also found to be significant at

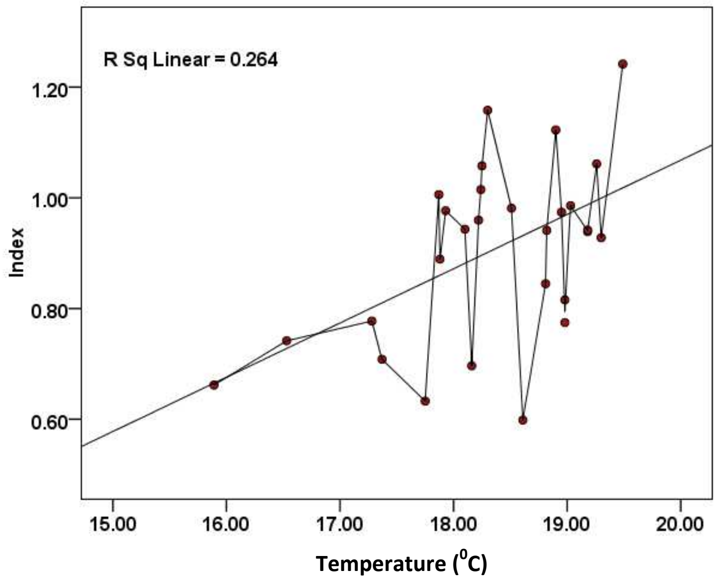


Fig. 56. D1: 30-40 cm; Correlation between Ring Width Index and temperature ^{0}C

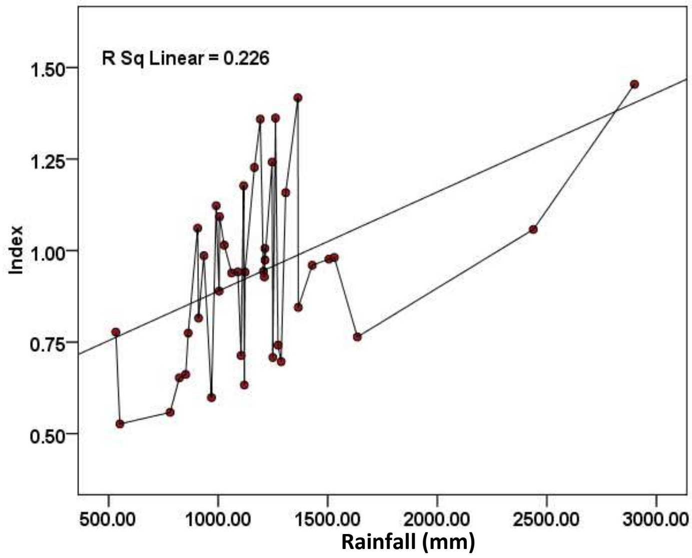


Fig. 57. D1: 30-40 cm; Correlation between Ring Width Index and rainfall (mm)

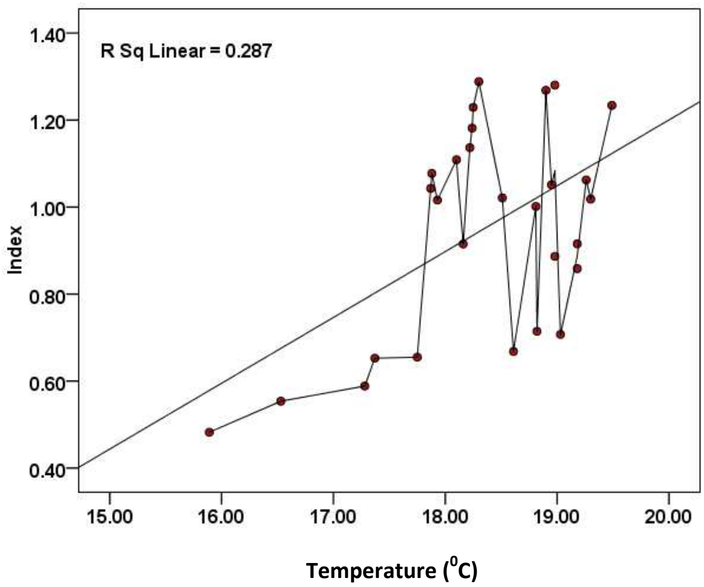


Fig. 58. D2: 40-50 cm; Correlation between Ring Width Index and temperature ^{0}C

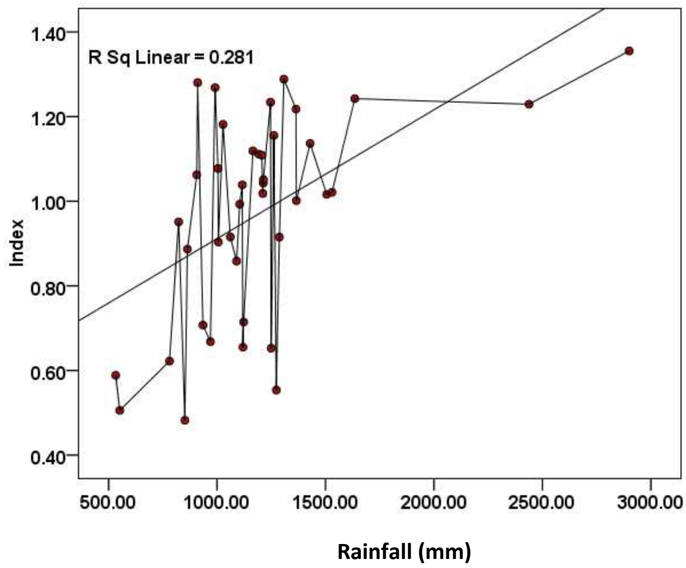


Fig. 59. D2: 40-50 cm; Correlation between Ring Width Index and rainfall (mm)

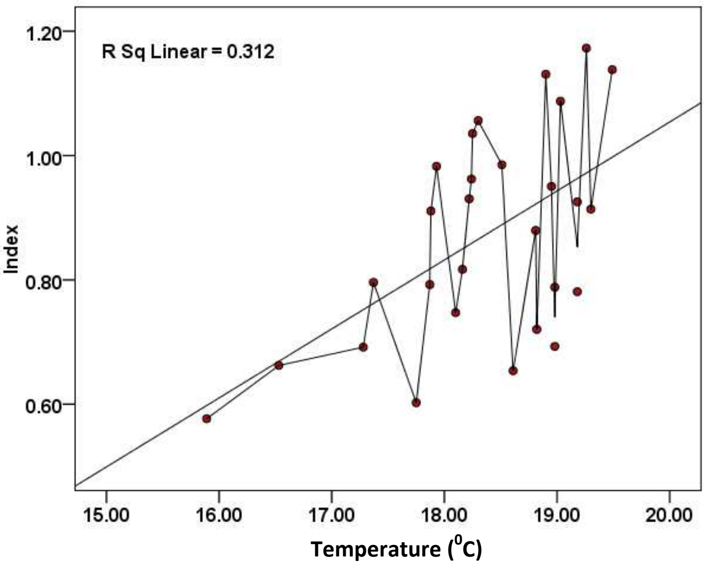


Fig. 60. D3: 50-60 cm; correlation between Ring Width Index and temperature ^{0}C

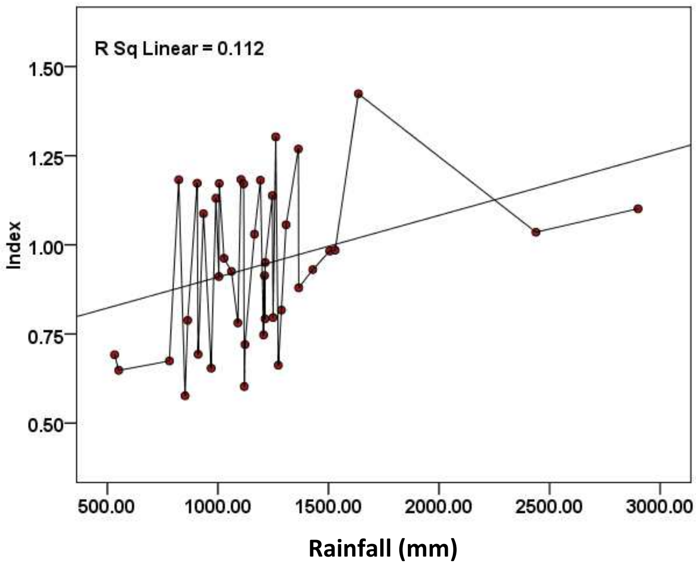


Fig. 61. D3: 50-60 cm; correlation between Ring Width Index and rainfall (mm)

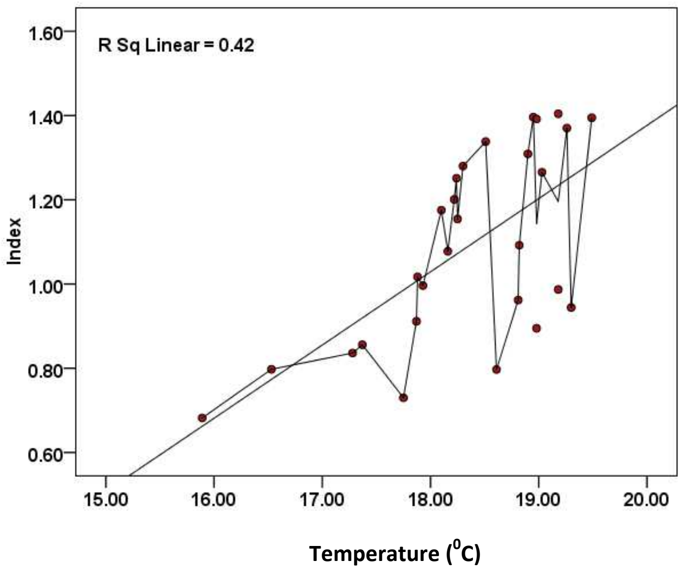


Fig. 62. D4: 60-70 cm; correlation between Ring Width Index and temperature ^{0}C

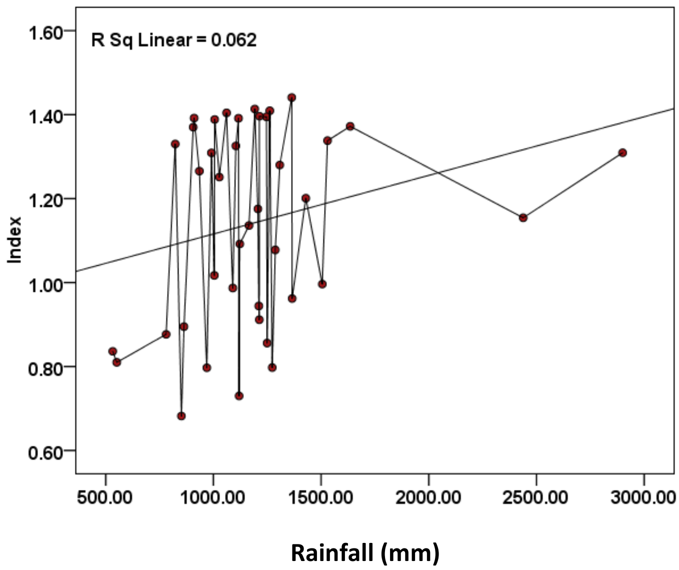


Fig. 63. D4: 60-70 cm; correlation between Ring Width Index and rainfall (mm)

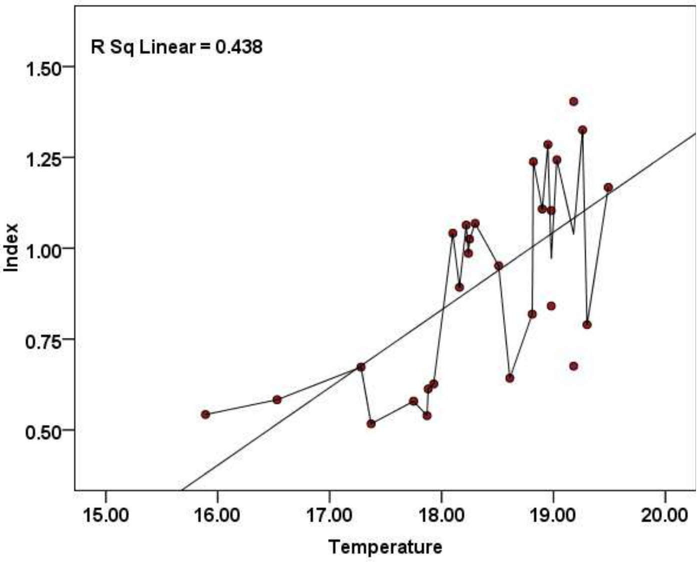


Fig.64. D5: >70 cm; Correlation between Ring Width Index and temperature ^{0}C

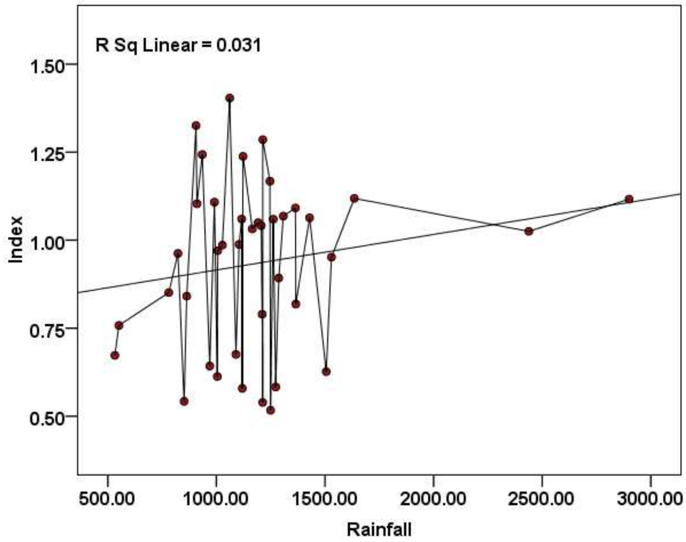


Fig.65. D5: >70 cm; Correlation between Ring Width Index and rainfall (mm)

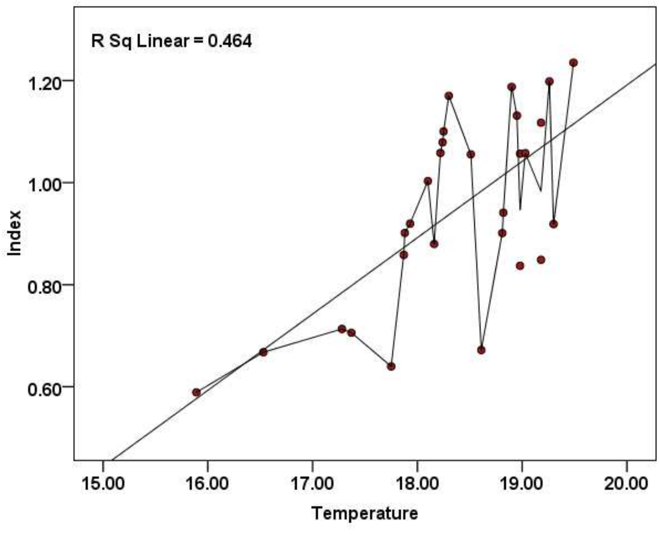


Fig. 66. Correlation between Master Chronology and temperature ^{0}C

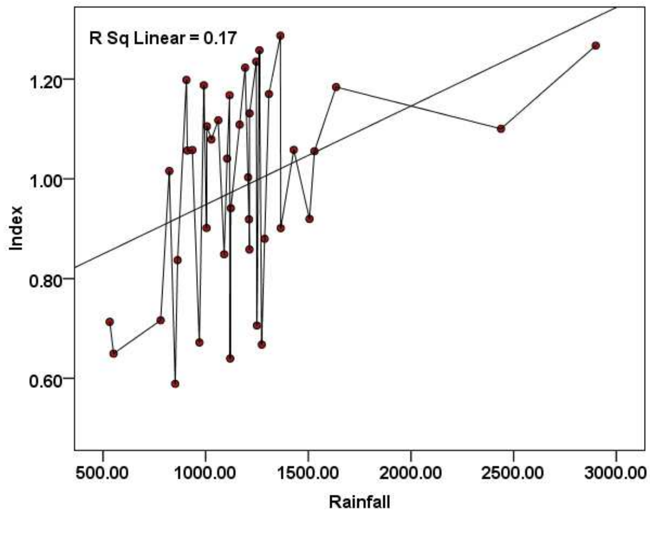


Fig. 67. Correlation between Master Chronology and rainfall (mm)

both 1% and 5% level of significance (R=0.723). Ring width was significantly affected by temperature (P < 0.05) in all diameter classes while precipitation had no significant effect on RWI in all diameter classes except D2. In all the diameter classes it was found that temperature had a stronger effect on growth than precipitation, with the effect becoming more pronounced in older age classes. ANOVA showing regression between RWI (dependant variable and temperature and total annual rainfall (independent variables) is given in Appendix IX.

Table 30. Correlation between RWI vs temperature

Diameter Class	B_0	B_1	R	R Square	Adjusted R Square	Std. Error of the Estimate	t	P value
D1 (30-40 cm)	-0.893 (0.589)	0.098 (0.032)	0.514**	0.264	0.236	0.14146	3.056	0.005*
D2 (40-50 cm)	-1.827 (0.859)	0.151 (0.047)	0.536**	0.287	0.260	0.20636	3.235	0.003*
D3 (50-60 cm)	-1.165 (0.594)	0.111 (0.032)	0.558**	0.312	0.285	0.14268	3.430	0.002*
D4 (60-70 cm)	-2.100 (0.736)	0.174 (0.040)	0.648**	0.420	0.397	0.17678	4.337	0.000*
D5 (> 70 cm)	-3.017 (0.872)	0.214 (0.047)	0.662**	0.438	0.417	0.20929	4.504	0.000*
Average Index	-1.800 (0.579)	0.150 (0.032)	0.681**	0.464	0.443	0.13911	4.742	0.000*

R value ** significant at both 5% and 1% level of significance
P value* significant at < 0.05

Table 31. Correlation between RWI vs precipitation

Diameter Class	B_0	B_1	R	R Square	Adjusted R Square	Std. Error of the Estimate	t	P value
D1 (30-40 cm)	0.619 (0.103)	0.000 (0.000)	0.475**	0.226	0.206	0.21305	3.331	0.002*
D2 (40-50 cm)	0.607 (0.100)	0.000 (0.000)	0.530**	0.281	0.262	0.20732	3.851	0.000*
D3 (50-60 cm)	0.736 (0.100)	0.000 (0.000)	0.334*	0.112	0.088	0.20792	2.185	0.035*
D4 (60-70 cm)	0.976 (0.111)	0.000 (0.000)	0.249	0.062	0.037	0.23117	1.584	0.121
D5 (>70 cm)	0.814 (0.115)	0.000 (0.000)	0.177	0.031	0.006	0.23899	1.108	0.275
Average Index	0.751 (0.089)	0.000 (0.000)	0.413**	0.170	0.149	0.18558	2.795	0.008*

R value * significant at 5% level of significance
R value ** significant at both 5% and 1% level of significance
P value * significant at < 0.05

Table 32. Multiple regression between RWI and temperature & RWI and precipitation

Diameter Class	B_0	B_1	B2	R	R Square	Adjusted R Square	Std. Error of the Estimate	t value (temperature)	t value (precipitation)	P value (temperature)	P value (precipitation)
D1 (30-40 cm)	-1.036 (0.571)	0.097 (0.031)	0.000 (0.000)	0.591**	0.349	0.297	0.13571	3.143	1.804	0.004*	0.083
D2 (40-50 cm)	-2.090 (0.800)	0.149 (0.043)	0.000 (0.000)	0.646**	0.417	0.371	0.19021	3.453	2.367	0.002*	0.026*
D3 (50-60 cm)	-1.316 (0.572)	0.110 (0.031)	0.000 (0.000)	0.631**	0.398	0.350	0.13609	3.551	1.892	0.002*	0.070
D4 (60-70 cm)	-2.193 (0.746)	0.173 (0.040)	0.000 (0.000)	0.662**	0.438	0.393	0.17745	4.298	0.897	0.000*	0.378
D5 (> 70 cm)	-3.051 (0.896)	0.213 (0.048)	0.000 (0.000)	0.663**	0.440	0.395	0.21312	4.415	0.272	0.000*	0.788
Average Index	-1.937 (0.563)	0.148 (0.030)	0.000 (0.000)	0.723**	0.522	0.484	0.13393	4.884	1.747	0.000*	0.093

R value **significant at both 1% and 5% level of significance
P value * significant at < 0.05

Chapter-5

DISCUSSION

Chapter-5

DISCUSSION

Results obtained from the present investigations have been discussed in this chapter. In the light of available scientific explication in literature for the major findings, cause and effect relationship has been discussed and presented as below:

5.1 Land use change of Solan Forest Division

5.2 Temporal change in carbon stock of forest stands

5.2.1 Temporal status of carbon in forest trees of Solan and Dharampur Ranges of Solan Forest Division

5.2.2 Carbon status of Solan and Dharampur Ranges of Solan Forest Division in 2011

5.2.3 Carbon mapping and carbon change analysis

5.3 Impact of climate change on forest growth

5.3.1 Past and present climatic trends

5.3.2 Tree ring standardization

5.3.3 Relationship between RWI and climatic variables

5.1 Land use change of Solan Forest Division

Supervised classification for 1998 and 2010 IRS LISS III images was performed which resulted in a total area of 56,320 ha in Solan Forest Division (recorded forest area + non-forest area, Fig. 26), out of which the forest compartments were extracted with an area of 13,067 ha (recorded forest area, Fig. 27). Classification accuracy as a result of maximum likelihood classification resulted in an overall accuracy of 87 per cent and 89 per cent and KHAT accuracy of 85 per cent and 87 per cent for 1998 and 2010, respectively (Table 13). Comparatively lower accuracy as per 1998 classification was due to relatively higher mixing of spectral signatures between land use categories than in 2008 classification. Cultivation land use category reported the highest User's accuracy of 93 per cent as per 1998 land use classification (Table 11), whereas as per 2010 land use classification (Table 12), Khair land use category reported the highest User's accuracy of 92 per cent due to conspicuous reflectance by them. On the other hand, however, bamboo had the highest producer's accuracy of 96 per cent and 92 per cent in 1998 and 2010 land use classification respectively. Sharma and Bren (2005) while working on land cover classification using IRS (LISS III) of different seasons reported 76 per cent of overall accuracy in summer dataset as compared to 49 per cent and 46 per cent in winter and spring dataset, respectively. On the similar line Brandt and Townsend (2006) were able to map land cover into six classes with an overall accuracy of 88% using traditional classification techniques and limited field data. Cheema and Bastiaanssen (2010) have reported an overall accuracy of 77%, with the producer's accuracy 78% and user's accuracy 83%.

Classification images of Solan Forest Division (recorded forest area + non-forest area) revealed that chirpine, showed an increase in area of 699 ha (5.36%), cultivation category underwent an increase in area of 566 ha (6.87%) while khair increased in area by 92 ha (12.06%) from 1998 to 2010. On the other hand ban oak reported a decrease in area of 652 ha (19.96%), broadleaved decreased in area by 547 ha (7.34%) while culturable blank reported a decrease in area of 120 ha (0.70%) The area under bamboo also decreased by 38 ha (0.60%) in Solan Forest Division (whole area) (Table 9).

Land use classification images of the recorded forest area showed that chirpine increased in area by 191 ha (4.55%), cultivation category increased in area by 129 ha (13.81%) and khair increased by 77 ha (23.40%) from 1998 to 2010. A decrease in area of 181 ha (16.58%) was reported in ban oak, 152 ha (6.30%) in broadleaved, 71 ha (2.72%) in culturable blank and 7 ha (0.47%) in bamboo (Table 10).

An increase in the area of chirpine may be attributed to the imposition of a ban on green felling in hilly states since 1985, an increase in the plantation area of chir pine and profuse regeneration under chir pine forests of the region. Infact, chir pine has also been planted as monoculture in many areas. Cultivation category underwent an increase in area probably due to the allotment of more area for agricultural production including an increase in the area of cash crops and floriculture in the region. An increase in the area of khair may be due to an increase in the area under plantations of khair. Besides, the mixing of the signatures of Khair with other broadleaved species may have caused some spectral confusion.

A decrease in area of ban oak may be attributed to heavy pressure on ban oak in hill states especially for fodder which results in heavy lopping of the species. The satellite sensors directly measure the reflectance of the crown and not the woody portions of the tree. Woody biomass does not contribute much to spectral reflectance (Mabowe, 2006), hence this effects the spectral characteristics of a degraded forest as compared to a healthy forest stand with lesser degree of degradation. Besides, poor regeneration under ban oak as compared to chir pine is also responsible for the reported decrease in area. Joshi and Tiwari (2011) expressed similar views on the biotic pressure on oak forests in hill states. The exploitive management practices and the biotic stress exerted by hill population in relation to oak species have encouraged the pine in various ways (Saxena *et al*., 1984). Villagers frequently graze their cattle in the adjoining forest which increases the pressure beside fodder and fuel wood extracted from oak forest and accidental fires (Singh and Singh, 1984).Much of the area now occupied by pine was originally under the potential natural vegetation of oaks (Champion and Seth, 1968). Conversion of oak forests to pine is still proceeding on a large scale and this trend has lead to severe reduction in the oak forest area in the region and an increase in the area under chir pine, as reported through land use classification of 1998 and 2010 imageries in the present study. Because of its aggressiveness and capacity to colonize disturbed areas, chir pine (*Pinus roxburghii*) is spreading at the expense of Banj oak (*Quercus leucotrichophora)* forests, the latter being under immense biotic pressure (Singh and Singh, 1984).

Broadleaved also decreased in area, may be due to felling both on Government forest land and private lands. Culturable Blank reported a decrease in area which may be explained in light of an increase in the area under cultivation as already mentioned. The area under Bamboo reported a decrease of 38 ha (0.60%) and 7 ha (0.47%) in Solan Forest Division (whole area) and recorded forest area respectively, which may be attributed to pressure on bamboo for its commercial purposes.

Change in land use and land cover type has been studied by various authors from time to time in various parts of India (Gupta, 1996; Kumar, 1999; Singh *et al.*, 2007) and world (Basnyet 1989; Flint and Richards, 1991; Debashis *et al.*, 2004; Semwal *et al*., 2005; Jain *et al.*, 2005; Fox and Vogler, 2005; Achard *et al.*, 2006; Brandt and Townsend, 2006; Hadeel *et al.,* 2009)

5.2 Temporal change in carbon stock of forest stands

5.2.1 Temporal status of carbon in forest trees of Solan and Dharampur Ranges of Solan Forest Division

The total tree biomass (above+below) in 1956 was 41817.31 t, which reduced to 24065.58 t in 1984, increased to 36468.26t in 2002 and further increased to 41173.39 t in 2011 (Table 14). The temporal distribution of tree biomass over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 17751.73 t, an increasing trend over 1984-2002 period by 12402.68 t and over 2002-2011 period there was a further increase by 4705.13 t. The tree biomass (above+below) in 1956 was 96.09 t ha^{-1}, which reduced to 55.30 t ha^{-1} in 1984, increased to 83.80 t ha^{-1} in 2002 and further increased to 94.61 t ha^{-1} in 2011. The temporal distribution of tree biomass over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 40.79 t ha^{-1}, an increasing trend over 1984-2002 period by 28.50 t ha^{-1} and over 2002-2011 period there was a further increase by 10.81 t ha^{-1}.

The tree carbon (above+below) in 1956 was 20908.66 t, which reduced to 12032.79 t in 1984, increased to 18234.13 t in 2002 and further increased to 20586.69 t in 2011 (Table 15). The temporal distribution of tree carbon over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 8875.87 t, an increasing trend over 1984-2002 period by 6201.34 t and over

2002-2011 period there was a further increase by 2352.56 t. The tree carbon density (above+below) in 1956 was 48.04 t ha^{-1}, which reduced to 27.65 t ha^{-1} in 1984, increased to 41.90 t ha^{-1} in 2002 and further increased to 47.30 t ha^{-1} in 2011. The temporal distribution of tree carbon density over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 20.39 t ha^{-1}, an increasing trend over 1984-2002 period by 14.25 t ha^{-1} and over 2002-2011 period there was a further increase by 5.4 t ha^{-1}.

The biomass and carbon stock decreased between 1956 to 1984 period because of increasing anthropogenic pressure on the forests. This in turn may have been responsible for large scale deforestation during this period due to industrialization, road construction, agricultural land expansion and an increase in construction activities in Solan Forest Division, all of which are contributory factors towards the degradation of forests and a subsequent decline in the biomass, carbon stock and productivity of the chir pine forests of the region. This decline in forest carbon stock may also be attributable to felling in compartments, due for routine felling prescribed in the working plan. Both the period of 1984-2002 and 2002-2011 showed an increase in biomass and carbon stock because of the imposition of a ban on green felling in hill states since 1985 and probably because of the increasing accumulation of soil organic matter over the years in the chir pine forests under study.

5.2.2. Carbon status of Solan and Dharampur Ranges of Solan Forest Division in 2011

Vegetation biomass and carbon stock are crucial ecological variables for understanding the evolution and potential future changes of the climate system. Vegetation biomass is a larger global store of carbon than the atmosphere, and changes in the amount of vegetation biomass already affect the global atmosphere by being a net source of carbon and having the potential either to sequester carbon in future or to become an even larger source. Depending on the quantity of biomass the vegetation cover can have a direct influence on local, regional and even global climate, particularly on air temperature and humidity. Therefore, a global assessment of biomass and carbon stock and its dynamics is an essential input to climate change forecasting models and mitigation and adaptation strategies.

The biomass and carbon stock in forest vegetation varies, according to geographical location, plant species and age of the stand (Van Noordwizk *et al.*, 1997). Estimates of biomass and carbon stock contained within undisturbed forests are critical aspects of determination of carbon loss associated with a wide range of land use and land cover changes processes. In order to assess the impact of deforestation and regrowth rates on the global carbon cycle, it is necessary to know the stocks of carbon as biomass per unit area of different types of vegetation. The above ground and below ground tree carbon, shrub and herb/grass carbon and soil carbon stock are needed to be estimated to enable better calculations of total carbon (Hamberg, 2000). Direct measurement of biomass and carbon stock of different components of forest ecosystem are used for estimating the current carbon status of chir pine forests in selected compartments falling in Solan and Dharampur Forest Ranges of Solan Forest Division.

(A) Soil physico-chemical properties

(i) Soil pH

In the humus layer the soil pH ranged from 5.12 to 6.67, 5.76 to 7.00 at 0-20 cm depth, 5.81 to 7.09 at 20-40 cm depth and from 5.98 to 7.26 at 40-100 cm depth (Table 16). The mean soil pH was minimum at D-181 Sirguli Ka Tiba III which was 5.79 and maximum at D-89 Gadhog I which was7.05. In general the soil pH increased with increasing soil depth. The low pH level in the soil of all the studied compartments was slightly acidic to neutral, and could be ascribed to the decomposition of organic matter and release of organic acids during the decomposition of litter resulting in more acidity in soil. The results are in line with Bishnoi *et al*., (1983) who reported that soil reaction varies between 5.0 to 6.8 under different locations in Himachal Pradesh and Sharma (1988) regarding slightly acidic reaction of HP soils. Similar results were also reported by Yadav (1963) in Chakrata Forest Division.

(ii) Soil Electrical Conductivity (dSm^{-1})

Electrical conductivity (dSm^{-1}) of the soils showed low level of soluble salts concentration (Table 16). The soil EC ranged from 0.15 to 0.24 dSm^{-1} in the humus layer 0.13 to 0.22 at a depth of 0-20 cm, 0.04 to 0.13 dSm^{-1} at 20-40 cm depth while at a depth of 40-100 cm the EC ranged from 0.03 to 0.10 dSm^{-1}. The mean soil EC was minimum at D-181 Sirguli Ka Tiba III (0.09 dSm^{-1}) and the maximum at D-90 Gadhog II (0.18 dSm^{-}1). In general the soil EC decreased with increasing depth. Similar findings have been reported by Shrikanth *et al.* (2002) and Jayabaskaran *et al*. (2001).

(iii) Soil Organic Carbon (%)

The soil organic carbon (%) ranged from 10.79 % to 11.47 % in the humus layer, from 1.24 % to 2.47 % at a depth of 0 to 20 cm, from 1.08 % to 2.27 % at 20 to 40 cm soil depth and at 40 to 100 cm depth the soil organic carbon (%) had a range from 1.01 % to 1.24 % (Table 17). The mean soil organic carbon (%) was the minimum at D-89 Gadhog I (3.53 %) and the maximum at D-181 Sirguli Ka Tiba III (4.37 %).a depth of 0-20 cm depth and from 1.05 % to 2.37 % at 20-40 cm depth respectively. It was found that the soil organic carbon (%) decreased with increasing soil depth. Higher organic carbon accumulation in surface soil than sub-surface layers could be attributed to higher amount of litter accumulation on surface. Leaf litter accumulation on the surface and its decomposition with time enrich the upper layer continuously. These results were in accordance with the findings of Banerjee and Badola (1980), Gupta *et al.* (1991), Kaushal (1992), Saralch (1994), Bhola (1995) and Nayak (1996). Gradual decline in the availability towards lower soil layers could be due to more accumulation and mineralization and reduced root biomass in deeper soil layers. The other reason may be cycling of nutrients i.e. deep tap root system may be extracting elements from lower layers and deposited in surface soils.

These results were also well supported by the findings of Malik (1992) for chir pine forests of Solan district in Himachal Pradesh, Banerjee and Nath (1991) for soils of Kinnaur, Kaushal (1992) for deodar forests soils, Saralch (1994) for soil under Eucalyptus plantation, Bhola (1995) and Nayak (1996) for high density plantations. Decrease in soil organic carbon with depth has also been reported by Ramachandran *et al*., (2007) in Kolli hills in Eastern Ghats, Kumar (2003), Minj (2008), Goswami (2009) in Solan, Sheikh *et al*., (2009) for Garhwal Himalaya, Dinakaran and Krishnayya (2008) for tropical soils and Alamgir and Amin (2008) for Chittagong (south) Forest Division, Bangladesh.

There was also a decrease in soil organic carbon (%) with an increase in elevation. The higher organic carbon at lower altitudes may be due to sliding of litter from higher altitudes due to rain, run off and gravity down the slope and its accumulation at lower altitudes. Similar observations have been recorded by Banerjee and Badola (1980), Gupta *et al.* (1991), Kaushal (1992) and Malik (1992). The results are also in line with the observation of Hart *et al*. (1992), Singh (2004) and Broquen *et al*. (1999).

(iv) Soil Bulk Density

Bulk density is a measure of the weight of the soil per unit volume (g cm^{-3}), usually given on an oven-dry (110° C) basis. Variation in bulk density is attributable to the relative proportion and specific gravity of solid organic and inorganic particles and to the porosity of the soil.

The soil bulk density ranged from 0.60 to 0.82 gcm^{-3} in the humus layer, from 1.01 to 1.36 gcm^{-3} at a depth of 0 to 20 cm, from 1.05 to 1.42 gcm^{-3} at a depth of 20 to 40 cm and from 1.10 to 1.45 gcm^{-3} at 40 to 100 cm soil depth (Table 17). The mean soil bulk density was the minimum at D-181 Sirguli Ka Tiba III (0.95 gcm^{-3}) and the maximum at D-89 Gadhog I (1.26 gcm^{-3}). It was found that the soil bulk density increased with increasing soil depth, with the minimum bulk density in the humus layer and the maximum at 40-100 cm soil depth. The increase in bulk density with increasing soil depth can be owed to decrease in the organic carbon with increasing soil depth. Similar findings have been reported by Minhas *et al*. (1997), Kumar (2003), Minj (2008), Goswami (2009) and Masoodi (2010) for the soils of Solan.

(B) Soil Carbon Stock of chir pine forests

Table 33. Summary of location, soil texture, soil taxonomic classes and estimated soil organic carbon C density (0-50, 0-100 cm) for different forest types of montane temperate forest, of India (Chhabra *et al.*, 2003)

Reference	State	Locations (coordinates)	Soil texture	Soil taxonomic names	Soil O C density (t ha^{-1})			
					Top 50 cm		Top 1m	
					No. of observations	Range	No. of observations	Range
Bandana (2011)	HP	Solan	Sandy loam, clay loam				21	156.64-238.53
Chaudhri *et al.* (1977)	HP	Badaghat FD	Loamy and loam, sandy loam, silt loam		6	12.1- 26.5	4	24.1- 42.8
Banerjee and Badola (1980)	UP	Chakrata FD			5	38.6- 106.3	5	57.1- 176.5
Singh *et al.* (1987)	W B	Drjeeling			5	42.2- 184.3	5	158.3- 525.7
Nair *et al.* (1989)	ME	E. Khasi hill	Loam, silty loam	Humic Hapludult, Typic Udorthent, Typic Dystrochrepts, Typic Haplumbrept				67.0- 222.4
Gupta and Singh (1990)	HP	Shimla	Loamy, Silty loam,Silty clay					44.8- 174.6
Raina *et al.* (1999)	U K	Mussorie	Silty loam,loam, silty, Clay loam		3	96.7- 159.5	3	140.3- 261.3
Chir pine forests (present study)	HP	Solan and Dharampur	Sandy loam					189.29

Soil carbon measurement is the focus of current and future international negotiations and treaties related to global change. However, more efficient methods of measuring soil carbon are required to support better estimates of terrestrial carbon inventories and inventories and fluxes for efficient management (National Research Council, 1999). Improved terrestrial carbon inventories may require many more measurements than can be delivered economically using current technologies and approaches. Worldwide, SOC stocks up to 1m average 12.2 Kg m^{-2} in temperate forests (Prentice *et al*., 2001 and Lal, 2005), 13.9 Kg m^{-2} in cool-temperate wet forests (Post *et al*., 1982), and 11.3 Kg m^{-2} among all forests (Sombroek *et al*., 1993). Morisada *et al*. (2004) reported an average SOC stock of 18.8 Kg m^{-2} for the Japanese forests (9.0 Kg m^{-2} for the upper 30 cm), much higher than the global estimate of temperate zone, probably due to the influence of volcanic ash on soil. A soil carbon density of 161.9 t ha^{-1} for the soil depth of 1 m was reported by Chhabra *et al*. (2003) for montane temperate forest. The soil carbon stock (SOC) exhibits considerable spatial variability, both horizontally according to land use and vertically within the soil profile. The SOC diminishes with depth regardless of vegetation type and soil texture (Trujilo *et al*., 1997).

The soil carbon density (t ha^{-1}) declined with the increasing soil depth. Soil organic carbon (SOC) depends upon various biotic and abiotic factors such as microclimate, faunal diversity, land use and management. Leaf litter and root litter input play a major role in forest soil. The upper layer remains in dynamic equilibrium with biological and anthropological activities and is generally richer in C than the lower layers. Similar results were also reported earlier by Shrestha *et al*. (2004) in mountain watershed of Nepal. The growth and functions of vegetation depends on the availability of plant nutrients in the soil, whilst, SOC dynamics depend on the input received from the vegetation grown. Thus, there is an inter-relationship between vegetation and soil carbon dynamics in an ecosystem. The input can be from above ground leaf litter and/or the below ground fine roots (Bloomfield *et al*., 1996) and their decomposition rates are governed by microbial activity. The chemical composition of vegetation determines the residence time of organic carbon in the terrestrial ecosystem (Rasse *et al.*, 2006). Some plant materials are easily decomposable, while some are highly recalcitrant and thus, remain in the ecosystem for longer periods. The soil carbon pools in the natural forest ecosystems in my study are on the higher side to that of other montane temperate forest of India (Banerjee and Badola, 1980; Chaudhri *et al*., 1977 and Gupta and Singh, 1990), but are comparable to that reported by other workers (Singh *et al*., 1987; Nair *et al*., 1989; Raina *et al*., 1999; Bandana, 2011).

The soil carbon stock ranged from 18.87 to 317.31 t at the humus layer, from 127.87 to 2069.10 t at a depth of 0 to 20 cm, from 118.37 to 1675.80 t at 20 to 40 cm depth and from 207.35 to 3441.20 t at 40 to 100 cm soil depth. Total soil carbon stock was 3527.38 t in humus, 21662.38 t in 0-20 cm layer, 18668.31 t in 20-40 cm layer, 39217.98 t in 40-100 cm layer and in 0-100 cm soil depth it was found to be 79548.68 t. in {Humus + Soil (0-100cm layer)}it was reported as 83076.05 t (Table 18).

Soil carbon density ranged from 6.73to 9.62 t ha^{-1} at the humus layer, from 33.73 to 55.80 t ha^{-1} at a depth of 0 to 20 cm, from 30.52 to 50.46 t ha^{-1} at 20 to 40 cm depth and from 81.84 to 99.83 t ha^{-1} at 40 to 100 cm soil depth (Table 18). Soil carbon density was 8.15 tha^{-1} in humus, 48.77 t ha^{-1} in 0-20 cm layer, 42.14 t ha^{-1} in 20-40 cm layer, 90.22 t ha^{-1} in 40-100 cm layer, 181.13 t ha^{-1} in 0-100 cm soil depth. In {Humus + Soil (0-100cm layer)} it was reported as 189.29 t ha^{-1}. It was found that the soil organic carbon stock decreased with increasing soil depth for the same reason as explained earlier for soil organic carbon (%).

(C) Vegetation Carbon Stock

The total tree carbon stock (t) of the 33 forest compartments of chir pine in the present study was 20586.69 t, with 13029.60 t in stem, 3127.07 t in branch, 651.49 t in leaf and 3778.55 t in root (Table 19). The tree carbon density was 47.31 t ha^{-1}, with 29.94 t ha^{-1} in stem, 7.19 t ha^{-1} in branch, 1.50 t ha^{-1} in leaf and 8.68 t ha^{-1} in root. Total herb carbon stock was 909.22 t with 425.97 t in shoot and 483.26 t in root, while the herb carbon density was 2.09 t ha^{-1} with 0.98 t ha^{-1} in shoot and 1.11 t ha^{-1} in root. Total shrub carbon stock was 757.46 t with 380.68 t in shoot and 376.78 t in root and the shrub carbon density was 1.74 t ha^{-1} with 0.87 t ha^{-1} in shoot and 0.86 t ha^{-1} in root. Total vegetation carbon stock was 22253.43 t. Reduction of light intensity under tree crown has been held as the main factor for low production of herbage under trees by Grelen and Whrey (1978), Singh *et al*. (1980), Ramakrishna (1984), Hazra and Patil (1986), Chaturvedi *et al*. (1988), Bhatt *et al*. (1994), Sharma and Dhiman (1994) and Dutt and Gupta (2005). Allelopathy and interference of needle in chir pine has been advocated for low herbage production under trees by Gupta *et al*., (2007). Vegetation carbon density was 51.13 t ha^{-1}.

(D) Detritus Carbon Stock

The standing dead tree carbon stock was 636.49 t and that the standing dead tree carbon density was 1.46 t ha^{-1}. Fallen tree carbon stock was 295.33 t and fallen tree carbon density was 0.68 t ha^{-1}. Carbon stock in floor material was recorded as 1613.12 t while carbon density was 3.71 t ha^{-1}. Total detritus carbon stock was 2544.94 t while the detritus carbon density was 5.61 t ha^{-1}. Detritus carbon density depends on the light requirement of species, leaf-shedding habit and stem density. Chir pine is a strong light demander, hence its trees and/or branches die because of natural thinning, natural pruning leading to more carbon density in the dead pool. In addition to it they regularly shed leaves, leading to the building up of leaf litter on the forest floor (Table 20).

(E) Ecosystem Carbon Stock

The total ecosystem carbon stock (plant+soil) (t) was 107874.40 t and the total ecosystem carbon density (t ha^{-1}) was 247.87 t ha^{-1} (Table 21). The results are in line with the results of Zhu *et al*. (2010) who found an ecosystem carbon density of 237 t ha^{-1} in temperate forests of Northeast China. This estimate is however higher than that reported by Nizami *et al*. (2009) in subtropical pine forests (100-128 t ha^{-1}) in Pakistan and Dixon *et al.* (1994) whose study reported that the tropical forests in Asia hold a carbon density of 132-174 t ha^{-1}. The soil vegetation ratio was 4.41 for the chir pine forests under study. This means that soil contained more organic carbon than vegetation. The results are in consonance with the results of Kumar (2003) who reported more carbon in the soil than in the vegetation for sub-tropical sub-temperate conditions of Himachal Pradesh.

Table 34. Comparison between estimates of biomass and biomass carbon density reported in earlier studies for India and Asia with the result of the present study

S No.	Region / forest types	Location	Above ground biomass (t ha^{-1})	Above ground carbon density (t C ha^{-1})	Total carbon density (above + below ground carbon density) (t ha^{-1})	Reference
1	*Pinus roxburghii*	India	91.5-232.3	46.65- 199.84		Chaturvedi and Singh (1987)
2	North- west Himalaya	Garhwal India	101.42-434.43		59.20- 245.31	Sharma *et al*.(2010)
3	Central Himalaya	India	137.00-245.00		68.50- 122.50	Tiwari and Singh (1987)
4	Central Himalaya (Good forests)	India			131.5- 225.60	Singh *et al*. (1985)
5	Central Himalaya (Medium forest)	India			75.2- 131.50	Singh *et al*. (1985)
6	Mixed oak-pine	India	325.8			Rana and Singh (1989)
7	Temperate Indian forest	India			47.42	Manhas *et al*. (2006)
8	Subtropical forests	China	81.80	40.94		Deo, (2008)
9	Subtropical forests	China			36-57.07	Zang *et al*., (2007)
10	Asian forests				132.00- 174.00	IPCC (1996)
11	Tropical forests				55-90	Brown and Lugo (1984)
12	Asian forests (moist- forest)			250		Ajay *et al*. (1979), Brown and Lugo (1984)
13	Asian forests (open forest)			60		Ajay *et al*. (1979), Brown and Lugo (1984)
14	Asian forest (seasonal forest)			150		Ajay *et al*. (1979), Brown and Lugo (1984)
15	Himalaya *Pinus roxburghii*	India	110.34	239.86	137.1	Sharma *et al*.(2010)
16	Siwalik *Pinus roxburghii*	India		126.23	73.3	Sharma *et al*.(2010)
17	Hard wood and conifer forest	India		53		Manhas *et al*. (2006)
18	Pine Forest		86.02	38.70		Baral *et al*. (2009)
19	Natural Chir pine forest	India	80.96	40.48	51.13	Present study

A cross-section of above-ground biomass values of trees for certain related forest ecosystem is given in Table 34. The aboveground biomass in the chir pine forests of Solan and Dharampur Forest Ranges was 80.96 t ha^{-1} which was less than that reported by Sharma *et al*. (2010) and by Chaturvedi and Singh

(1987) but in line with that reported by Deo (2008) and Baral *et al*. (2009). The above ground carbon density (t C ha^{-1}) was reported as 40.48 t C ha^{-1} which was also considerably lower than that reported by Sharma *et al*. (2010) but close to that estimated by Baral *et al*. (2009), Chaturvedi and Singh (1987) and Deo (2008). However, the total carbon density (above + below ground carbon density) (t ha^{-1}) was 51.13 t ha^{-1} which was and in line with that reported by Brown and Lugo (1984) and Zang *et al.* (2007), higher than that reported by Manhas *et al*. (2006) for Temperate Indian forests and lower than that reported by Sharma *et al*. (2010), Chaturvedi and Singh (1987), Tiwari and Singh (1987) and Singh *et al*. (1985).

5.2.3. Carbon mapping and carbon change analysis

Relationship of biomass and spectral data has shown different results in different research studies. Zheng *et al*. 2004, obtained strong relationship in a temperate forest ranging in biomass upto 220 t ha^{-1} and Kurtz *et al*. (2010) reported a significant relationship between total above ground biomass and NDVI (R^2 = 0.5). In the present study a significant linear relationship was observed between carbon and NDVI (R = 0.741) for 1998 and NDVI (R = 0.663) for 2010 (Table 22).

However, poor relationships were observed in some studies (Foody *et al*., 2003; Kasischke, 2004; Labrecque *et al*., 2006; Lu, 2006; Schlerf *et al*., 2005). In general a number of reasons may be responsible for poor correlation between biomass and vegetation indices as given below:

- The saturation of the relationship between biomass and NDVI is a well known problem (Mutanga, 2004). Saturation is when a dependant variable (biomass) levels off and ceases to increase with increase in the independent variable (vegetation index). The most logical explanation is that as canopy cover increases, the amount of Red light that can be absorbed by the leaves reaches a peak while NIR reflectance increases because of multiple scattering with leaves (Thenkabail *et al*., 2000). Further, NIR reflectance also saturates with increasing leaf area index (LAI) ≥3 and so does NDVI (Schlerf *et al*., 2005). The imbalance between a slight decrease in the Red and high NIR reflection results in a slight change in the NDVI ratio, hence results in a poor relationship with biomass (Mutanga, 2004). Rauste (2005) reports that saturation level may depend on the tree species and forest type as well as the ground surface type because, Imhoff, (1995) found saturation level at 40 t ha^{-1} of dry biomass in temperate forests in U.S.A, Luckman *et al*., (1998) observed saturation level at 60 t ha^{-1} in a tropical forest in Brazil, Fransson and Israelsson (1999) observed saturation at 143 m^3ha^{-1} i.e. 85.8 t ha^{-1} in a boreal forest in Sweden. Steininger, 2000 found that the canopy reflectance saturated when the AGB approached about 15 kgm^{-2} i.e. 150 t/ha in a tropical secondary forest in Manaus, Brazil.

- One fundamental reason for poor prediction of biomass from optical remote sensing is that satellite sensors can only see the forest canopy and cannot detect how much biomass is found under the canopy. In dense canopy forest, the stem biomass that is hidden from the sensor comprises majority of the aboveground biomass.

- Another reason is the physico-chemical properties of leaves such as structure, chlorophyll content and water content (Ingram *et al*., 2005; Steininger, 2000). Leaf senescence of deciduous species could have effect on spectral characteristics of the forest. Vegetation appears dark in the red band due to chlorophyll absorption of red wavelengths and appears bright in near-infrared band due to high reflectance and multiple scattering of photons. Middle infra-red bands are subject to absorption by water in leaf.

- Generally estimations of aboveground biomass are concerned with the woody material of biomass and exclude foliage grass, small trees and shrubs which are photosynthetically active material. Similarly the satellite sensor directly measures the reflectance of the crown and not the woody portions of the tree. Woody biomass does not contribute much to spectral reflectance. As such a relationship between woody biomass and crown has to be first sought before biomass could be related to spectral reflectance. However, this relationship is very difficult to find.

- Where there is more biomass, one would expect high photosynthetic activity but this is not really the case because woody biomass accumulates or is made over time and photosynthetic activity is measured at an instant, hence low correlation between aboveground woody biomass and vegetation indices. With increase in the age of forest or woodlands there is a steady decrease in chlorophyll accumulation (Thenkabail, 2004). For example, a maize field may have high photosynthetic activity and low biomass whereas a fully grown forest or woodland may have a low photosynthetic activity and high biomass.

Kasischke *et al*. (2004) has suggested using remote sensing to first stratify forest types based on composition and structure and then use field sample plots to estimate the timber volume of each stratum. Using this approach Kasischke *et al*. (2004), Deo, (2008) and Zheng *et al*. (2004) obtained stronger relationship between the attributes (LAI and biomass) of conifer forests and vegetation indices (VI's). On the other hand even after stratifying the forest by species and cover types and using polynomial and multiple regressions based on VI's and band ratios, the maximum R^2 value obtained by Labrecque *et al*. (2006) was 0.16 in a temperate forest with average biomass range of 88 to 125 t ha^{-1}.

As estimated from the remote sensing based models dependant on NDVI, the carbon density (t ha^{-1}) ranged from < 10.49 t ha^{-1} to 168.03 t ha^{-1} as per the 1998 imagery and as per the 2010 imagery it ranged from < 11.32 t ha^{-1} to 181.23 t ha^{-1}. The percent change in carbon stock ranged from < 0.71 t ha^{-1} to 11.49 t ha^{-1}. Deo, (2008) mapped an average biomass density of 65.36 t ha^{-1} and an average carbon sequestration rate of 1.52 t ha^{-1} for cool temperate forests of China (Appendix III).

5.3 Impact of climate change on forest growth

5.3.1 Past and present climatic trends

5.3.1.1 Seasonal variation trends in Temperature (°C)

Past and present climatic trends and variations in temperature were analyzed season wise. Maximum temperature, minimum temperature and average temperature for three different periods P1, P2 and BL for the region are given in Table 23. T_{max} during the period 1991-2000 and 2001- 2010 compared over the baseline has shown increase in every season (Fig. 38). Winter temperature showed highest increase over the baseline. It increased by 2.56 °C during 1991-2000 and 5.02 °C during 2001-2010 period. During spring T_{max} rose by 1.16 °C over the baseline during 1991-2000 and 3.12 °C during 2001-2010 period. An increase of 0.20 °C during 1991-2000 and 0.91 °C during 2001-2010 period in summer over the baseline occurred. In autumn, it increased by 1.38 °C during 1991-2000 and 2.43 °C during 2001-2010 period over the baseline.

A decrease of 0.52 °C in T_{min} (Fig. 39) over the baseline in winter during 1991-2000 and 0.45 °C during 2001-2010 period occured. In spring T_{min} decreased by 1.39 °C during 1991-2000 and 0.67 °C during 2001-2010 period. In summer an increase of 0.64 °C during 1991-2000 and 0.49 °C during 2001-2010 period occurred and among all seasons this was the highest increase in T_{min} over the baseline. In autumn, it decreased by 0.07 °C during 1991-2000 and 0.37 °C during 2001-2010 period over the baseline.

The average temperature (T_{av}) during the period 1991-2000 and 2001-2010 increased by 1.02 °C and 2.29 °C respectively over the baseline in winter (Fig. 40). It decreased in spring by 0.11 °C during 1991-2000 and 1.22 °C during 2001-2010 period. In summers of 1991-2000 an increase of 0.42 °C whereas of 0.70 °C during 2001-2010 over the baseline occurred. An increase of 0.65 °C during 1991-2000 and 1.03 ^{o}C during 2001-2010 period in autumn over the baseline was observed.

5.3.1.2 Monthly variation trends in Temperature (^{o}C)

Month wise variation in past and present temperatures: $T_{max,}$ T_{min} and T_{av} have been presented in Table 24. $T_{max,}$ increased in all the months during 1991-2000 and 2000-2010 except August of 1991-2000 period, where it decreased over the baseline period. During 1991-2000 T_{max} increased from January to July, then it decreased in August and then again increased from September to December. During 2001-2010 T_{max} increased from January to December over the baseline period. Increase in T_{max} in December (3.51 ^{o}C) of P1 and February (5.32 ^{o}C) of P2 was observed maximum in all the months over BL (Fig. 41).

T_{min} showed an increasing as well as decreasing trend in the period of 1991-2000 and 2001-2010 over the baseline period. During 1991-2000 T_{min} decreased from January to June, then it increased from July to September and then again decreased in October, increased in November and then again decreased in December over the baseline. During 2001-2010 T_{min} decreased from January to March, increased in April, decreased in May and June, increased from July to September and then again decreased from October to December over BL. Maximum increase in T_{min} was observed in the month of August (1.47 ^{o}C) for P1 and July (1.10 ^{o}C) for P2 over the baseline (Fig. 42).

Average monthly temperature increased in all the months in the period of 1991-2000 and 2001-2010 except March of 1991-2000 period, where it decreased 0.69 ^{o}C over the baseline. During 1991-2000, T_{av} increased in January and February, then it decreased in March, increased in April and May, then decreased in June and then increased from July to December over the baseline, while maximum increase was in December (1.64 ^{o}C). During 2001-2010 T_{av} increased from January to December over the baseline, with the maximum increase in February (2.25 ^{o}C) (Fig. 43). The findings are in line with Kothawale and Rupa Kumar (2005), who reported that India’s mean annual temperature increased by 0.58 ^{o}C during 1901-2003. Long-term trends in the maximum, minimum and mean temperatures over the northwestern Himalaya during the 20th century

(Bhutiyani *et al*., 2007) suggest a significant rise in air temperature in the northwestern Himalaya, with winter warming occurring at a faster rate. The study also shows that significant warming started in the late 1960's, with the highest rate of increase between 1990 and 2009. Dash and Hunt (2007) and Dash *et al*., (2007) found large differences in trends in minimum temperature between north and south India and asymmetry in increasing temperature trends between different seasons. Dimri and Kumar (2008) and Shekhar *et al*. (2010) found increasing trend of temperature over the western Himalaya in the past few decades.

5.3.1.3 Seasonal variation trends in Precipitation (mm)

Total rainfall in the period of 1991-2000 decreased over the years by 66.18 mm in spring and 6.4 mm in summer while it increased in winter and autumn by 32.14 mm and 13.33 mm respectively over the baseline period. During 2001-2010 total rainfall decreased in winter by 20.57 mm, in spring by 88.25 mm and in summer by 144.50 mm respectively whereas in autumn it increased by 45.78 mm over the baseline. Maximum decrease was recorded in spring rainfall during P1 and in summer rainfall in P2 (Table 25, Fig. 44).

5.3.1.4 Monthly variation trends in Precipitation (mm)

Mean monthly rainfall for 1991-2000 and 2001-2010 period over the baseline showed increasing as well as decreasing trend. In the period of 1991-2000 mean monthly rainfall increased in January, February, June, August, September and November and decreased during the months of March, April, May, July, October and December. During 2001-2010 mean rainfall decline was more over the baseline. It decreased in the months of January, March, April, May, June, July, August, October, November and December and increased in February and September over the baseline. Maximum reduction in mean rainfall was recorded in May by 51.04 mm in 1990-2000 period and in July by 91.70 mm in 2001-2010 period (Table 26, Fig. 45).

An increase in total monthly rainfall during 1991-2000 over the baseline was observed except in May, which later during 2001-2010 showed considerable decrease. In the period of 1991-2000 total rainfall increased from January to

April, decreased in May and then again increased from June to December over the baseline. Maximum increase in total rainfall was recorded in August (702.10 mm) followed by June (419.70 mm) and the maximum reduction was in May (293.40 mm) in 1991-2000 over the baseline. During 2001-2010 total rainfall increased from January to March, whereas in April and May total rainfall declined, increased in June, decreased in July, then increased in August and September and then again decreased from October to December over the baseline. Maximum increase in total rainfall was recorded in September (878.40 mm) and maximum reduction was in May (391.20 mm) in 2001-2010 period over the baseline (Table 26, Fig. 46).

5.3.1.5 Mean annual and total annual Precipitation (mm)

Mean annual rainfall followed a declining trend over the years and decreased by 27.12 mm in 1991-2000 and in 2001-2010 it decreased by 207.55 mm over the baseline (Table 27, Fig. 47).

The total rainfall for 1991-2000 as well as 2001-2010 increased by 2250.80 mm and 446.50 mm respectively over the baseline, but the total rainfall during P2 followed a declining trend over P1 (Table 27, Fig. 48).

Studies by (Khan *et al*., 2000; Shrestha *et al*., 2000; Mirza, 2002; Lal, 2003; Min *et al*., 2003 and Dash *et al*., 2007) showed that, in general, the frequency of more intense rainfall events in many parts of Asia has increased, while the number of rainy days and total annual amount of precipitation has decreased. Some past studies relating to changes in rainfall over India have concluded that there is no clear trend of increase or decrease in average annual rainfall over the country (Mooley and Parthasarathy, 1984; Sarker and Thapliyal, 1988; Thapliyal and Kulshreshtha, 1991; Lal, 2001). Kumar *et al.,* (2010) reported that annual and monsoon rainfall decreased, while pre-monsoon, post-monsoon and winter rainfall increased at the national scale. Rainfall in June, July and September decreased, while in August it increased, at the national scale. The total annual and monsoon precipitation variations in the north western Himalaya (Bhutiyani *et al*., 2009) for the period 1866-2006 have shown decreasing trend.

Dimri and Kumar (2008) also found decreasing trend of precipitation over the western Himalaya.

5.3.2 Tree ring standardization

In 1979 and 1980 all the tree ring samples were characterized by narrow rings (Table 29). Climatic records procured from the Department of Environmental Sciences, U.H.F., Nauni, revealed that these two years had very low rainfall. This decrease in moisture availiability probably caused a decline in radial tree growth and hence index values of 0.64958 and 0.71642 respectively were obtained which means that in these two years growth was less than normal. Subsequently in 1982 a broad ring was common to all the tree ring samples and an index value of 1.26723 was obtained indicating a year favourable for growth with the actual growth greater than normal, which is probably attributable to the highest recorded total annual rainfall in the data available, which might have caused an increase in radial growth. Thereafter three narrow rings were common to all composite plots in 1983, 1984 and 1985, with index values of 0.66764, 0.71328 and 0.58897 indicating that during these three years growth was less than normal and when compared with climatic data it was found that the lowest recorded annual average temperature (average of maximum and minimum temperature) coincided with these three dates, and in 1984 and 1985 the total annual rainfall was also low, which might have caused a reduction in growth during this period. In 1986, a broad ring was recorded in all the composite plots with an index value of 1.23517, which when compared with the climatic data for the region revealed an increase in temperature and rainfall in 1986. Subsequently narrow rings were again found in 1989 and 1992, with low index values of 0.70584 and 0.85841 which coincided with low average annual temperature. A broad ring with an index value of 1.17021 in 1993 was probably due to relatively high temperature and rainfall in that year as evident from the available climatic records. Again a narrow ring was recorded in 1997 with an index of 0.63978 and a broad ring thereafter in 1999 with an index value of 1.13145 probably due to a fall and then a subsequent rise in the average annual temperature as observed in the climatic records available.

5.3.3 Relationship between RWI and climatic variables

The correlation between ring width indices (dependant variable) and average annual temperature (average of maximum and minimum temperature, independent variable) was analysed (Table 30). A significant linear relationship was observed between RWI and average annual temperature (^{0}C) (R=0.514, P < 0.05) incase of D1. A significant linear relationship was found between the RWI and average temperature (^{0}C) (R=0.536, P < 0.05) for D2. D3 showed significant correlation between RWI and temperature (^{0}C) (R=0.558, P < 0.05). A significant relationship between RWI and temperature (^{0}C) was found incase of D4 (R=0.648, P < 0.05) and D5 (R=0.662, P < 0.05). The master chronology was found to have a significant relationship with the average annual temperature (^{0}C) (R=0.681, P < 0.05). It was observed that the correlation coefficient (R) and the p value increased with an increase in the diameter class indicating stronger temperature related growth responses in mature trees. Similar results were found by Ettl and Peterson, (1995), Gray, (1982), Szeicz and MacDonald, (1995) who found systematic decreases in climatic sensitivity in younger trees.

The results are in line with Carrer and Urbinati, (2006) who studied age-dependent tree-ring growth responses to climate in *Larix decidua* and *Pinus cembra* and found that the older the trees are, the higher the variance explained by climate, the significance of the models, and the percentage of trees with significant responses. R^2 increased substantially from younger to older age classes (from 0.48 and 0.46 to 0.68 and 0.61, in *P. cembra* and *L. decidua* respectively). Significance values (*r*/*s* [mean multiple correlation coefficient divided by its standard deviation] and *P*) confirm this tendency: in the youngest age class mean chronologies (AGC) response function is not significant, but almost reaches the 95% threshold in the second class and is significant in the two oldest classes. The situation does not change with the single-tree responses; the percentage of individuals with a globally significant response function (%ST) is below 10% for the youngest class, but drastically increases in the older classes up to 63%. It is hypothesized that an endogenous parameter linked to hydraulic status becomes increasingly limiting as trees grow and age, inducing more stressful conditions and a higher climate sensitivity in older individuals.

The results are also in line with the work of Wang *et al*., (2009) who found that the response of *L. gmelinii* radial growth to climate differed between trees ≥150 years old and <150 years old in northeastern China. Mean sensitivity and standard deviation for trees increased with age in the <150 years old tree class; whereas trees ≥150 years old had no significant relationship with age. These results suggested the importance of incorporating trees of all ages into the chronology to recover a detailed climatic signal in a reconstruction *L. gmelinii* for the region.

In contrast, Esper *et al*. (2008) showed that sensitivity remained constant and Vieira *et al*. (2009) found that sensitivity even decreased with tree age The explanation for such different conclusions is not clear and it has been suggested that it might relate to the fact that some physiological age/size related constraints for tree growth may run counter to others (Carrer and Urbinati, 2006, Esper *et al*., 2008).

Most tree-ring studies typically involve trees with larger diameters to minimize the effect of competition and to simplify cross-dating, as there are fewer missing rings (Fritts, 1976, Chhin *et al*., 2008). Also, it is commonly believed that large trees are more sensitive to year-to-year climate variations and that they are more suitable for dendrochronological purposes (Carrer and Urbinati, 2006).

Although standard sampling protocols usually imply that selection occurs among the dominant (and probably older) trees of the investigated stands (Fritts, 1976, Schweingruber *et al*., 1990), based on the assumption that trees with reduced competition are more coupled with atmosphere and should provide a higher and clearer amount of common signal recorded. It is also stated that increased mechanical stresses superpose the climatic signal in juvenile tree-rings. However, in the present study a significant linear relationship was found between RWI and the total annual rainfall (mm) incase of D1 ($R=0.475$, $P < 0.05$) and D2 ($R=0.530$, $P < 0.05$). Although poor, a significant linear relationship was also found in D3 (R=0.334, $P < 0.05$). However, D4 and D5 exhibited non significant relationship between RWI and rainfall (Table 31). The average site index for the site showed significant linear relationship with rainfall (R= 0.413, $P < 0.05$). This implies that effect of precipitation is more pronounced in younger trees, probably because of a shallow rooted system which restricts tree growth as compared to a mature tree with a well developed root system that can draw water from deeper layers of the soil, as and when precipitation becomes limiting.

When multiple linear regression analysis was done between RWI (dependant variable) and temperature and precipitation (independent variables) to extract the relative contribution of temperature and precipitation to the radial growth of chir pine, it was found that in all the diameter classes temperature had a stronger effect on growth than precipitation, with the effect becoming more pronounced in older age classes (Table 32).

The present study demonstrates that climate–growth relationship can be mediated by tree-size. The results confirmed that the climate signal is maximized in older trees but that some climatic signal can also be extracted from younger trees, and also that a sampling procedure non-stratified by age and size could lead to biased mean chronologies. Comparisons of young and old age classes, and separate calibration of these categories against instrumental climate data might further the estimation of long-term uncertainty changes in tree-ring based climate reconstructions. Sampling both old and young trees in field campaigns and checking for climate signal age effects (CSAE) in existing chronologies should be considered, whenever feasible.

Chapter-6

SUMMARY AND CONCLUSION

Chapter-6

SUMMARY AND CONCLUSION

The present investigation entitled “Evaluation of forest carbon stock and land use of Solan Forest Division” was carried out during 2009-2012 in Solan District of Himachal Pradesh, located between 30^{o} 45’ 00’’ to 31^{o} 10’00’’ N latitude and 76^{o} 55’00’’ to 77^{o} 15’00’’ E longitude, at an elevation from 600m to 2260 m a.m.s.l. The forests in Solan Forest Division have pure crop of Chil and mostly conform to Champion and Seth’s Forest type 9 C1a- Lower or Shiwalik Chir pine forests. The present investigation was conducted to determine land use change from the year 1998 to 2010 in the division, to study the temporal distribution of forest carbon stock and to assess the impact of climate change on forest growth, as summarized below:

Land Use change of Solan Forest Division

To meet the first objective the stock map of the division was scanned and then digitized to create various data layers i.e. forest boundary, forest ranges, compartments, land uses and roads and streams. Supervised classification (Maximum Likelihood) was performed to classify the satellite images of 1998 and 2010 into various land uses. The results revealed that out of a total recorded forest area of 13,067 ha in Solan Forest division; in 1998, Chir pine, Culturable Blank, Broadleaved, Bamboo, Ban oak, Cultivation and Khair land use categories covered 4200 ha, 2608 ha, 2413 ha, 1491 ha, 1092 ha, 934 ha and 329 ha area respectively, which accounted for 32.14%, 19.96%, 18.47%, 11.41%, 8.36%, 7.15%, and 2.52% of the total recorded area. In 2010, Chir pine, Culturable Blank, Broadleaved, Bamboo, Cultivation, Ban oak and Khair land use categories covered 4391 ha, 2537 ha, 2261 ha, 1498 ha, 1063 ha, 911 ha and 406 ha, which accounted for 33.60%, 19.42%, 17.30%, 11.46%, 8.13%, 6.97% and 3.11% of the total recorded area, respectively.

Chir pine, Cultivation and Khair reported an increase in area of 191 ha (4.55%), 129 ha (13.81%) and 77 ha (23.40%), whereas Ban oak, Broadleaved, Culturable Blank and Bamboo reported a decrease in area of 181 ha (16.58%), 152 ha (6.30%), 71 ha (2.72%) and 7 ha (0.47%), respectively from 1998 to 2010.

The accuracy assessment was run on classified images of 1998 and 2010. The resulted descriptive statistics (error matrix) comprising of user's error (error of commission), producer's error (error of omission), overall accuracy (total percent correct), and the Kappa index of agreement (KHAT accuracy) reported overall accuracy of 89 per cent and 87 per cent for 2010 and1998 land use classification, respectively. However, KHAT accuracy was 85 per cent and 87 per cent for 1998 and 2010 land use classification, respectively.

Temporal change in carbon stock

The distribution of biomass and carbon stock in 33 compartments of Solan and Dharampur Forest Ranges for the years 1956, 1984, 2002 and 2011 was studied. The data for 1956, 1984 and 2002 were obtained from the records in the working plan of the division while the estimation of the forest carbon stock of the year 2011 was done by fresh enumeration of 33 compartments (12 in Solan and 21 in Dharampur Forest Range) from July to October, 2011.

The tree carbon (above+below) stock in 1956 was 20908.66 t, which reduced to 12032.79 t in 1984, increased to 18234.13 t in 2002 and in 2011 there was a further increase to 20586.69 t. There was a declining trend over 1956-1984 period by 8875.87 t, an increasing trend over 1984-2002 period by 6201.34 t and over 2002-2011 period there was a further increase by 2352.56 t. The tree carbon density (above+below) in 1956 was 48.04 t ha^{-1}, which reduced to 27.65 t ha^{-1} in 1984, increased to 41.90 t ha^{-1} in 2002 and to 47.30 t ha^{-1} in 2011. The temporal distribution of tree carbon density over the period of 1956 to 2011 showed a declining trend over 1956-1984 period by 20.39 t ha^{-1}, an increasing trend over 1984-2002 period by 14.25 t ha^{-1} and over 2002-2011 period there was a further increase by 5.4 t ha^{-1}.

Carbon Inventory

It was found that the soil organic carbon (%) decreased with increasing soil depth, while soil bulk density showed the reverse trend, it increased with increasing soil depth. The soil carbon stock ranged from 18.87 to 317.31 t at the humus layer, from 127.87 to 2069.10 t at a depth of 0 to 20 cm, from 118.37 to 1675.80 t at 20 to 40 cm depth and from 207.35 to 3441.20 t at 40 to 100 cm soil depth. Similarly, the soil carbon density ranged from 6.73 to 9.62 t ha^{-1} at the humus layer, from 33.73 to 55.80 t ha^{-1} at a depth of 0 to 20 cm, from 30.52 to 50.46 t ha^{-1} at 20 to 40 cm depth and from 81.84 to 99.83 t ha^{-1} at 40 to 100 cm soil depth. Soil carbon stock {Humus + Soil (0-100cm layer)} was minimum at D-117 Chabil Ki Dhar IV (473.70 t) and maximum at D-176 Charoti Ki Dhar I (7503.41 t). Soil carbon density {Humus+Soil (0-100cm layer)} was minimum at D-135 Kaldhar I (160.90 t ha^{-1}) and maximum at D-155 Bhallon (211.20 t ha^{-1}).

The total tree carbon stock was 20586.69 t, with 13029.60 t in stem, 3127.07 t in branch, 651.49 t in leaf and 3778.55 t in root. Total herb carbon stock was 909.22 t with 425.97 t in shoot and 483.26 t in root. Total shrub carbon stock was 757.46 t with 380.68 t in shoot and 376.78 t in root. Total vegetation carbon stock was 22253.43 t. Vegetation carbon stock (trees + herbs + shrubs) was the minimum at D-97 Kiar Tatul (95.57 t) and the maximum at D-119 Chabil Ki Dhar II (2213.36 t).

The total tree carbon density was 47.31 t ha^{-1}, with 29.94 t ha^{-1} in stem, 7.19 t ha^{-1} in branch, 1.50 t ha^{-1}in leaf and 8.68 t ha^{-1} in root. Total herb carbon density was 2.09 t with 0.98 t ha^{-1}in shoot and 1.11 t ha^{-1} in root. Total shrub carbon density was 1.74 t with 0.87 t ha^{-1} in shoot and 0.86 t ha^{-1} in root. Total vegetation carbon density was 51.13 t ha^{-1}.Vegetation carbon density (trees + herbs + shrubs) was the minimum at D-153 Gulhari I (22.59 t ha^{-1}) while it was the maximum in D-118 Chabil Ki Dhar III (181.61 t ha^{-1}).

Soil carbon stock {Humus + Soil (0-100cm layer)} was 83076.05 t. It was minimum at D-117 Chabil Ki Dhar IV (473.70 t) and maximum in D-176 Charoti Ki Dhar I (7503.41 t). Soil carbon density {Humus+Soil (0-100cm layer)} was 189.29 t ha^{-1}. It was minimum in D-135 Kaldhar I (160.90 t ha^{-1}) and maximum in D-155 Bhallon (211.20 t ha^{-1}). Detritus carbon stock was 2544.94 t and it was minimum at D-117 Chabil Ki Dhar IV (12.74 t) and the maximum at D-176 Charoti Ki Dhar I (233.70 t). Detritus carbon density was 5.61 t ha^{-1}. It was minimum at D-135 Kaldhar I (4.52 t ha^{-1}) and the maximum at D-118 Chabil Ki Dhar III (6.31 t ha^{-1}). The total ecosystem carbon stock (t) was 107874.40 t. The ecosystem carbon stock was minimum at D-159 Anji III (761.57 t) and maximum at D-176 Charoti Ki Dhar I (9267.08 t). The overall ecosystem carbon density (t ha^{-1}) was 247.87 t ha^{-1}. The ecosystem carbon density was minimum at D-135 Kaldhar I (191.34 t ha^{-1}) and maximum at D-118 Chabil Ki Dhar III (379.95 t ha^{-1}).

Carbon mapping and carbon change analysis

The carbon stock of the selected sample plots that existed in Solan and Dharampur Forest Ranges of the Solan Forest Division for each year i.e. 1984 and 2011 was regressed against their corresponding NDVI values. A significant linear relationship was observed both for 1998 (R = 0.741) and 2011 (R = 0.663). Carbon maps for Solan Forest Division were then prepared using the estimated relationships. The carbon density (t ha^{-1}) ranged from < 10.49 t ha^{-1} to 168.03 t ha^{-1} in 1998 and in 2010 it ranged from < 11.32 t ha^{-1} to 181.23 t ha^{-1}. The percent change in carbon stock ranged from < 0.71% to 11.49% between 1998 and 2010.

Impact of Climate Change on forest growth

Past and present climatic trends were analysed to determine any climatic anomaly in the region. The effect of climate change on forest growth was studied by dendrochronological analysis of tree ring samples.

An increase in T_{max} by 5.02 ^oC, 3.12 ^oC, 0.91 ^oC and 2.43 ^oC, whereas in T_{min} a decrease of 0.45 ^oC, 0.67 ^oC, an increase by 0.49 ^oC and then again a decrease by 0.37 ^oC in winter, spring, summer and autumn season, respectively over the baseline was observed. Thus, T_{max} compared over the baseline showed increase in every season. Winter temperature showed highest increase over the baseline. Increase in T_{max} in February (5.32 ^oC) was observed maximum in all the months over the baseline. T_{min} showed an increasing as well as decreasing trend, with maximum increase in July (1.10 ^oC) and maximum decrease in March (1.87 ^oC).

The total rainfall decreased in winter, spring and summer by 20.57 mm, 88.25 mm and 144.50 mm respectively, with maximum reduction in summer rainfall, while in autumn it increased by 45.78 mm over the baseline. Maximum increase in total rainfall was recorded in September (878.40 mm) and maximum reduction was in May (391.20 mm) in 2001-2010 period over the baseline. Maximum reduction in mean annual rainfall occurred in the month of July (91.70 mm). Mean annual rainfall followed a declining trend and decreased by 207.55 mm over the baseline, while total annual rainfall increased by 446.50 mm over the baseline.

The tree ring samples were fist processed and then subjected to standard dendrochronological procedures like crossdating and standardization. Regression analysis of climate with the standardized chronology was done. Regression between RWI and average annual temperature yielded correlation coefficients of 0.514, 0.536, 0.558, 0.648 and 0.662, for D1, D2, D3, D4 and D5 respectively, indicating an increase in the temperature related growth responses in mature trees. The average site index was found to have a highly significant relationship with the average annual temperature (^{0}C) ($R=0.681$, $p < 0.05$). Similarly correlation coefficients of 0.475, 0.530 and 0.334 for D1, D2 and D3, were obtained through regression between RWI and rainfall. However, D4 and D5 exhibited non significant relationship between RWI and rainfall. The average site index for the site showed significant linear relationship with rainfall ($R= 0.413$, $p < 0.05$). Multiple regression between RWI and temperature and precipitation showed that temperature had a stronger effect on growth than precipitation, with the effect becoming more pronounced in the older age classes.

Conclusions

- ❖ An increase in the area of Chir pine, Cultivation and Khair by 191 ha (4.55%), 129 ha (13.81%) and 77 ha (23.40%), respectively, whereas a decrease in the area of Ban oak, Broadleaved, Culturable Blank and Bamboo by 181 ha (16.58%), 152 ha (6.30%), 71 ha (2.72%) and 7 ha (0.47%), respectively from 1998 to 2010 was reported.
- ❖ Overall accuracy was 87 per cent for 1998 classification and 89 per cent for 2010 classification. KHAT accuracy was 85 per cent and 87 per cent for 1998 and 2010 land use classification, respectively.

- The temporal distribution of carbon stock over the period of 1956 to 1984 showed a declining trend by 8875.87 t (20.39 t ha^{-1}), an increasing trend over 1984-2002 period by 6201.34 t (14.25 t ha^{-1}) and over 2002-2011 period there was a further increase by 2352.56 t (5.4 t ha^{-1}).
- Soil organic carbon (%) decreased with increasing soil depth while bulk density increased with increasing soil depth. Vegetation carbon density was 51.13 t ha^{-1}, soil carbon density was 189.29 tha^{-1}, detritus carbon density was 5.61 t ha^{-1} and ecosystem carbon density was 247.87 t ha^{-1}.
- Significant relationships between carbon stock and NDVI were obtained which implies that remote sensing can be effectively used for carbon mapping and carbon change analysis.
- Current and past climatic scenario revealed that the region has experienced an increase in the maximum temperature and a decrease in the minimum temperature except in summer. Precipitation in the form of rainfall decreased except in autumn season.
- Multiple regression between RWI and temperature and precipitation showed that in all the diameter classes temperature had a stronger effect on growth than precipitation, with the effect becoming more pronounced in older age classes Thus, climate change is effecting the growth of chir pine in the region, hence adaptive measures need to be taken to strengthen the resilience of our forests to the changing climatic scenario.
- The climate signal is maximized in older trees but some climatic signal can also be extracted from younger trees. Sampling procedure should therefore be stratified by age and size to produce unbiased mean chronologies. Comparisons of young and old age classes, and separate calibration of these categories against instrumental climate data might further the estimation of long-term uncertainty changes in tree-ring based climate reconstructions.

Chapter-7

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ABSTRACT

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Title of Thesis	:	**Evaluation of Forest Carbon Stock and Land use of Solan Forest Division**
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ABSTRACT

The present investigation entitled, "Evaluation of Forest Carbon Stock and Land use of Solan Forest Division " was carried out during 2009-2012 in Solan Forest Division of Himachal Pradesh, located between 30^o 45' 00'' to 31^o 10'00'' N latitude and 76^o 55'00'' to 77^o 15'00' E longitude, at an elevation ranging from 600m to 2260 m a.m.s.l. to study land use change from 1998 to 2010 using IRS (LISS III) data, the temporal distribution of carbon stock and to assess the impact of climate change on forest growth. The major land use categories were Culturable Blank, Chir pine (*Pinus roxburghii*), Cultivation, Broadleaved, Bamboo (*Dendrocalamus strictus*), Ban oak (*Quercus leucotrichophora*) and Khair (*Acacia catechu*). Chir pine, Cultivation and Khair reported an increase in area of 191 ha (4.55%), 129 ha (13.81%) and 77 ha (23.40%), whereas Ban oak, Broadleaved, Culturable Blank and Bamboo reported a decrease in area of 181 ha (16.58%), 152 ha (6.30%), 71 ha (2.72%) and 7 ha (0.47%), respectively from 1998 to 2010. There was a declining trend in carbon stock over 1956-1984 period by 8875.87 t (20.39 t ha^{-1}), an increasing trend over 1984-2002 period by 6201.34 t (14.25 t ha^{-1}) and over 2002-2011 period there was a further increase by 2352.56 t (5.4 t ha^{-1}). In 2011 total Vegetation Carbon Stock was 22253.43 t (51.13 t ha^{-1}). In 2011the Soil Carbon Stock {Humus + Soil (0-100cm depth)} was 83076.05 t (189.29 t ha^{-1}). Detritus carbon stock was 2544.94 t (5.61 t ha^{-1}) and the total Ecosystem Carbon Stock (t) was 107874.40 t (247.87 t ha^{-1}. A significant linear relationship was observed between carbon stock and NDVI for 1998 ($R = 0.741$) and 2010 ($R = 0.663$). The carbon prediction models were then used to develop carbon maps for Solan Forest Division. The carbon density (t ha^{-1}) ranged from < 10.49 t ha^{-1} to 168.03 t ha^{-1} as per the 1998 imagery and as per the 2010 imagery it ranged from < 11.32 t ha^{-1} to 181.23 t ha^{-1}. The percent change in carbon stock ranged from < 0.71% to 11.49%. Current (2001-2010) and past (1983-2000) climatic scenario revealed that the region has experienced an increase in the maximum temperature while minimum temperature showed both an increasing as well as decreasing trend. Temperature in different seasons of the year viz. winter, spring, summer and autumn has shown increasing trends while precipitation in the form of rainfall decreased except in autumn. Ring width Index (RWI) was found to have a significant relationship with the average annual temperature (^{0}C) ($R=0.68$, $P < 0.05$) and with rainfall ($R= 0.41$, $P < 0.05$). Multiple regression between RWI & temperature and RWI & precipitation showed that temperature had a stronger effect on growth than precipitation and the effect of temperature became more pronounced in trees with advancement of age.

Signature of Major Advisor **Signature of the Student**

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APPENDICES

APPENDIX I

Data base showing name of the forest, species, elevation, recorded area and total number of trees in different diameter classes

Poly ID	Name of the Forest	Species	Elevation (m)	Recorded Area	Number of trees							
					10-20 cm	20-30cm	30-40cm	40-50cm	50-60cm	60-70cm	70-80cm	Total
1	R57 Banasar	chil	1450-1782	113.2	28203	5636	1019	410	344	219	120	36023
2	D192 Nabon partha	chil.ban.b/l	0	149.6	1360	1497	398	24	0	0	0	3279
3	R58 Jagatgarh	chil.ban	1380-1500	6	781	220	110	108	75	20	8	1322
4	D178 Charoti ki dhar	chil	1340-1572	71.4	16883	4924	2464	1261	533	191	51	26307
5	D176 Charoti ki dhar	chil	1250-1450	38	10914	4747	1091	401	218	104	42	17517
6	D175 Bohali	chil	1360-1550	33.2	3018	2218	1013	500	179	59	16	7003
7	R45 Khader ki dhar	b/l,bamboo	0	110.4	12714	9347	5138	1416	264	0	0	28879
8	D189 Jgatgarh	chil,b/l	0	29.6	9856	4043	1973	432	144	83	20	16531
9	D200 Danota chakali	chil,b/l,bamboo	0	255.2	20344	16703	6002	3140	2710	981	133	50013
10	D191 Shogi nabon	chil,ban	0	64.4	698	754	235	38	0	0	0	1725
11	D222 Banasar top	chil	1320-1600	72.4	16342	2825	345	142	182	126	73	20035
12	R41 Gulzar	chil.b/l	1250-1400	129.2	38101	7984	2128	261	185	79	30	48669
13	D179 Sirguli ka tiba	chil	1380-1540	13.6	2901	863	142	81	55	86	26	4151
14	D180 Sirguli ka tiba	chil	1300-1550	47.2	13563	1332	402	196	116	48	12	15669
15	D214 Tiba guljar	chil.b/l	0	141.6	58274	7558	2227	285	126	56	0	68526
16	D215 Kaba	chil,b/l	0	43.2	2346	734	211	66	49	12	0	3418
17	R40 Bohali	chil	1280-1612	115.6	11957	4817	1008	346	207	118	53	18506
18	R39 Charoti ki dhar	chil	1280-1550	44.4	4589	1784	525	208	38	37	8	7240
19	D179 Sirguli ka tiba	chil	0	16	4151	2185	461	116	80	44	27	7064
20	D177 Charoti ki dhar	chil	1295-1400	21.2	3025	1863	646	301	257	120	56	6268
21	D184 Rathal	chil,b/l	1300-1500	122.4	35266	9455	1681	261	139	196	117	47115
22	D169 Kiard II	chil	1240-1369	39.6	5957	768	999	715	263	104	39	8845
23	D142 Jhaja bahali	chil.ban	1420-1520	13.2	5358	2259	1381	583	277	31	2	9791
24	R38 Kiard	chil	0	37.2	3990	1310	1039	450	290	35	5	7119
25	D236 Kurar	chil,b/l	0	81.2	9970	2529	609	115	80	45	35	13383
26	D233 Datiyar	chil,b/l,bamboo	0	417.6	58002	25690	10539	2566	773	237	4	97831
27	D202 Kalath no II	chil.b/l	0	28.4	4147	3560	1301	776	539	238	36	10597
28	D186 kalath V	chil.b/l	1220-1360	20.4	5221	695	160	49	31	44	57	6257
29	D232 Bamola totela	chil	0	6.8	409	119	29	17	13	7	3	597
30	D231 Shlu jangeshu	b/l	0	51.2	256	282	231	205	128	26	0	1128
31	D190 jabrog	chil,b/l	0	87.6	3359	3557	1275	241	0	0	0	8432
32	R55 Mashobra C1	chil.b/l	0	5.4	364	182	113	71	21	11	0	762
33	D241 Shewla	chil	0	22.4	1406	427	249	124	35	11	1	2253

34	D120 Chabal ki dhar	chil	1300-1420	3.6	356	94	12	155	440	32	3	1092
35	R55 Mashobra C2	chil	0	5.8	458	139	81	39	12	4	0	733
36	D234 Ranigoan	chil,b/l	0	72	2716	2764	1260	293	1	0	0	7034
37	D221 Kiarwa	b/l,bamboo	0	8.4	1549	1139	626	178	32	0	0	3524
38	0		0	0	0	0	0	0	0	0	0	0
39	R61 Naraini	b/l,khair,bamboo	0	484.4	18653	13955	6960	1748	215	0	0	41531
40	R59 Jandhouri	b/l	0	14.4	563	421	219	60	6	0	0	1269
41	D195 Pratha	b/l,bamboo	0	11.2	520	392	204	52	8	0	0	1176
42	R60 Jandhouri	b/l	0	6.8	262	196	102	26	3	0	0	589
43	D195 Pratha			0	0	0	0	0	0	0	0	0
44	D160 Anji no I	chil	1280-1420	10.4	4459	940	108	71	33	9	5	5625
45	D171 Bhog sari	chil	1200-1340	5.6	1050	155	219	126	79	14	12	1655
46	D172 Bhog sari III	chil	1180-1300	4.4	1955	185	123	40	23	8	5	2339
47	D170 Bhog sari	chil	1360-1600	12.4	3621	278	254	140	83	28	23	4327
48	D173 Bohali ki chali	chil	1360-1600	10.4	1331	722	373	66	33	10	13	2548
49	D87 Diarag daun	ban,deo,b/l,chil	1500-1650	5.2	3603	784	336	86	10	0	0	4819
50	D238 Dhamiana	b/l,eucalupt	0	16.4	1548	1040	198	10	3	1	0	2800
51	D158 Anji I	chil	1380-1400	11.2	1171	1008	1068	192	101	56	0	3596
52	D174 Bigaur	chil,ban	1420-1540	4	1893	440	223	38	18	5	0	2617
53	D159 Anji III	chil	1440-1520	3.6	2083	123	43	44	15	10	2	2320
54	D243 Suji	chil,b/l	0	8.8	436	202	39	62	16	5	0	760
55	R36 Anji	chil	1400-1556	10.4	7700	451	103	73	32	18	6	8383
56	R34 Mansa devi	chil	0	3.2	307	153	101	54	26	4	2	647
57	R38 Kiard	chil		37.2	3990	1310	1039	450	290	35	5	7119
58	D145 Chewa khil chunjari	chil	1575-1600	12.4	3296	258	230	253	152	65	8	4262
59	R34 Mansa devi	chil	0	3.2	307	153	101	54	26	4	2	647
60	D198 Bhaour lugon	b/l,bamboo	0	30.8	1807	1352	703	179	14	0	0	4055
61	D199 Chawal ashnalla	chil,b/l,bamboo	0	66.4	6701	4782	1623	430	317	153	5	14011
62	D209 Bhagour	bamboo	0	15.6	0	0	0	0	0	0	0	0
63	R43 Halda kaba	chil,b/l,bamboo	0	180	2891	3630	2168	380	1158	61	38	10326
64	D194 Pratha III	b/l	0	49.2	1976	1489	775	198	31	0	0	4669
65	D193 Partha umera	bamboo,b/l,chil	0	17.2	2018	479	813	238	55	2	5	3610
66	D207 Sath dadhog	b/l,bamboo	0	30.4	844	302	76	13	13	0	0	1248
67	R42 Ajmergarh	chil,b/l	1200-1512	82.8	11111	4370	1772	690	343	147	29	18462
68	D203 Qila Ajmergarh	chil,b/l,bamboo	980-1400	83.6	23755	6599	2400	1073	397	116	23	34363
69	D205 Neri I	chil,b/l,bamboo	0	52	3215	1236	327	96	79	21	2	4976
70	D213 Kaba bahaur	chil,b/l		107.6	33799	5699	1658	86	54	21	0	41317
71	R44 Jhanai	b/l,bamboo,khair	0	139.6	13144	9663	5266	1491	271	0	0	29835
72	D220 Barog C2	bamboo	0	2.9	0	0	0	0	0	0	0	0
73	D218 Kamlog	b/l,bamboo	0	7.2	861	633	348	99	18	0	0	1959

74	D218 Kamlog	b/l,bamboo		7.2	0	0	0	0	0	0	0	0
75	D220 Barog C1	b/l	0	28.7	6916	5085	2795	795	144	0	0	15735
76	D247 Satrol	b/l	0	7.2	915	688	361	91	14	7	0	2076
77	D219 Satrol II	b/l	0	1.2	157	118	62	16	2	1	0	356
78	D196 Mauri	b/l,bamboo	0	6	520	392	204	52	4	0	0	1172
79	D217 Niun shanog	b/l	0	43.2	8667	6372	3503	996	181	0	0	19719
80	D216 Bhanog bhallon	chil,b/l,bamboo	0	90	6317	2192	566	115	103	8	0	9301
81	D211 Halda I	b/l,chil	0	10	555	699	418	60	149	2	6	1889
82	D197 Pratha I	b/l,bamboo	0	4.8	157	118	62	16	2	1	0	356
83	D206 Neri II	chil,b/l,bamboo	0	24.4	521	442	166	151	105	64	7	1456
84	D206 Neri II			24.4	521	442	166	151	105	64	7	1456
85	D157 Kadon I	chil	1475-1500	13.6	9935	585	384	246	114	43	9	11316
86	R35 Kadon	chil	1500-1618	40.1	15281	971	940	489	262	85	13	18041
87	D155 Bhallon	chil	1360-1400	3.2	1697	96	127	70	20	8	1	2019
88	D156 Kadon II	chil	1475-1525	2.3	1621	97	67	51	16	13	0	1865
89	D161 Sehardi	chil	1325-1575	42	15816	1587	1026	754	372	104	0	19659
90	D157			13.6	9935	585	384	246	114	43	9	11316
91	D157			13.6	9935	585	384	246	114	43	9	11316
92	D143 Chewa khil chunjari	chil	1760-1825	2.4	2467	140	94	49	11	2	0	2763
93	R27 Nauni	ban,chil,deo	1660-2014	80	12570	2085	277	111	0	0	0	15043
94	R28 Khaldhar	ban,chil,deo	1560-1915	122	13316	3811	2686	1165	770	357	153	22196
95	D137 Nauni	chil,ban	0	11.2	881	402	157	31	4	0	0	1475
96	D146 Chewa khil chunjari IV	chil	1360-1660	47.2	7919	1161	1091	1134	728	445	117	12595
97	D140 Kainthari	chil	1620-1700	6	4491	545	151	111	58	10	1	5367
98	D154 Dawala	chil	1350-1500	12.8	7253	454	202	228	155	49	5	8346
99	D98 Bhawan ki dhar	chil,b/l	1280-1380	19.2	13581	2999	259	78	75	59	25	17076
100	D90 Gadhon II	chil,ban	1580-1750	13.2	4143	310	231	173	86	18	2	4963
101	D86 Diarag niun	ban,deo,chil	1500-1950	33.6	6520	2699	1053	308	30	0	0	10610
102	D97 Kiar tatul	chil	1260-1350	4.4	1273	84	6	17	20	7	4	1411
103	R26 Nagali	chil,b/l	1250-1400	33.6	11836	3783	564	95	74	67	49	16468
104	D95 Nagali I	chil	1350-1420	3.6	595	186	47	58	36	20	13	255
105	D96 Nagali II	chil	1240-1345	4	462	41	12	21	23	16	7	582
106	D88 Shawag badrog	ban,deo	1750-1825	13.2	3276	535	242	47	15	5	0	4120
107	D84 Damkari	ban,chil,deo	0	39.2	7741	1319	557	79	2	0	0	9698
108	D123 Beola	chil	1500-1800	4.4	679	183	210	169	115	27	1	1384
109	D125 Sheel ka dhala	chil	1200-1400	21.2	3648	1526	234	115	126	94	59	8534
110	D85 Niun	ban,chil,deo,b/l	1420-1740	10.4	5459	2183	802	225	23	2	0	8694
111	D89 Gadhog I	chil,ban	1800-1940	9.2	3228	441	231	106	29	6	0	4041
112	R25 Shawag badrog	ban,deo,chil	1700-2002	102.4	29893	5657	1903	202	15	28	0	37698

113	R33 Gulhari	chil,ban	1500-1600	119.6	17587	4241	4467	2603	919	145	38	30000
114	D246 Kasauli C1	chil	0	9.6	1190	346	86	48	33	19	9	1736
115	D246 Kasauli C2	chil	0	3.6	446	130	32	18	14	7	4	651
116	D151 Gulhari I	chil	1400-1550	42.8	19681	1672	2417	1534	688	298	73	26363
117	D152 Gulhari II	chil	1500-1600	8.8	1462	262	240	123	52	10	1	2150
118	D245 Sanawar	chil	1500-1725	60.4	20706	2515	1786	1183	500	126	9	26825
119	D153 Gulhari I	chil	1450-1600	5.2	169	72	50	28	7	1	2	329
120	D148 Samol	chil	0	4	496	144	36	20	16	8	3	723
121	D118 Chabal ki dhar	chil	1270-1530	10.4	7293	2906	1148	617	372	105	63	12504
122	D150 Gulhari IV	chil	1575-1650	4.4	47	181	209	68	14	4	0	523
123	D149 Sanhol	chil		8.4	1041	302	76	42	34	17	8	1520
124	D204 Tikkari	chil,b/l	0	22.4	1299	1153	526	180	67	34	11	3270
125	0		0	0	0	0	0	0	0	0	0	0
126	R50 Kalath	chil	1325-1460	5.2	1903	193	76	25	17	14	19	2247
127	D195 Pratha	b/l,bamboo	0	11.2	520	392	204	52	8	0	0	1176
128	D208 Sari	bamboo	0	2.4	0	0	0	0	0	0	0	0
129	0			0	0	0	0	0	0	0	0	0
130	D210 Oder janghiria	bamboo,b/l	0	97.7	764	959	569	83	194	0	0	2569
131	D141 Barog	chil	0	2	164	131	121	97	78	0	0	591
132	R33 Gulhari	chil,ban	1500-1600	119.6	17587	4241	4467	2603	919	145	38	30000
133	D131 Mathan	chil	1500-1760	38.4	11332	1787	784	626	472	246	142	15389
134	D135 Khaldhar	chil	1550-1775	5.6	230	168	95	73	22	6	0	594
135	D138 Khaldhar III	chil,ban	1750-1900	11.2	8394	577	459	203	109	50	21	9813
136	D136 Khaldhar	chil,ban	0	16	4419	1261	684	118	102	54	30	6468
137	D147 Kainthri	chil	1700-1800	19.8	11370	837	411	165	124	51	13	13071
138	D242 Gahidhar	chil	0	89.4	10911	650	544	747	506	109	49	13509
139	D224 Sandhog	b/l,bamboo	0	90	10117	4511	1795	394	131	44	0	16992
140	0			0	0	0	0	0	0	0	0	0
141	D244 Cheola	chil.b/l	1200-1440	136.8	20455	4611	981	796	534	160	55	27592
142	D223 Khadeen	b/l	0	76	12012	5356	2132	519	156	51	0	20226
143	D228 Ambota	chil,b/l,bamboo	0	86.4	481	427	341	294	180	37	0	1760
144	D239 Sari dhar	chil,b/l	1400-1782	48	2653	805	469	235	67	33	0	4262
145	R56 Parwanoo	bamboo,b/l,khair	0	124	0	1915	3486	8393	5418	3657	3135	25994
146	D225 Gumma	bamboo	0	84	0	0	0	0	0	0	0	0
147	D227 Annu I	b/l	0	8	82	91	74	65	37	9	0	358
148	D165 Maltu IV	chil,b/l	1240-1480	41.2	7393	1115	783	582	338	98	18	10327
149	D185 Kurla and Johari	chil,b/l	0	94.7	17453	4440	1372	395	160	111	76	24007
150	D235 Chamgah	kahir,b/l	0	52.8	9820	6727	1820	118	0	0	0	18485
151	R37 Maltu	chil,b/l	1380-1569	49.6	9214	950	588	586	226	72	10	11646
152	D162 Maltu I	chil.b/l	1300-1600	28.4	1848	720	584	382	406	89	14	4043
153	D163 Maltu I	chil,b/l	1420-1480	11.2	2783	541	312	234	168	43	17	4098

154	D164 Maltu III	chil,b/l	0	15.6	6076	2200	238	87	59	39	39	8738
155	D166 Dhar	chil,b/l,khair	0	69.6	9316	1914	835	492	281	70	0	12908
156	D237 Sherla	chil,b/l	0	16.8	1604	474	191	104	73	44	30	2520
157	D94 Nandal	chil,ban	1280-1380	8.4	864	192	81	69	101	60	14	1381
158	D82 Jawa rajgarh	ban,chil	1780-2010	43.6	11246	1817	635	32	0	0	0	13730
159	D83 Rajgarh	ban,deo	1325-2090	133.2	55895	9730	3940	712	310	132	18	70737
160	D230 Jangeshu kandi	b/l,chil	0	157.2	4272	2228	1318	1099	708	170	24	9819
161	D240 Dochi	chil	1425-1875	104.8	8307	2410	602	335	267	132	64	12117
162	0			0	0	0	0	0	0	0	0	0
163	R24 Rajgarh	deo,ban	1775-2100	68.8	28964	4645	1753	197	56	37	3	35655
164	D92 Deora	chil,b/l	1400-1585	25.6	5725	1508	469	93	53	38	25	7911
165	D91 Bhawan ki dhar	chil,b/l	1350-1460	11.6	3894	549	178	170	101	51	15	4958
166	D93 Nandal nagali	chil	1250-1350	12.4	2532	147	79	81	56	42	30	2967
167	D80 Seri	ban,chil	1200-1690	20.8	2543	435	187	29	5	2	0	3201
168	D182 Kalath III	chil	1225-1450	25.6	11326	6709	1261	217	84	75	47	19719
169	D81 Charech	ban,chil,deo	1300-1800	72.4	19427	3237	1330	182	34	16	2	24228
170	0			0	0	0	0	0	0	0	0	0
171	D229 Tiron	bamboo,b/l	0	32.8	152	167	137	122	76	15	0	669
172	R52 Gumma	chil,b/l,bamboo	0	179.6	3747	4119	3077	2718	1691	339	0	15691
173	R49 Gadiar	chil,b/l	0	31.2	12387	3373	545	103	38	25	17	16488
174	D185 Johari	chil,b/l	0	24.3	2700	560	157	39	7	6	7	3476
175	D226 Annu II	b/l,bamboo	0	30.8	288	319	257	227	129	34	0	1254
176	D201 Kalath I	chil,b/l	0	55.6	7733	5927	2074	685	407	162	0	16988
177	R31 Barog	chil,ban	1120-1887	500.8	102307	26187	10024	3639	2176	671	286	145290
178	R30 Chabal ki dhar	chil	1175-1600	265.2	74419	9560	7626	5742	3160	1153	380	102040
179	D132 Charar	chil,ban.b/l	1500-1915	181.6	5681	2569	1525	836	711	408	277	12007
180	D130 Chawal	chil	1360-1520	4	735	117	89	78	92	81	14	1205
181	D129 Rano	chil	1200-1500	18.8	1931	1442	371	173	787	17	4	4016
182	D127 Shashal	chil,b/l	1200-1466	82.4	10929	4325	2120	913	338	123	23	18771
183	D103 Dharot ka cheon	chil,ban b/l	1300-1420	5.6	602	244	232	177	63	14	1	1424
184	D117 Chabal ki dhar IV	chil	1250-1338	2.4	3025	1863	646	301	257	120	56	6268
185	R29 Kathani	chil	0	16	11	11	6	2	2	2	1	35
186	D69 Palech I	,chil	1300-1700	22.4	7732	2985	206	65	45	18	0	11042
187	D68 Hathon	chil	1260-1380	6	690	251	41	34	30	10	0	1056
188	D133 Koon	chil,b/l	1300-1320	10.4	530	615	432	280	94	12	1	1964
189	D128 Kali kufer	chil	1250-1700	91.6	23330	6076	2127	1148	582	270	80	33613
190	D70 Palech II	chil	0	3.2	368	134	22	19	16	6	0	565
191	D99 Salumna	ban,chil	1240-1580	23.2	2897	355	94	36	45	12	0	3439
192	D102 Baran ki cheon	chil,ban,b/l	1300-1540	18.8	2055	805	558	455	276	38	3	4190
193	D78 Karol VIII	ban	1640-1800	4.8	235	14	5	5	0	0	0	259
194	D76 Karol VI	ban	1540-1880	0.8	49	3	1	1	0	0	0	54

195	D75 Karol V	ban,deo	1575-2100	19.2	11478	4992	636	102	37	19	0	17264
196	R23 Karol III	ban,deo,chil,b/l	1420-1540	8	4168	2056	488	16	0	0	0	6728
197	R22 Karol	ban,chil,deo,b/l	1300-1660	12.4	6457	3181	743	25	2	0	0	10408
198	D79 Daid	ban,deo	1300-1410	14.4	1516	864	492	240	100	96	0	3308
199	D72 Karol II	ban	1520-1836	16.4	8880	3440	150	0	0	0	0	12470
200	D71 Karol I	ban,deo	1600-1740	5.2	731	85	46	16	11	6	0	895
201	D101 Kuroli	ban,chil	1400-1600	19.6	6248	3256	795	27	0	0	0	10326
202	D100 Dharot	ban,chil,b/l	1500-1830	34.4	7675	4375	1430	165	29	10	1	13685
203	D73 Karol III	ban,deo,chil,b/l	1520-1680	10.4	7638	3183	403	53	16	6	3	11302
204	D74 Karol IV	ban,deo	1620-1890	5.6	577	158	89	40	19	16	0	899
205	D58 Basha	ban	1800-2000	11.2	950	218	38	3	3	0	0	1212
206	D55 Surron I	ban,deo,chil	1700-1800	2	210	10	5	0	1	0	0	226
207	D54 Shadial	ban,deo,chil.b/l	1530-1720	8.4	3303	883	80	70	1	5	0	4341
208	D59 Bagetu	deo,chil	1580-1640	2.4	446	138	103	29	2	2	2	722
209	D57 Kamhal	chil,deo,ban,b/l	0	4.8	782	371	197	39	3	0	0	1392
210	D56 Surron II	ban,deo,chil,b/l	1600-1680	2.8	600	154	56	12	1	0	0	823
211	D110 Raikot	chil,b/l	0	34.8	134	82	31	5	5	0	0	257
212	D113 Sarighat	Chil, eucalypt, ban, deo	0	17.6	2289	1956	1137	330	47	0	0	5759
213	D109 Panewa	eucalypt,b/l	0	38.4	46	294	242	4	0	0	0	586
214	D53 Sungal	ban,deo,chil,b/l	1680-1840	11.2	2730	455	79	7	8	2	1	3282
215	D112 Alobra	khair,eucalypt,b/l	0	54.4	479	2	1	0	0	0	0	482
216	D111 Thothal	chil,khair,eucalypt,b/l	0	5.2	115	305	250	16	0	0	0	686
217	D62 Bisha	chil,ban	1590-1880	80	6151	2289	478	130	21	0	66	9135
218	D134 Kothi	chil,c/dry	1000-1450	87.6	14693	2423	2064	1544	770	258	48	21800
219	D67 Sainj	ban,chil	1400-1580	12.8	3218	878	115	0	10	0	0	4221
220	D60 badoon sikar	ban,deo	1350-1650	28.4	5605	1307	257	21	17	0	0	7207
221	D121 Pansora	chil	0	3.6	81	57	43	16	0	0	0	197
222	D122 Shangari	chil,b/l	1175-1250	6.4	433	304	236	93	29	4	2	1101
223	D124 Katyara	chil,b/l	1300-1520	82.8	6916	2220	960	485	265	44	32	10987
224	D61 Danoli dochi	ban,chil	1580-1700	6.4	1509	299	9	0	0	0	0	1817
225	D63 Kiari	chil,deo	0	23.6	3069	1054	290	72	0	0	0	4485
226	R20 Bisha	ban,deo,chil,b/l	1660-1880	66	7026	5944	1056	398	58	0	174	14656
227	D66 Kasauli	ban	1520-1600	5.6	281	18	5	5	0	0	0	309
228	D65 Birni kasauli	ban	1460-1580	7.2	943	43	22	0	7	0	0	1015
229	D64			0	0	0	0	0	0	0	0	0
230	D77 Karol VII	ban	1600-1625	1.2	533	293	68	2	0	0	0	896
231	D106 Naloh	ban	1050-1450	36.8	3155	173	63	23	13	0	0	3427
232	R21 Karol	ban,deo,chil,b/l	1540-2250	279.6	129339	92776	27506	3140	176	112	0	252715
233	D104 Karol	ban	1950-2250	67.2	29757	5061	2367	790	66	0	0	38041
234	D105 Mathia	ban,deo,chil	1300-1800	48	4046	677	122	27	8	0	0	4880

235	D119 Chabal ki dhar II	chil	0	26.4	8269	1969	1150	1137	619	104	38	13286
236	R29 Kathani	chil	0	16	11	11	6	2	2	2	1	35
237	D126 Manlog	chil	1200-1450	51.4	19175	1975	492	387	264	136	89	22518
238	D107 Dhalain	ban,chil	1275-1500	18.4	550	135	70	20	0	0	0	775
239	D114 Kathani	chil,b/l,eucalypt	0	287.8	393	319	191	73	34	8	0	1018
240	R51 Gauri ki dhar	b/l	0	42	5821	2595	1033	277	75	25	0	9826
241	R 46 Jagatgarh	chil,b/l	0	135.9	17002	6641	3035	601	356	226	57	28058
242	D188 Karalghat	chil,b/l	1140-1440	102.8	37269	5925	1083	405	291	245	227	45445
243	D187 Kalth	chil,b/l	0	8.8	2184	300	66	17	11	17	22	2617
244	D181 Sirguli ka tiba	chil	1170-1290	25.2	6760	3630	354	63	76	78	42	11003
245	0			0	0	0	0	0	0	0	0	0
246	D212 Halda II	b/l	0	16	154	193	115	16	39	0	0	517
247	R54 Karal dev	chil	0	151.6	11976	3638	2121	1059	302	260	0	19356
248	R53 Tiron	b/l,eucalypt,bamboo	0	85.6	1182	1294	1050	708	400	80	0	4714
249	R48 Kalath	chil,b/l,bamboo	1350-1600	167.6	333131	12881	3792	1718	977	581	517	53780
250	D183 Kalath IV	chil	1280-1425	36.3	21272	5797	1123	170	115	78	48	28603
251	D168 Kiard I	chil	1420-1606	9.2	1090	358	290	125	81	15	3	1962
252	D167 Gadiar	chil,b/l	1075-1350	28.2	12230	3488	1110	546	475	169	74	18092
253	D144 Chewa khil chunjari	chil	1650-1800	5.2	1301	180	161	92	38	22	5	1799
254	R32 Chunjari	chil	1760-1940	67.6	38384	16216	726	174	153	122	55	55830
255	R 47 Karalghat	chil,b/l	0	136.8	41815	6607	1747	544	336	159	60	51222
256	D139 Banjani	chil	0	4	69	24	78	38	3	0	0	212

* 0 value indicates absence of data in inventory report

APPENDIX II

Data base showing name of the forest and total volume of trees in different diameter classes

Poly ID	Name of the forest	Volume (m^3)							
		(10-20cm)	(20-30cm)	(30-40cm)	(40-50cm)	(50-60cm)	(60-70cm)	(70-80cm)	Total
1	R57 Banasar	1421.431	1408.4364	746.8986	555.304	777.1992	744.4686	608.1873	5761.9253
2	D192 Nabon partha	70.5164	368.3237	248.2472	28.4686	0	0	0	715.5559
3	R58 Jagatgarh	39.384	54.9795	73.7868	143.104	167.9289	64.9232	44.6376	588.744
4	D178 Charoti ki dhar	589.68	877.6488	897.5106	1042.888	824.6445	526.907	284.5647	5043.8436
5	D176 Charoti ki dhar	550.8684	1186.2918	728.6682	521.7088	477.3414	342.8108	230.6347	4038.3241
6	D175 Bohali	153.054	554.3528	658.0518	653.8124	397.581	199.03221	78.1361	2694.02031
7	R45 Khader ki dhar	1922.357	3146.2002	3810.8546	1911.0336	571.4808	0	0	11361.926
8	D189 Jgatgarh	765.576	1037.3961	1358.7098	585.1008	325.3392	282.1502	111.594	4465.8661
9	D200 Danota chakali	2638.339	5144.4261	4323.9507	4248.8032	6014.859	3273.8202	742.1001	26386.2985
10	D191 Shogi nabon	36.216	188.4538	143.6634	39.4864	0	0	0	407.8196
11	D222 Banasar top	823.6368	705.9675	236.187	192.3248	411.1926	428.3244	407.3181	3204.9512
12	R41 Gulzar	4506.415	2356.5672	1043.4048	353.2392	194.2998	268.5526	167.391	8889.8698
13	D179 Sirguli ka tiba	146.2104	215.6637	97.2132	109.7064	124.2615	292.3484	295.7241	1281.1277
14	D180 Sirguli ka tiba	683.5752	332.8668	275.2092	265.4624	262.0788	163.1712	66.9564	2049.32
15	D214 Tiba guljar	8331.019	2434.7808	1627.3271	385.6008	284.6718	190.3664	0	13253.7661
16	D215 Kaba	240.408	221.0544	150.6745	89.304	108.9083	40.7928	0	851.142
17	R40 Bohali	602.6328	1203.7683	690.0769	468.6224	467.6751	401.1292	295.7241	4129.6288
18	R39 Charoti ki dhar	231.2856	445.8216	360.0996	281.7152	198.8184	125.7778	44.6376	1688.1558
19	D179 Sirguli ka tiba	152.46	465.5637	442.2516	407.6744	580.6401	407.928	267.3776	2723.8954
20	D177 Charoti ki dhar	152.46	465.5637	442.2516	407.6744	580.6401	407.928	312.4632	2768.981
21	D184 Rathal	3750.365	2632.2681	1190.9539	352.9656	314.0427	666.2826	652.8249	9559.7026
22	D169 Kiard II	300.2328	191.9232	683.9154	968.396	594.1959	353.5376	217.6083	3309.8092
23	D142 Jhaja bahali	268.8048	564.5509	929.3544	765.0384	625.8261	105.3814	11.2594	3270.2154
24	R38 Kiard	201.096	327.369	711.2994	609.48	655.197	118.979	27.8985	2651.3189
25	D236 Kurar	1497.082	841.3776	444.5007	155.756	180.744	152.973	195.2895	3467.7224
26	D233 Datiyar	8648.842	8615.6085	7804.614	3463.5824	1676.6241	825.5621	22.3188	31057.1515
27	D202 Kalath no II	508.1832	1069.5465	930.5204	1050.2704	1206.7891	797.67412	200.8692	5763.85292
28	D186 kalath V	374.4216	192.4077	295.4058	66.3656	70.0383	149.5736	318.0429	1466.2555
29	D232 Bamola totela	20.6136	29.7381	19.8534	23.0248	29.3709	23.7958	16.7391	163.1357
30	D231 Shlu jangeshu	38.7072	94.9212	238.0857	276.668	277.0816	83.28164	0	1008.74534
31	D190 jabrog	372.5064	1066.1091	927.2242	325.3352	0	0	0	2691.1749
32	R55 Mashobra C1	19.9584	52.071	80.2719	95.9752	46.3101	35.62706	0	330.21366
33	D241 Shewla	70.8624	106.7073	170.4654	167.9456	79.0755	37.3934	5.5797	638.0293

34	D120 Chabal ki dhar	17.9424	23.4906	8.2152	209.932	994.092	108.7808	16.7391	1379.1921
35	R55 Mashobra C2	23.0832	34.7361	55.4526	52.8216	27.1116	13.5976	0	206.8027
36	D234 Ranigoan	401.0832	921.0855	1253.4875	395.4424	2.2593	0	0	2973.3579
37	D221 Kiarwa	234.2088	383.3974	464.3042	240.2288	69.2704	0	0	1391.4096
38	0	0	0	0	0	0	0	0	0
39	R61 Naraini	2788.073	4529.6046	5117.1786	2359.1008	465.4105	0	0	15259.3673
40	R59 Jandhouri	85.1256	141.7086	162.4323	80.976	12.9882	0	0	483.2307
41	D195 Pratha	78.624	131.9472	151.3068	70.1792	17.3176	0	0	449.3748
42	R60 Jandhouri	39.6144	65.9736	75.6534	35.0896	6.4941	0	0	222.8251
43	D195 Pratha	0	0	0	0	0	0	0	0
44	D160 Anji I	224.7336	234.906	73.9368	96.1624	74.5569	30.5946	27.8985	762.7888
45	D171 Bhog sari	52.92	38.7345	149.9274	170.6544	178.4847	47.5916	66.9564	705.269
46	D172 Bhog sari III	98.532	46.2315	84.2058	54.176	51.9639	27.1952	27.8985	390.2029
47	D170 Bhog sari	177.4584	69.4722	173.8884	189.616	187.5219	95.1832	128.3331	1021.4732
48	D173 Bohali ki chali	67.0824	180.4278	255.3558	89.3904	74.5569	33.994	72.5361	773.3434
49	D87 Diarag daun	285.4837	175.1334	199.6725	98.2786	16.3294	0	0	774.8976
50	D238 Dhamiana	208.9848	339.0924	138.1554	11.2472	1.8	0.6	0	698.5598
51	D158 Anji I	59.0184	251.8992	731.1528	260.0448	228.1893	190.3664	0	1720.6709
52	D174 Bigaur	99.864	109.987	133.8024	46.314	39.9081	16.997	0	446.8725
53	D159 Anji III	104.9832	30.7377	29.4378	59.5936	33.8895	33.994	11.1594	303.7952
54	D243 Suji	25.0992	51.0867	26.6994	83.9728	36.1488	16.997	0	240.0039
55	R36 Anji	388.08	112.7049	70.5138	98.8712	72.2976	61.1892	33.4782	837.1349
56	R34 Mansa devi	15.4728	38.2347	69.1446	73.1376	58.7418	13.5976	11.1594	279.4885
57	R38 Kiard	201.096	327.369	984.5994	927.817	655.197	118.979	27.8985	3242.9559
58	D145 Chewa khil chunjari	166.1184	64.4742	157.458	342.6632	343.4136	220.961	44.6476	1339.736
59	R34 Mansa devi	15.4728	38.2347	69.1446	73.3544	58.7418	13.5976	11.1594	279.7053
60	D198 Bhaour lugon	273.2184	455.0832	521.4151	241.5784	30.3058	0	0	1521.6009
61	D199 Chawal Ashnalla	996.156	1591.0674	1198.8114	580.7552	691.9805	495.18318	27.8985	5581.85218
62	D209 Bhagour	0	0	0	0	0	0	0	0
63	R43 Halda kaba	421.3944	1204.6914	1603.4947	351.2896	1689.6345	206.3821	212.0286	5688.9153
64	D194 Pratha III	298.7712	501.1974	574.8175	267.2208	67.1057	0	0	1709.1126
65	D193 Partha umera	304.7184	161.1447	602.945	321.2192	119.7824	6.7988	27.8985	1544.507
66	D207 Sath dadhog	127.6128	101.6532	56.3692	17.5448	28.1411	0	0	331.3211
67	R42 Ajmergarh	682.2648	1158.0417	1228.0143	934.2912	573.9575	499.7118	161.8113	5238.0926
68	D203 Qila Ajmergarh	3561.415	2160.7935	1732.4586	1451.548	891.0769	394.3304	128.3331	10319.9557
69	D205 Neri no I	476.7336	405.807	239.7951	129.7968	174.1331	71.3874	11.1594	1508.8124
70	D213 Kaba bahaur	4904.676	1871.4654	1219.2322	116.4784	122.0022	71.3874	0	8305.2416
71	R44 Jhanai	1982.006	3225.2742	3895.6331	2012.2536	586.6337	0	0	11701.801
72	D220 Barog C2	0	0	0	0	0	0	0	0
73	D218 Kamlog	130.1832	213.0678	258.1116	133.6104	38.9646	0	0	773.9376
74	D218 kamlog	0	0	0	0	0	0	0	0

75	D220 Barog C1	1045.699	1711.611	2073.0515	1072.932	311.7168	0	0	6215.0105
76	D247 Satrol	138.348	231.5808	267.7537	122.8136	30.3058	22.42198	0	813.22388
77	D219 Satrol II	23.7384	39.7188	45.9854	21.5936	4.3294	3.20314	0	138.56874
78	D196 Mauri	78.624	131.9472	151.3068	70.1792	8.6588	0	0	440.716
79	D217 Niun shanog	1310.45	2144.8152	2598.1751	1344.2016	391.8107	0	0	7789.453
80	D216 Bhanog bhallon	878.9526	720.4872	415.9194	155.3576	224.8561	27.1952	0	2422.7681
81	D211 Halda I	83.8152	234.9366	309.9164	80.9856	323.0133	6.60254	33.4782	1072.74784
82	D197 Pratha I	23.7384	39.7188	45.9854	21.5936	4.3294	3.20314	0	138.56874
83	D206 Neri II	50.5512	117.912	114.8998	204.4952	236.8481	217.5616	39.0579	981.3258
84	D206 Neri II	0	0	0	0	0	0	0	0
85	D157 Kadon I	500.724	146.1915	262.8864	333.1824	257.5602	146.1742	50.2173	1696.936
86	R35 Kadon	770.1624	242.6529	643.524	662.3016	591.9366	288.949	72.5361	3272.0626
87	D155 Bhallon	85.5288	23.9904	86.9442	94.808	45.186	27.1952	5.5797	369.2323
88	D156 Kadon II	81.6984	24.2403	45.8682	69.0744	36.1488	44.1922	0	301.2223
89	D161 Sehardi	797.1264	396.5913	702.3996	1021.2176	840.4596	353.5376	0	4111.3321
90	D157	0	0	0	0	0	0	0	0
91	D157	0	0	0	0	0	0	0	0
92	D143 Chewa khil chunjari	124.3368	34.986	64.3524	66.3656	24.8523	6.7988	0	321.6919
93	R27 Nauni	682.4412	514.7397	160.5659	112.7138	0	0	0	1470.4606
94	R28 Khaldhar	675.2972	951.3268	1801.9981	1514.3626	1733.1164	1213.7259	853.6941	8743.5211
95	D137 Nauni	47.4336	100.4982	88.872	30.4908	6	0	0	273.2946
96	D146 Chewa khil chunjari IV	399.1176	290.1339	746.8986	1535.8896	1644.7704	1512.733	652.8249	6782.368
97	D140 Kainthari	226.3464	136.1955	103.3746	150.3384	131.0394	33.994	5.5797	786.868
98	D154 Dawala	365.5512	113.4546	138.2892	308.8032	350.1915	166.5706	27.8985	1470.7588
99	D98 Bhawan ki dhar	684.8856	749.7969	177.3114	105.6384	169.4475	200.5646	137.11594	2224.76034
100	D90 Gadhon II	209.3004	77.4762	154.9776	233.5184	192.7812	59.6568	11.1594	938.87
101	D86 Diarag niun	359.022	663.9091	591.5048	300.954	45	0	0	1960.3899
102	D97 Kiar tatul	64.1596	20.9916	4.1076	23.0248	45.186	23.7958	22.3188	203.5842
103	R26 Nagali	597.744	970.1679	387.9987	128.668	167.0936	227.7598	271.02874	2750.46074
104	D95 Nagali I	29.988	46.4814	32.1762	78.5552	81.3348	67.988	72.5361	409.0597
105	D96 Nagali II	23.3848	10.2459	8.2152	28.4424	51.9639	54.3904	39.0579	215.7005
106	D88 Shawag badrog	179.6929	128.7636	142.8308	56.9288	38.226	17.6975	0	564.1387
107	D84 Damkari	423.4128	321.0752	315.5298	81.8456	3	0	0	1144.8638
108	D123 Beola	34.2216	45.7317	143.766	228.8936	259.8195	91.7838	5.5797	809.7959
109	D125 Sheel ka dhala	319.9392	381.3474	160.1964	199.0968	284.6718	319.5436	329.2023	1993.9975
110	D85 Niun	417.1549	564.4021	462.6309	221.8156	35.1647	3.734	0	1704.9022
111	D89 Gadhog I	163.7136	110.2204	153.9648	143.5664	65.5197	20.3964	0	657.3813
112	R25 Shawag badrog	1616.283	1413.3805	1064.4192	195.6208	22.5	52.276	0	4364.4799
113	R33 Gulhari	886.3884	1059.8277	3053.0442	3515.1968	2070.2223	489.8482	212.0286	11286.5562
114	D246 Kasauli C1	82.4544	118.9524	80.7828	89.3904	117.4836	88.3844	72.5361	658.9841
115	D246 Kasauli C2	0	0	0	0	0	0	0	0

116	D151 Gulhari I	991.9224	417.8328	1654.6782	2077.6496	1554.3984	1013.0212	407.3181	8116.8207
117	D152 Gulhari II	73.6848	65.4738	164.304	166.5912	117.4836	33.994	5.5797	577.1111
118	D245 Sanawar	1943.582	628.4985	1222.6956	1602.2552	1129.65	428.3244	50.2173	7005.2234
119	D153 Gulhari I	8.5176	17.9928	34.23	37.9232	15.8151	3.3994	11.1594	129.0375
120	D148 Samol	24.9984	35.9856	24.6456	27.088	36.1488	27.1952	16.7391	192.8007
121	D118 Chabal ki dhar	367.5672	726.2094	785.9208	835.6648	840.4596	356.937	351.5211	4264.2799
122	D150 Gulhari IV	2.3688	45.2319	143.0814	92.0992	31.6302	13.5976	0	328.0091
123	D149 Sanhol	52.4664	75.4698	52.0296	56.8848	76.8162	57.7898	44.5376	415.9942
124	D204 Tikkari	139.9608	327.93	369.6924	243.6288	151.3731	115.5796	61.3767	1409.5414
125	0	0	0	0	0	0	0	0	0
126	R50 Kalath	95.9112	48.2307	52.0296	33.86	38.4081	47.5916	106.0143	422.0455
127	D195 Pratha	0	0	0	0	0	0	0	0
128	D208 Sari	0	0	0	0	0	0	0	0
129	0	0	0	0	0	0	0	0	0
130	D210 Oder janghiria	115.5168	322.7994	422.0273	112.0168	419.9518	0	0	1392.3121
131	D141 Barog	8.2656	32.7368	82.8366	131.3768	176.2254	0	0	431.4413
132	R33 Gulhari	886.3884	1059.8277	3053.0442	3515.1968	2070.2223	489.8482	181.4348	11256.7336
133	D131 Mathan	571.1328	446.5713	536.7264	847.8544	1066.3896	836.2524	792.3174	5097.2443
134	D135 Khaldhar	11.592	41.9832	65.037	98.8712	49.7046	20.3964	0	287.5844
135	D138 Khaldhar III	423.2304	144.1962	308.7876	270.5828	246.2637	169.97	117.1737	1680.2044
136	D136 Khaldhar	223.128	315.1248	467.76	156.648	228.1707	183.5676	167.391	1741.7901
137	D147 Kainthri	573.048	209.1663	281.3706	358.916	280.1532	173.3694	72.5361	1948.5596
138	D242 Gahidhar	549.9144	239.1578	372.4224	1002.1972	1143.2058	370.5346	273.4053	3950.8375
139	D224 Sandhog	1529.69	1518.4026	1331.3515	531.7424	283.5757	140.93816	0	5335.70076
140	0	0	0	0	0	0	0	0	0
141	D244 Cheola	1322.546	1217.1405	678.5588	1078.088	1206.4662	543.904	306.8835	6353.5874
142	D223 Khadeen	1816.214	1802.8296	1581.3044	700.4424	337.6932	163.36014	0	6401.84414
143	D228 Ambota	60.0264	140.4336	251.6635	396.8352	389.9298	118.71244	0	1627.60094
144	D239 Sari dhar	4663.832	1150.4172	1340.0495	1255.3752	813.8099	667.75172	693.63914	10584.8747
145	R56 Parwanoo	0	500.55	2006.4975	7752.22	8275.5225	8751.8565	8407.454	35694.1005
146	D225 Gumma	0	0	0	0	0	0	0	0
147	D227 Annu I	12.3984	30.6306	54.8858	87.724	80.0939	28.82826	0	294.56096
148	D165 Maltu IV	424.4184	282.0198	536.156	788.2608	763.6434	333.1412	100.4346	3228.0742
149	D185 Kurla and Johari	2236.298	1416.5709	1072.1058	587.392	376.8301	397.53354	463.1151	6549.84584
150	D235 Chamgah	1477.109	2215.3566	1346.3604	159.2528	0	0	0	5198.0786
151	R37 Maltu	633.1248	244.1676	402.5448	793.6784	510.6018	244.7568	55.797	2884.6712
152	D162 Maltu I	195.7536	203.5971	402.3759	517.3808	917.2758	302.5466	78.1158	2617.0456
153	D163 Maltu I	168.588	137.6235	213.6523	316.9296	379.5624	146.1742	94.8549	1457.3849
154	D164 Maltu III	324.8784	554.115	162.9348	117.8328	133.2987	132.5766	217.6083	1643.2446
155	D166 Dhar	808.7448	518.3529	576.7597	666.3648	634.8633	237.958	0	3443.0435
156	D237 Sherla	232.7472	150.705	135.0982	140.8576	164.9289	149.5736	167.391	1141.3015

157	D94 Nandal	606.8592	43.7508	47.9844	53.6802	93.0572	203.964	74.4031	1025.7145
158	D82 Jawa rajgarh	606.8592	454.2445	358.2546	33.4308	0	0	0	1452.7891
159	D83 Rajgarh	3076.752	2329.7368	1692.1354	924.2722	790.004	398.6415	98.1144	9309.6565
160	D230 Jangeshu kandi	286.3728	545.8938	735.7562	1112.6608	1080.8698	445.24378	133.9128	4340.70998
161	D240 Dochi	418.6728	602.259	329.9772	453.729	603.2331	448.7208	357.1008	3213.6927
162	0	0	0	0	0	0	0	0	0
163	R24 Rajgarh	1586.367	1136.7516	1011.3019	237.7106	142.7104	95.839	14.4411	4225.1218
164	D92 Deora	325.6848	387.3399	323.1901	125.9448	119.7429	129.1772	139.4925	1550.5722
165	D91 Bhawan ki dhar	196.3872	137.1957	121.8588	230.248	228.1893	173.3694	83.6955	1170.9439
166	D93 Nandal nagali	127.6128	36.7353	54.0834	109.7064	126.5208	142.7748	167.391	764.8245
167	D80 Seri	136.8936	108.7468	105.4854	28.5748	10.5372	6.7988	0	397.0366
168	D182 Kalath III	570.8304	1676.5791	863.2806	293.9048	189.7812	254.955	262.2459	4111.587
169	D81 Charech	1054.328	797.9623	769.9562	208.44	86.6456	46.597	9.6274	2973.5561
170	0	0	0	0	0	0	0	0	0
171	D229 Tiron	22.9824	56.2122	101.6129	164.6512	164.5172	48.0471	0	558.023
172	R52 Gumma	542.6568	1380.213	2279.8127	3668.3136	3661.0753	1086.257	0	12618.3284
173	R49 Gadiar	626.4216	843.3462	373.1641	139.5032	85.8534	84.985	94.8549	2248.1284
174	D185 Johari	419.2272	192.9738	124.4307	59.512	15.8151	20.3964	39.0579	871.4131
175	D226 Annu II	43.5456	107.3754	190.6169	306.3592	279.2463	108.90676	0	1036.05016
176	D201 Kalath I	1077.502	1894.8897	1511.5059	926.0552	894.2769	524.40396	0	6828.63326
177	R31 Barog	5168.678	6538.1778	6773.9836	4809.3452	4861.5672	2262.6086	1595.7942	32010.1542
178	R30 Chabal ki dhar	3750.718	2389.044	5220.7596	7776.9648	7139.388	3919.5082	2120.286	32316.6682
179	D132 Charar	289.2204	644.5297	1017.2156	1060.0856	1501.2005	1281.2196	1410.0314	7203.5028
180	D130 Chawal	36.9936	29.2383	60.9294	105.6432	207.8556	275.3514	78.1158	794.1273
181	D129 Rano	97.3224	360.3558	253.9866	234.3112	176.2254	57.7898	22.3188	1202.31
182	D127 Shashal	558.4824	1082.6382	1452.0372	1236.5672	763.6434	418.1262	128.3331	5639.8277
183	D103 Dharot ka cheon	31.4136	60.9764	221.1258	239.7288	142.3359	47.5916	5.5797	748.7518
184	D117 Chabal ki dhar IV	70.56	51.2295	141.7122	148.984	370.5252	44.1922	94.8549	922.058
185	R29 Kathani	0.5544	2.7489	4.1076	2.7088	4.5286	6.7988	5.5797	27.0268
186	D69 Palech I	412.6824	746.2067	127.1016	88.036	101.6685	61.1892	0	1536.8844
187	D68 Hathon	34.776	62.7249	28.0686	46.0496	67.779	33.994	0	273.3921
188	D133 Koon	30.1392	154.2954	295.8043	212.3742	40.7928	40.7928	5.5797	779.7784
189	D128 Kali kufer	1175.832	1518.3924	1456.1442	1554.8512	1314.9126	917.838	446.376	8384.3464
190	D70 PalechII	18.5472	33.4866	15.0612	25.7336	36.1488	20.3964	0	149.3738
191	D99 Salumna	153.954	88.7248	57.7692	48.7584	90.279	40.7928	0	480.2782
192	D102 Baran ki cheon	107.7984	201.885	373.7083	616.252	623.5668	129.1772	16.7391	2069.1268
193	D78 Karol VIII	12.69	3.5	2.79	4.79	0	0	0	23.77
194	D76 Karol VI	2.646	0.75	0.558	0.958	0	0	0	4.912
195	D75 Karol V	631.9362	1165.2908	423.2424	144.4116	94.2908	67.2505	0	2526.4223
196	R23 Karol III	3612.988	510.056	276.728	15.328	0	0	0	4415.0996
197	R22 Karol	391.1227	788.9771	418.7136	26.8476	4.5186	0	0	1630.1796

198	D79 Daid	97.896	124.944	346.488	339.792	250.6464	339.792	0	1499.5584
199	D72 Karol no II	479.52	860	83.7	0	0	0	0	1423.22
200	D71 Karol no I	40.643	17.1308	30.4648	22.6528	22.7904	21.237	0	154.9188
201	D101 Kuroli	335.2176	813.9856	450.1932	26.6588	0	0	0	1626.0552
202	D100 Dharot	418.1184	1097.3991	871.368	211.1876	64.7604	33.994	5.5797	2702.4072
203	D73 Karol III	468.0896	757.9205	267.7474	74.7304	39.618	21.237	14.4411	1643.784
204	D74 Karol IV	32.8948	29.0936	61.654	56.632	45.2744	56.632	0	282.1808
205	D58 Basha	51.3	54.5	21.204	2.874	4.5	0	0	134.378
206	D55 Surron I	11.3522	2.4998	2.9196	0	1.5	0	0	18.2716
207	D54 Shadial	209.7699	198.3625	46.0225	67.06	0	9.335	0	530.5499
208	D59 Bagetu	31.451	19.75754	72.8671	41.0582	5.0968	7.079	11.1594	188.46904
209	D57 Kamhal	41.2763	92.977	134.0371	52.0288	6.6833	0	0	327.0025
210	D56 Surron II	41.4928	31.6478	37.6937	16.9896	1.5	0	0	129.3239
211	D110 Raikot	19.4544	26.9076	22.7072	6.7528	10.9181	0	0	86.7401
212	D113 Sarighat	127.7618	107.1532	778.2056	446.952	106.1871	0	0	1566.2597
213	D109 Panewa	6.0624	91.728	121	24	0	0	0	242.752
214	D53 Sungal	172.7172	110.7074	45.5911	7.1638	12	3.734	1.867	353.7805
215	D112 Alobra	62.748	0.6732	0.7147	0	0	0	0	64.1629
216	D111 Thothal	13.5384	94.539	126.4768	18.6528	0	0	0	253.207
217	D62 Bisha	318.2652	572.233	277.485	124.54	31.5	0	0	0
218	D134 Kothi	0	0	0	0	0	0	0	0
219	D67 Sainj	171.3816	219.4746	65.3094	0	15	0	0	471.1656
220	D60 badoon sikar	318.7187	308.4304	152.2501	25.6116	25.5	0	0	830.5108
221	D121 Pansora	4.0824	14.2443	29.4378	21.6704	0	0	0	69.4349
222	D122 Shangari	22.3272	75.9696	161.5656	125.9592	65.5197	13.5976	11.1594	476.0983
223	D124 Katyara	357.0336	557.8992	658.3009	656.8648	596.3606	346.7388	245.5068	3418.7047
224	D61 Danoli dochi	80.6184	74.7469	5.655	0	0	0	0	161.0203
225	D63 Kiari	177.3527	226.356	204.4056	101.9376	0	0	0	710.0519
226	R20 Bisha	401.2064	1487.098	590.7672	381.284	87	0	324.858	3272.2136
227	D66 Kasauli	15.174	4.5	2.79	4.79	0	0	0	27.254
228	D65 Birni kasauli	50.922	10.75	12.276	0	10.5	0	0	84.448
229	D64	0	0	0	0	0	0	0	0
230	D77 Karol VII	28.782	73.25	37.944	1.916	0	0	0	141.892
231	D106 naloh	170.37	43.25	53.154	22.034	19.5	0	0	290.308
232	R21 Karol	8042.758	24528.289	15513.993	2828.268	448.5184	622.952	0	51984.7791
233	D104 Karol	1606.878	1265.25	1320.786	756.82	99	0	0	5048.734
234	D105 Mathia	224.3891	163.179	69.2752	25.866	12	0	0	494.7093
235	D119 Chabal ki dhar II	416.7576	492.0531	7907.13	1539.9528	1398.5067	353.5376	212.0286	12319.9664
236	R29 Kathani	0.5544	2.7489	4.1076	2.7088	4.5186	6.7988	5.5797	27.0168
237	D126 Manlog	966.42	493.5525	336.8232	524.1528	596.4552	462.3184	496.5933	3876.3122
238	D107 Dhalain	26.622	33.7385	47.289	25.106	0	0	0	132.7555

239	D114 kathani	21.6636	80.5359	130.9299	98.8664	76.7216	27.1952	0	435.9126
240	R51 Gauri ki dhar	880.1352	873.477	766.1761	373.8392	162.3525	80.0785	0	3136.0585
241	R 46 Jagatgarh	1687.795	1748.0199	2091.465	949.4008	804.3108	768.2644	541.2309	8590.487
242	D188 Karalghat	2418.545	1570.1319	745.6472	548.532	657.4563	832.853	1266.5919	8039.7571
243	D187 Kalth	169.344	84.9405	45.7546	23.0248	24.8523	57.7898	122.7534	528.4594
244	D181 Sirguli ka tiba	340.704	907.137	242.3484	85.3272	171.7068	265.1532	234.3474	2246.724
245	0	0	0	0	0	0	0	0	0
246	D212 Halda II	23.2848	64.9638	85.2955	21.5936	84.4233	0	0	279.561
247	R54 Karal dev	603.5904	909.1362	1452.0366	1434.3096	682.3086	883.844	0	5965.2254
248	R53 Tiron	172.8408	431.2062	746.6389	904.544	865.88	256.2512	0	3377.3611
249	R48 Kalath	1217.16	2364.5232	1746.3166	1182.0168	1064.393	832.52346	334.782	8741.71506
250	D183 Kalath IV	1072.109	1448.6703	768.8058	230.248	259.8195	265.1532	267.8256	4312.6312
251	D168 Kiard I	54.936	89.4642	198.534	169.3	183.0033	50.991	16.7391	762.9676
252	D167 Gaduar	1050.235	945.1728	769.0991	739.5024	1073.1675	574.4986	412.89978	5564.5734
253	D144 Chewa khil chunjari	65.5704	44.982	110.2206	124.6048	85.8534	74.7868	27.8985	533.9165
254	R32 Chunjari	1934.554	4052.3784	497.0196	235.6656	345.6729	414.7268	306.8835	7786.9004
255	R 47 Karalghat	5168.066	1867.059	1259.1164	735.1784	758.2734	539.5233	334.782	10661.9989
256	D139 Banjani	3.4776	5.9976	53.3988	51.4672	6.7779	0	0	1211.1191

* 0 value indicates absence of data in inventory report

APPENDIX III

Description of the study sites

S.No	Name of the Forest	Elevation in m.	Area (ha)	Aspect	Slope	Rock	Soil	Density	Site Quality	PB. No.
1	**D-93 Nandal Nagali**	1250-1350	12.4	Western	Moderate to Steep	Sandstone	Sandy loam of fair depth in depressions, shallow elsewhere	0.3-0.4	III	I
2	**D-95 Nagali I**	1350-1420	3.6	Western and South western	Moderate to Steep	Sandstone	Sandy loam of fair depth	0.5-0.7	III	I
3	**D-96 Nagali II**	1240-1345	4	Northern	Moderate	Sandstone	Fairly deep sandy loam	0.5	III	I
4	**D-97 Kiar Tatul**	1260-1350	4.4	Mainly Northern, partly North eastern	Moderate	Sandstone	Sandy loam of fair depth in depressions, dry and shallow on spurs	0.3-0.4	III	I
5	**D-123 Beola**	1350-1420	4.4	Mainly Eastern, partly North Eastern,	Moderate to steep	Sandstone	Sandy loam of fair depth in depressions, dry and shallow on spurs	0.4 - 0.5	III	I
6	**D-135 Kaldhar I**	1550-1775	5.6	All except Southern	Moderate to steep	Limestone	Fairly deep sandy soil, especially in depressions	0.5 – 0.6	III	I
7	**R-26 Nagali**	1250-1400	33.6	Mainly western but all aspects are represented	Gentle to steep	Sandstone	Sandy loam of fair depth, shallow on ridges and in the upper portion	0.7 - 0.8; 0.9 at places	III	IV
8	**D-92 Deora**	1400-1585	25.6	North eastern	Moderate to steep	Limestone, with the rock being exposed at places and shale	Sandy loam dry and shallow on spurs, moderately deep in depressions	0.5 – 0.6	III	IV
9	**D-94 Nandal**	1280-1380	8.4	North Western	Moderate to Steep	Sandstone	Sandy loam of fair depth	0.5-0.6	III	Inter
10	**D-89 Gadhog I**	1800-1940	9.2	Mainly eastern	Moderate	Limestone	Fairly deep sandy loam, except along northern boundary	0.4-0.5	III	Inter
11	**D-90 Gadhog II**	1580-1750	13.2	Eastern	Moderate; steep in the eastern portion	Limestone and shale	Sandy loam of moderate depth except in the lower portion	0.3-0.4	III	Inter
12	**D-98 Bhawan Ki Dhar**	1280-1380	19.2	All aspects represented	Moderate	Sandstone	Sandy loam of fair depth	0.8	III	IV
Dharampur Forest Range										

13	**R-36 Anji**	1400-1556	10.40	Mainly eastern, partly south eastern in the south	Moderate to steep	Sandstone	Sandy loam of shallow depth	Young chil: 0.5– 0.6; Overwood : 0.3	III	IV
14	**R-49 Gadiar**	1200-1450	31.20	North to North Eastern	Gentle to steep	Sandstone with a few rock outcrops	Sandy loam, fairly deep, except in exposed places	0.7	III	IV
15	**D-117 Chabil Ki Dhar IV**	1250-1338	2.40	North eastern	Moderate	Sandstone	Sandy loam, of shallow depth, rocky	0.6-0.7	III	IV
16	**D-118 Chabil Ki Dhar III**	1270-1530	10.40	North Eastern and North Western	Moderate to steep	Sandstone	Sandy loam, fairly deep in depressions, dry and shallow especially on spurs	0.8	III	IV
17	**D-164 Maltu III**	1280-1460	15.60	Mainly Southern, though all aspects are represented	Moderate to steep	Sandstone	Poor sandy loam, shallow and dry	Overwood: 0.2-0.3; Regeneration: 0.5-0.6	III	IV
18	**D-181 Sirguli Ka Tiba III**	1170-1290	25.20	All except eastern	Moderate to steep	Sandstone	Sandy loam, fairly deep	0.6-0.7	III	IV
19	**D-182 Kalath III**	1225-1450	25.60	Northern, North Eastern and North Western	Gentle to steep	Sandstone	Sandy loam of fair depth, except on spurs and lower reaches where it is coarse and dry	0.7-0.8	III	IV
20	**D-172 Bhog Seri III**	1180-1300	4.40	Mainly Eastern; partly Northern	Moderate to steep	Sandstone	Sandy loam, of shallow depth	Overwood: 0.2-0.3; Understorey: 0.5-0.6	III	IV
21	**D-159 Anji III**	1440-1520	3.60	North eastern	Moderate	Sandstone	Sandy loam, fairly deep in depressions, dry and shallow on spurs	Overwood: 0.3–0.4; Underwood: 0.6	III	IV
22	**D-160 Anji I**	1280-1420	10.40	Mainly eastern	Moderate	Sandstone	Sandy loam of fair depth	0.4 – 0.5	III	IV
23	**D-120 Chabil Ki Dhar I**	1300-1420	3.60	Northern and North Western	Moderate to steep	Sandstone	Sandy loam, dry and shallow	0.7-0.8	III	Inter
24	**D-150 Gulhari IV**	1575-1650	4.40	North Eastern and Eastern	Moderate to steep	Sandstone	Sandy loam, of fair depth	0.3 – 0.4	III	Inter
25	**D-152 Gulhari II**	1450-1550	8.80	North and North Eastern	Moderate to steep	Sandstone	Sandy loam, fairly deep especially in depressions and near nalas	0.6	III	Inter
26	**D-153 Gulhari I**	1500-1600	5.20	North Eastern	Moderate to steep	Sandstone	Coarse sandy loam, fairly deep especially near nalas and depressions	0.5	III	Inter
27	**D-154 Dawala**	1350-1500	12.80	North to North Eastern	Moderate to steep	Sandstone	Sandy loam, adequately deep	0.5 – 0.6	III	Inter

28	**D-155 Bhallon**	1360-1400	3.20	Mainly Northern and Western	Moderate	Sandstone	Sandy loam of shallow depth, better in depressions	0.4	III	Inter
29	**D-162 Maltu II**	1300-1600	28.40	Western and South Western	Moderate to steep	Sandstone	Sandy loam, of fair depth in depressions, dry and shallow on spurs	Western aspect: 0.4-0.5; South Western aspect: 0.3	III	Inter
30	**D-163 Maltu I**	1420-1480	11.20	Mainly Southern and partly Eastern	Moderate	Sandstone	Sandy loam, shallow and dry in the upper parts	0.3-0.4	III	Inter
31	**D-173 Bohali Ki Cheol**	1350-1480	10.40	Mainly South western, partly South eastern	Moderate	Sandstone	Sandy, rather dry, shallow in higher reaches, of better depth in depressions	0.5 in the upper portion; 0.2-0.3 on spurs and lower southern portion	III	Inter
32	**D-176 Charoti Ki Dhar I**	1250-1450	38.00	North eastern and South Eastern	Moderate	Sandstone	Sandy loam, fairly deep in depressions, shallow on spurs	0.5-0.6	III	Inter
33	**D-119 Chabil Ki Dhar II**	1220-1350	26.40	All aspects are represented	Moderate	Sandstone	Sandy loam, of fair depth	0.7	III	I

APPENDIX IV

Temporal distribution of Volume in selected compartments of Solan and Dharampur Forest Ranges of Solan Forest Division

S.No	Name of the Forest	Elevation in m.	Area (ha)	1956 Volume (m^3)	1984 Volume (m^3)	2002 Volume (m^3)	2011 Volume (m^3)
Solan Forest Range							
1	D-93 Nandal Nagali	1250-1350	12.4	1319.54 (106.41)	917.74 (74.01)	788.98 (63.63)	825.07 (66.54)
2	D-95 Nagali I	1350-1420	3.6	830.25 (230.62)	543.24 (150.90)	419.53 (116.54)	433.59 (120.44)
3	D-96 Nagali II	1240-1345	4	789.04 (197.26)	1343.56 (335.89)	221.24 (55.31)	243.55 (60.89)
4	D-97 Kiar Tatul	1260-1350	4.4	998.69 (226.98)	791.01 (179.77)	206.80 (47.00)	205.16 (46.63)
5	D-123 Beola	1350-1420	4.4	691.39 (157.13)	631.57 (143.54)	810.60 (184.23)	608.92 (138.39)
6	D-135 Kaldhar I	1550-1775	5.6	968.65 (172.97)	379.36 (67.74)	287.58 (51.35)	310.95 (55.53)
7	R-26 Nagali	1250-1400	33.6	3754.70 (111.75)	1382.58 (41.15)	2661.18 (79.20)	3250.03 (96.73)
8	D-92 Deora	1400-1585	25.6	1158.64 (45.26)	1388.76 (54.25)	1449.64 (56.63)	1767.21 (69.03)
9	D-94 Nandal	1280-1380	8.4	1681.32 (200.16)	1343.60 (159.95)	728.26 (86.70)	755.75 (89.97)
10	D-89 Gadhog I	1800-1940	9.2	481.23 (52.31)	323.68 (35.18)	587.38 (63.85)	1200.49 (130.49)
11	D-90 Gadhog II	1580-1750	13.2	1090.04 (82.58)	1216.05 (92.13)	894.35 (67.75)	939.94 (71.21)
12	D-98 Bhawan Ki Dhar	1280-1380	19.2	2130.04 (110.94)	732.63 (38.16)	2237.58 (116.54)	3297.88 (171.76)
Dharampur Forest Range							
13	R-36 Anji	1400-1556	10.40	1475.39 (141.86)	903.91 (86.91)	841.97 (80.96)	1449.05 (139.33)
14	R-49 Gadiar	1200-1450	31.20	5035.44 (161.39)	2065.18 (66.19)	2256.22 (72.31)	2830.06 (90.71)
15	D-117 Chabil Ki Dhar IV	1250-1338	2.40	1009.17 (420.49)	246.81 (102.84)	935.75 (389.89)	917.94 (382.48)
16	D-118 Chabil Ki Dhar III	1270-1530	10.40	1450.33 (139.45)	1902.99 (182.98)	4315.01 (414.90)	4769.41 (458.60)
17	D-164 Maltu III	1280-1460	15.60	1453.04 (93.14)	703.20 (45.08)	1629.85 (104.48)	1802.91 (115.57)
18	D-181 Sirguli Ka Tiba III	1170-1290	25.20	3377.83 (134.04)	2040.25 (80.96)	2280.54 (90.50)	2657.69 (105.46)
19	D-182 Kalath III	1225-1450	25.60	3023.49 (118.11)	1165.84 (45.54)	4149.42 (162.09)	4408.62 (172.21)
20	D-172 Bhog Seri III	1180-1300	4.40	722.78 (164.27)	159.02 (36.14)	394.23 (89.60)	712.14 (161.85)
21	D-159 Anji III	1440-1520	3.60	945.89 (262.75)	379.65 (105.46)	305.41 (84.83)	294.26 (81.74)
22	D-160 Anji I	1280-1420	10.40	1680.62 (161.60)	1125.02 (108.18)	766.81 (73.73)	772.94 (74.32)
23	D-120 Chabil Ki Dhar I	1300-1420	3.60	486.43 (135.12)	940.51 (261.25)	1381.61 (383.78)	1152.35 (320.10)
24	D-150 Gulhari IV	1575-1650	4.40	522.75 (118.81)	186.71 (42.43)	328.01 (74.55)	352.60 (80.14)
25	D-152 Gulhari II	1500-1600	8.80	1603.15 (182.18)	305.65 (34.73)	627.92 (71.35)	627.71 (71.33)
26	D-153 Gulhari I	1450-1600	5.20	390.47 (75.09)	281.84 (54.20)	130.65 (25.12)	250.90 (48.25)
27	D-154 Dawala	1350-1500	12.80	2414.01 (188.59)	623.31 (48.70)	1474.78 (115.22)	2031.50 (158.71)

28	D-155 Bhallon	1360-1400	3.20	620.64 (193.95)	330.22 (103.19)	370.04 (115.64)	471.98 (147.50)
29	D-162 Maltu II	1300-1600	28.40	2478.81 (87.28)	732.89 (25.81)	2349.13 (82.72)	2449.04 (86.23)
30	D-163 Maltu I	1420-1480	11.20	999.42 (89.23)	717.67 (64.08)	1418.42 (126.64	1518.56 (135.59)
31	D-173 Bohali Ki Cheol	1350-1480	10.40	1197.23 (115.12)	578.44 (55.62)	783.81 (75.37)	847.44 (81.48)
32	D-176 Charoti Ki Dhar I	1250-1450	38.00	3936.62 (103.60)	3375.01 (88.82)	3841.03 (101.08)	3580.83 (94.23)
33	D-119 Chabil Ki Dhar II	1220-1350	26.40	3296.55 (124.87)	1377.62 (52.18)	5230.72 (198.13)	5445.37 (206.26)
Total Volume				**55595.08 (5564.27)**	**31135.52 (3063.96)**	**47104.45 (3921.62)**	**53181.85 (4329.69)**

* Figures in parenthesis denote volume in m^3 ha^{-1}

APPENDIX V

Temporal distribution of biomass in selected compartments of Solan and Dharampur Forest Ranges of Solan Forest Division

S.No	Name of the Forest	Biomass (t)															
		1956				1984				2002				2011			
		Stem	Branch	Leaf	Root	Stem	Branch	Leaf	Root	Stem	Branch	Leaf	Root	Stem	Branch	Leaf	Root
Solan Forest Range																	
1	**D-93 Nandal Nagali**	646.57 (52.14)	155.18 (12.51)	32.33 (2.61)	187.51 (15.12)	440.31 (35.51)	105.67 (8.52)	22.02 (1.78)	127.69 (10.30)	386.60 (31.18)	92.78 (7.48)	19.33 (1.56)	112.11 (9.04)	404.29 (32.60)	97.03 (7.82)	20.21 (1.63)	117.24 (9.46)
2	**D-95 Nagali I**	406.82 (113.01)	97.64 (27.12)	20.34 (5.65)	117.98 (32.77)	266.19 (73.94)	63.89 (17.75)	13.31 (3.70)	77.19 (21.44)	205.57 (57.10)	49.34 (13.70)	10.28 (2.86)	59.61 (16.56)	212.46 (59.02)	50.99 (14.16)	10.62 (2.95)	61.61 (17.11)
3	**D-96 Nagali II**	386.63 (96.66)	92.79 (23.20)	19.33 (4.83)	112.12 (28.03)	642.70 (160.68)	154.25 (38.56)	32.14 (8.03)	186.38 (46.60)	108.41 (27.10)	26.02 (6.50)	5.42 (1.36)	31.44 (7.86)	119.34 (29.83)	28.64 (7.16)	5.97 (1.49)	34.61 (8.65)
4	**D-97 Kiar Tatul**	489.36 (111.22)	117.45 (26.69)	24.47 (5.56)	141.91 (32.25)	387.59 (88.09)	93.02 (21.14)	19.38 (4.40)	112.40 (25.55)	101.33 (23.03)	24.32 (5.53)	5.07 (1.15)	29.39 (6.68)	100.53 (22.85)	24.13 (5.48)	5.03 (1.14)	29.15 (6.63)
5	**D-123 Beola**	338.78 (77.00)	81.31 (18.48)	16.94 (3.85)	98.25 (22.33)	309.47 (70.33)	74.27 (16.88)	15.47 (3.52)	89.75 (20.40)	397.19 (90.27)	95.33 (21.67)	19.86 (4.51)	115.19 (26.18)	298.37 (67.81)	71.61 (16.27)	14.92 (3.39)	86.53 (19.67)
6	**D-135 Kaldhar I**	474.64 (84.76)	113.91 (20.34)	23.73 (4.24)	137.65 (24.58)	185.89 (33.19)	44.61 (7.97)	9.29 (1.66)	53.91 (9.63)	140.92 (25.16)	33.82 (6.04)	7.05 (1.26)	40.87 (7.30)	152.36 (27.21)	36.57 (6.53)	7.62 (1.36)	44.19 (7.89)
7	**R-26 Nagali**	1839.81 (54.76)	441.55 (13.14)	91.99 (2.74)	533.54 (15.88)	677.46 (20.16)	162.59 (4.84)	33.87 (1.01)	196.46 (5.85)	1303.98 (38.81)	312.96 (9.31)	65.20 (1.94)	378.15 (11.25)	1592.52 (47.40)	382.20 (11.38)	79.63 (2.37)	461.83 (13.74)
8	**D-92 Deora**	567.74 (22.18)	136.26 (5.32)	28.39 (1.11)	164.64 (6.43)	680.49 (26.58)	163.32 (6.38)	34.02 (1.33)	197.34 (7.71)	710.33 (27.75)	170.48 (6.66)	35.52 (1.39)	205.99 (8.05)	865.93 (33.83)	207.82 (8.12)	43.30 (1.69)	251.12 (9.81)
9	**D-94 Nandal**	823.85 (98.08)	197.72 (23.54)	41.19 (4.90)	238.92 (28.44)	658.36 (78.38)	158.01 (18.81)	32.92 (3.92)	190.93 (22.73)	356.85 (42.48)	85.64 (10.20)	17.84 (2.12)	103.49 (12.32)	370.32 (44.09)	88.88 (10.58)	18.52 (2.20)	107.39 (12.78)
10	**D-89 Gadhog I**	235.80 (25.63)	56.59 (6.15)	11.79 (1.28)	68.38 (7.43)	158.60 (17.24)	38.06 (4.14)	7.93 (0.86)	45.99 (5.00)	287.82 (31.28)	69.08 (7.51)	14.39 (1.56)	83.47 (9.07)	588.24 (63.94)	141.18 (15.35)	29.41 (3.20)	170.59 (18.54)
11	**D-90 Gadhog II**	534.12 (40.46)	128.19 (9.71)	26.71 (2.02)	154.89 (11.73)	595.87 (45.14)	143.01 (10.83)	29.79 (2.26)	172.80 (13.09)	438.23 (33.20)	105.18 (7.97)	21.91 (1.66)	127.09 (9.63)	460.57 (34.89)	110.54 (8.37)	23.03 (1.74)	133.57 (10.12)
12	**D-98 Bhawan Ki Dhar**	1043.72 (54.36)	250.49 (13.05)	52.19 (2.72)	302.68 (15.76)	358.99 (18.70)	86.16 (4.49)	17.95 (0.93)	104.11 (5.42)	1096.41 (57.10)	263.14 (13.71)	54.82 (2.86)	317.96 (16.56)	1615.96 (84.16)	387.83 (20.20)	80.80 (4.21)	468.63 (24.41)

Dharampur Forest Range																	
13	**R-36 Anji**	722.94 (69.51)	173.51 (16.68)	36.15 (3.48)	209.65 (20.16)	442.91 (42.59)	106.30 (10.22)	22.15 (2.13)	128.45 (12.35)	412.56 (39.67)	99.02 (9.52)	20.63 (1.98)	119.64 (11.50)	710.03 (68.27)	170.41 (16.39)	35.50 (3.41)	205.91 (19.80)
14	**R-49 Gadiar**	2467.37 (79.08)	592.17 (18.98)	123.37 (3.95)	715.54 (22.93)	1011.94 (32.43)	242.86 (7.78)	50.60 (1.62)	293.46 (9.41)	1105.55 (35.43)	265.33 (8.50)	55.28 (1.77)	320.61 (10.28)	1386.73 (44.45)	332.81 (10.67)	69.34 (2.22)	402.15 (12.89)
15	**D-117 Chabil Ki Dhar IV**	494.49 (206.04)	118.68 (49.45)	24.72 (10.30)	143.40 (59.75)	120.94 (50.39)	29.03 (12.09)	6.05 (2.52)	35.07 (14.61)	458.52 (191.05)	110.04 (45.85)	22.93 (9.55)	132.97 (55.40)	449.79 (187.41)	107.95 (44.98)	22.49 (9.37)	130.44 (54.35)
16	**D-118 Chabil Ki Dhar III**	710.66 (68.33)	170.56 (16.40)	35.53 (3.42)	206.09 (19.82)	932.47 (89.66)	223.79 (21.52)	46.62 (4.48)	270.42 (26.00)	2114.35 (203.30)	507.44 (48.79)	105.72 (10.17)	613.16 (58.96)	2337.01 (224.71)	560.88 (53.93)	116.85 (11.24)	677.73 (65.17)
17	**D-164 Maltu III**	711.99 (45.64)	170.88 (10.95)	35.60 (2.28)	206.48 (13.24)	344.57 (22.09)	82.70 (5.30)	17.23 (1.10)	99.92 (6.41)	798.62 (51.19)	191.67 (12.29)	39.93 (2.56)	231.60 (14.85)	883.43 (56.63)	212.02 (13.59)	44.17 (2.83)	256.19 (16.42)
18	**D-181 Sirguli Ka Tiba III**	1655.14 (65.68)	397.23 (15.76)	82.76 (3.28)	479.99 (19.05)	999.72 (39.67)	239.93 (9.52)	49.99 (1.98)	289.92 (11.50)	1117.47 (44.34)	268.19 (10.64)	55.87 (2.22)	324.07 (12.86)	1302.27 (51.68)	312.54 (12.40)	65.11 (2.58)	377.66 (14.99)
19	**D-182 Kalath III**	1481.51 (57.87)	355.56 (13.89)	74.08 (2.89)	429.64 (16.78)	571.26 (22.31)	137.10 (5.36)	28.56 (1.12)	165.67 (6.47)	2033.22 (79.42)	487.97 (19.06)	101.66 (3.97)	589.63 (23.03)	2160.22 (84.38)	518.45 (20.25)	108.01 (4.22)	626.47 (24.47)
20	**D-172 Bhog Seri III**	354.16 (80.49)	85.00 (19.32)	17.71 (4.02)	102.71 (23.34)	77.92 (17.71)	18.70 (4.25)	3.90 (0.89)	22.60 (5.14)	193.17 (43.90)	46.36 (10.54)	9.66 (2.20)	56.02 (12.73)	348.95 (79.31)	83.75 (19.03)	17.45 (3.97)	101.20 (23.00)
21	**D-159 Anji III**	463.48 (128.75)	111.24 (30.90)	23.17 (6.44)	134.41 (37.34)	186.03 (51.67)	44.65 (12.40)	9.30 (2.58)	53.95 (14.99)	149.65 (41.57)	35.92 (9.98)	7.48 (2.08)	43.40 (12.06)	144.19 (40.05)	34.60 (9.61)	7.21 (2.00)	41.81 (11.62)
22	**D-160 Anji I**	823.51 (79.18)	197.64 (19.00)	41.18 (3.96)	238.82 (22.96)	551.26 (53.01)	132.30 (12.72)	27.56 (2.65)	159.87 (15.37)	375.74 (36.13)	90.18 (8.67)	18.79 (1.81)	108.96 (10.48)	378.74 (36.42)	90.90 (8.74)	18.94 (1.82)	109.84 (10.56)
23	**D-120 Chabil Ki Dhar I**	238.35 (66.21)	57.20 (15.89)	11.92 (3.31)	69.12 (19.20)	460.85 (128.01	110.60 (30.72)	23.04 (6.40)	133.65 (37.12)	676.99 (188.05)	162.48 (45.13)	33.85 (9.40)	196.33 (54.54)	564.65 (156.85)	135.52 (37.64)	28.23 (7.84)	163.75 (45.49)
24	**D-150 Gulhari IV**	256.15 (58.22)	61.48 (13.97)	12.81 (2.91)	74.28 (16.88)	91.49 (20.79)	21.96 (4.99)	4.57 (1.04)	26.53 (6.03)	160.72 (36.53)	38.57 (8.77)	8.04 (1.83)	46.61 (10.59)	172.77 (39.27)	41.47 (9.42)	8.64 (1.96)	50.10 (11.39)
25	**D-152 Gulhari II**	785.54 (89.27)	188.53 (21.42)	39.28 (4.46)	227.81 (25.89)	149.77 (17.02)	35.94 (4.08)	7.49 (0.85)	43.43 (4.94)	307.68 (34.96)	73.84 (8.39)	15.38 (1.75)	89.23 (10.14)	307.58 (34.95)	73.82 (8.39)	15.38 (1.75)	89.20 (10.14)
26	**D-153 Gulhari I**	191.33 (36.79)	45.92 (8.83)	9.57 (1.84)	55.49 (10.67)	138.10 (26.56)	33.14 (6.37)	6.91 (1.33)	40.05 (7.70)	64.02 (12.31)	15.36 (2.95)	3.20 (0.62)	18.57 (3.57)	122.94 (23.64)	29.51 (5.67)	6.15 (1.18)	35.65 (6.86)
27	**D-154 Dawala**	1182.86 (92.41)	283.89 (22.18)	59.14 (4.62)	343.03 (26.80)	305.42 (23.86)	73.30 (5.73)	15.27 (1.19)	88.57 (6.92)	722.64 (56.46)	173.43 (13.55)	36.13 (2.82)	209.57 (16.37)	995.44 (77.77)	238.90 (18.66)	49.77 (3.89)	288.68 (22.55)

28	**D-155 Bhallon**	304.11 (95.04)	72.99 (22.81)	15.21 (4.75)	88.19 (27.56)	161.81 (50.56)	38.83 (12.14)	8.09 (2.53)	46.92 (14.66)	181.32 (56.66)	43.52 (13.60)	9.07 (2.83)	52.58 (16.43)	231.27 (72.27)	55.51 (17.35)	11.56 (3.61)	67.07 (20.96)
29	**D-162 Maltu II**	1214.62 (42.77)	291.51 (10.26)	60.73 (2.14)	352.24 (12.40)	359.11 (12.64)	86.19 (3.03)	17.96 (0.63)	104.14 (3.67)	1151.07 (40.53)	276.26 (9.73)	57.55 (2.03)	333.81 (11.75)	1200.03 (42.25)	288.01 (10.14)	60.00 (2.11)	348.01 (12.25)
30	**D-163 Maltu I**	489.72 (43.72)	117.53 (10.49)	24.49 (2.19)	142.02 (12.68)	351.66 (31.40)	84.40 (7.54)	17.58 (1.57)	101.98 (9.11)	695.03 (62.06)	166.81 (14.89)	34.75 (3.10)	201.56 (18.00)	744.10 (66.44)	178.58 (15.94)	37.20 (3.32)	215.79 (19.27)
31	**D-173 Bohali Ki Cheol**	586.64 (56.41)	140.79 (13.54)	29.33 (2.82)	170.13 (16.36)	283.44 (27.25)	68.03 (6.54)	14.17 (1.36)	82.20 (7.90)	384.07 (36.93)	92.18 (8.86)	19.20 (1.85)	111.38 (10.71)	415.24 (39.93)	99.66 (9.58)	20.76 (2.00)	120.42 (11.58)
32	**D-176 Charoti Ki Dhar I**	1928.94 (50.76)	462.95 (12.18)	96.45 (2.54)	559.39 (14.72)	1653.75 (43.52)	396.90 (10.44)	82.69 (2.18)	479.59 (12.62)	1882.10 (49.53)	451.70 (11.89)	94.11 (2.48)	545.81 (14.36)	1754.61 (46.17)	421.11 (11.08)	87.73 (2.31)	508.84 (13.39)
33	**D-119 Chabil Ki Dhar II**	1615.31 (61.19)	387.67 (14.68)	80.77 (3.06)	468.44 (17.74)	675.04 (25.57)	162.01 (6.14)	33.75 (1.28)	195.76 (7.42)	2563.05 (97.09)	615.13 (23.30)	128.15 (4.85)	743.29 (28.15)	2668.23 (101.07)	640.38 (24.26)	133.41 (5.05)	773.79 (29.31)
Total		**27241.59 (60.81)**	**6352.00 (14.60)**	**1323.33 (3.04)**	**7675.33 (17.64)**	**15231.37 (35.00)**	**3655.53 (8.40)**	**761.57 (1.75)**	**4417.10 (10.15)**	**23081.18 (53.04)**	**5539.48 (12.73)**	**1154.06 (2.65)**	**6693.54 (15.38)**	**26059.11 (59.88)**	**6254.19 (14.37)**	**1302.96 (2.99)**	**7557.14 (17.36)**

* Figures in parenthesis denote biomass density in t ha^{-1}

Appendix VI

Temporal distribution of Carbon Stock in various compartments of Solan Forest Division

S No.	Name of the Forest	Area	Carbon Stock (t)		Per cent Change
			1998	2010	
1	R 57 Banasar	113.20	2937.64 (25.95)	3167.35 (27.98)	7.82
2	D 192 Nabon Partha	149.60	3572.44 (23.88)	3844.50 (25.70)	7.61
3	R 58 Jagatgarh	6.00	159.21 (26.53)	170.96 (28.49)	7.38
4	D 178 Charoti ki Dhar	71.40	2054.12 (28.77)	2192.93 (30.71)	6.75
5	D 176 Charoti ki Dhar	38.00	1120.58 (29.49)	1200.97 (31.60)	7.17
6	D 175 Bohali	33.20	831.31 (25.04)	899.23 (27.08)	8.17
7	R 45 Khader ki Dhar	110.40	3436.95 (31.13)	3679.53 (33.33)	7.06
8	D 189 Jagatgarh	29.60	763.36 (25.79)	827.98 (27.97)	8.46
9	D 200 Danota Chakali	255.20	9116.25 (35.72)	9708.31 (38.04)	6.49
10	D 191 Shogi Nabon	64.40	1935.36 (30.05)	2061.51 (32.01)	6.52
11	D 222 Banasar Top	72.40	924.90 (12.77)	998.56 (13.79)	7.96
12	R 41 Gulzar	129.20	1856.66 (14.37)	2034.73 (15.75)	9.60
13	D 179 Sirguli ka Tiba C1	13.60	401.89 (29.55)	431.98 (31.76)	7.48
14	D 180 Sirguli ka Tiba	47.20	976.22 (20.68)	1054.08 (22.33)	7.97
15	D 214 Tiba Guljar	141.60	4970.59 (35.10)	5338.86 (37.70)	7.41
16	D 215 Kaba	43.20	1399.69 (32.40)	1497.99 (34.67)	7.02
17	R 40 Bohali	115.60	3339.87 (28.89)	3618.11 (31.30)	8.33
18	R 39 Charoti ki Dhar	44.40	1135.39 (25.57)	1218.23 (27.44)	7.29
19	D 179 Sirguli ka Tiba C2	16.00	1025.64 (64.10)	1088.16 (68.01)	6.09
20	D 177 Charoti ki Dhar	21.20	629.83 (29.70)	677.25 (31.95)	7.53
21	D 184 Rathal	122.40	4077.15 (33.31)	4357.19 (35.60)	6.87
22	D 169 Kiard II	39.60	1225.58 (30.95)	1308.10 (33.03)	6.73
23	D 142 Jhaja Bahali	13.20	317.80 (24.07)	340.38 (25.79)	7.10
24	R 38 Kiard	37.20	368.80 (9.91)	394.02 (10.59)	6.84
25	D 236 Kurar	81.20	2233.50 (27.51)	2413.22 (29.72)	8.05
26	D 233 Datiyar	417.60	13476.68 (32.27)	14508.32 (34.74)	7.65
27	D 202 Kalath II	28.40	955.60 (33.65)	1023.00 (36.02)	7.05
28	D 186 Kalath V	20.40	785.96 (38.53)	845.09 (41.43)	7.52
29	D 232 Bamola Totela	6.80	241.94 (35.58)	263.32 (38.72)	8.84

30	D 231 Shlu Jangeshu	51.20	932.75 (18.22)	999.44 (19.52)	7.15
31	D 190 Jabrog	87.60	2141.55 (24.45)	2323.48 (26.52)	8.49
32	R 55 Mashobra C1	5.4	249.31 (46.17)	266.55 (49.36)	6.91
33	D 241 Shewla	22.40	602.46 (26.89)	647.87 (28.92)	7.54
34	D 120 Chabil ki Dhar	3.60	308.74 (85.76)	332.09 (92.25)	7.56
35	R 55 Mashobra C2	5.80	256.23 (44.18)	273.43 (47.14)	6.71
36	D 234 Ranigaon	72.00	1866.01 (25.92)	2039.74 (28.33)	9.31
37	D 221 Kiarwa	8.40	570.21 (67.88)	611.25 (72.77)	7.20
38	R 61 Naraini	484.40	11941.30 (24.65)	12852.31 (26.53)	7.63
39	R 59 Jandhouri	14.40	404.48 (28.09)	437.74 (30.40)	8.22
40	D 195 Pratha	11.20	79.04 (7.06)	84.92 (7.58)	7.44
41	R 60 Jandhouri	6.80	146.58 (21.56)	158.71 (23.34)	8.28
42	D 160 Anji I	10.40	675.32 (64.93)	722.65 (69.48)	7.00
43	D 171 Bhog Seri	5.60	138.81 (24.79)	154.44 (27.58)	11.26
44	D 172 Bhog Seri III	4.40	269.48 (61.25)	285.16 (64.81)	5.82
45	D 170 Bhog Seri	12.40	270.63 (21.82)	291.81 (23.53)	7.82
46	D 173 Bohali ki Cheol	10.40	283.17 (27.23)	300.84 (28.93)	6.24
47	D 87 Diarag Daun	5.20	149.21 (28.69)	163.06 (31.36)	9.28
48	D 238 Dhamiana	16.40	300.51 (18.32)	323.26 (19.71)	7.57
49	D 158 Anji I	11.20	277.25 (24.75)	299.57 (26.75)	8.05
50	D 174 Bigaur	4.00	130.74 (32.68)	145.76 (36.44)	11.49
51	D 159 Anji III	3.60	119.21 (33.11)	127.18 (35.33)	6.68
52	D 243 Suji	8.80	77.58 (8.82)	83.17 (9.45)	7.21
53	R 36 Anji	10.40	546.32 (52.53)	584.73 (56.22)	7.03
54	R 54 Mansa Devi	3.20	42.60 (13.31)	45.98 (14.37)	7.94
55	R 38 Kiard	37.20	226.51 (6.09)	243.14 (6.54)	7.34
56	D 145 Chewa Khil Chunjari	12.40	450.47 (36.33)	488.27 (39.38)	8.39
57	R 34 Mansa Devi	3.20	29.33 (9.16)	31.99 (9.99)	9.10
58	D 198 Bhaour Lugon	30.80	993.35 (32.25)	1054.10 (34.22)	6.11
59	D 199 Chawal Ashnalla	66.40	3546.75 (53.41)	3776.55 (56.87)	6.48
60	D 209 Bhagour	15.60	198.76 (12.74)	211.74 (13.57)	6.53
61	R 43 Halda Kaba	180.00	4873.36 (27.07)	5235.65 (29.09)	7.43

62	D 194 Pratha III	49.20	1769.58 (35.97)	1901.81 (38.65)	7.47
63	D 193 Pratha Umera	17.20	365.14 (21.23)	392.56 (22.82)	7.51
64	D 207 Sath Dadhog	30.40	699.85 (23.02)	748.70 (24.63)	6.98
65	R 42 Ajmergarh	82.80	2807.56 (33.91)	3022.65 (36.50)	7.66
66	D 202 Qila Ajmergarh	83.60	2722.98 (32.57)	2941.35 (35.18)	8.02
67	D 205 Neri I	52.00	1263.20 (24.29)	1357.54 (26.11)	7.47
68	D 213 Kaba Bahaur	107.60	2886.65 (26.83)	3079.88 (28.62)	6.69
69	R 44 Jhanai	139.60	4112.94 (29.46)	4445.14 (31.84)	8.08
70	D 220 Barog C2	2.90	390.58 (134.68)	421.86 (145.46)	8.01
71	D 218 Kamlog	7.20	71.50 (9.93)	75.32 (10.46)	5.34
72	D 220 Barog C1	28.70	627.09 (21.85)	667.73 (23.26)	6.48
73	D 247 Satrol	7.20	292.53 (40.63)	313.02 (43.47)	7.00
74	D 219 Satrol II	1.20	201.63 (168.02)	217.48 (181.23)	7.86
75	D 196 Mauri	6.00	627.60 (104.60)	672.02 (112.00)	7.08
76	D 217 Niun Shanog	43.20	1304.65 (30.20)	1404.66 (32.51)	7.66
77	D 216 Bhanog Bhallon	90.00	2214.34 (24.60)	2361.81 (26.24)	6.66
78	D 211 Halda I	10.00	485.27 (48.53)	520.07 (52.00)	7.17
79	D 197 Pratha I	4.80	309.86 (64.55)	333.36 (69.45)	7.58
80	D 206 Neri II	24.40	285.62 (11.70)	309.87 (12.70)	8.50
81	D 157 Kadon I	13.60	159.20 (11.71)	172.58 (12.69)	8.40
82	R 35 Kadon	40.10	1637.54 (40.84)	1772.87 (44.21)	8.26
83	D 155 Bhallon	3.20	121.79 (38.06)	130.75 (40.86)	7.35
84	D 156 Kadon II	2.30	77.42 (33.66)	83.97 (36.50)	8.47
85	D 161 Sehardi	42.00	827.76 (19.71)	894.84 (21.30)	8.10
86	D 143 Chewa Khil Chunjari	2.40	52.62 (21.92)	56.32 (23.46)	7.03
87	R 27 Nauni	80.00	1869.68 (23.37)	1998.29 (24.98)	6.88
88	R 28 Khaldhar	122.00	2980.77 (24.43)	3216.37 (26.36)	7.90
89	D 137 Nauni	11.20	348.10 (31.16)	373.13 (33.31)	6.91
90	D 146 Chewa Khil Chunjari IV	47.20	1437.97 (30.46)	1550.24 (32.84)	7.81
91	D 140 Kainthari	6.00	265.83 (44.30)	280.86 (46.81)	5.65
92	D 154 Dawala	12.80	601.77 (47.01)	649.11 (50.71)	7.87
93	D 98 Bhawan ki Dhar	19.20	807.60 (42.06)	864.00 (45.00)	6.98

94	D 90 Gadhog II	13.20	465.67 (35.28)	498.99 (37.80)	7.15
95	D 86 Diarag Niun	33.60	1111.96 (33.09)	1192.13 (35.48)	7.21
96	D 97 Kiar Tatul	4.40	295.06 (67.06)	317.89 (72.25)	7.74
97	R 26 Nagali	33.60	541.94 (16.13)	588.01 (17.50)	8.50
98	D 95 Nagali I	3.60	147.82 (41.06)	154.87 (43.02)	4.77
99	D 96 Nagali II	4.00	64.52 (16.13)	69.74 (17.43)	8.08
100	D 88 Shawag Badrog	13.20	399.90 (30.29)	436.78 (33.09)	9.22
101	D 84 Damkari	39.20	1090.25 (27.81)	1175.00 (29.97)	7.77
102	D 123 Beola	4.40	146.16 (33.22)	155.35 (35.31)	6.29
103	D 125 Sheel ka Dhala	21.20	442.34 (20.86)	479.68 (22.63)	8.44
104	D 85 Niun	10.40	354.62 (34.09)	379.50 (36.49)	7.02
105	D 89 Gadhog I	9.20	293.13 (31.86)	309.37 (33.63)	5.54
106	R 25 Shawag Badrog	102.40	2529.22 (24.70)	2714.72 (26.51)	7.33
107	R 33 Gulhari	119.60	576.55 (4.82)	620.78 (5.19)	7.67
108	D 246 Kasauli C1	9.60	81.32 (8.47)	87.80 (9.15)	7.97
109	D 246 Kasauli C2	3.60	108.96 (30.27)	119.32 (33.14)	9.51
110	D 151 Gulhari I	42.80	511.85 (11.96)	546.76 (12.77)	6.82
111	D 152 Gulhari II	8.80	147.02 (16.71)	158.09 (17.96)	7.53
112	D 245 Sanawar	60.40	2727.31 (45.15)	2910.91 (48.19)	6.73
113	D 153 Gulhari I	5.20	638.15 (122.72)	681.77 (131.11)	6.83
114	D 148 Samol	4.00	167.89 (41.97)	182.04 (45.51)	8.43
115	D 118 Chabil ki Dhar	10.40	629.75 (60.55)	670.80 (64.50)	6.52
116	D 150 Gulhari IV	4.40	274.64 (62.42)	294.49 (66.93)	7.23
117	D 149 Sanhol	8.40	201.69 (24.01)	221.33 (26.35)	9.74
118	D 204 Tikkari	22.40	788.72 (35.21)	850.88 (37.98)	7.88
119	R 50 Kalath	5.20	161.88 (31.13)	174.47 (33.55)	7.77
120	D 195 Pratha	11.20	281.44 (25.13)	307.29 (27.44)	9.18
121	D 208 Sari	2.40	72.42 (30.17)	77.57 (32.32)	7.11
122	D 210 Oder Janghiria	97.70	4555.94 (46.63)	4910.96 (50.26)	7.79
123	D 141 Barog	2.00	266.57 (133.28)	288.37 (144.18)	8.18
124	R 33 Gulhari	119.60	439.83 (3.68)	476.65 (3.98)	8.37
125	D 131 Mathan	38.40	1732.96 (45.13)	1865.46 (48.58)	7.64

126	D 135 Khaldhar	5.60	389.30 (69.52)	417.77 (74.60)	7.31
127	D 138 Khaldhar III	11.20	307.97 (27.50)	329.19 (29.39)	6.89
128	D 136 Khaldhar	16.00	622.23 (38.89)	672.96 (42.06)	8.15
129	D 147 Kainthri	19.80	739.92 (37.37)	803.57 (40.58)	8.60
130	D 242 Gahidhar	89.40	2222.23 (24.86)	2389.63 (26.73)	7.53
131	D 224 Sandhog	90.00	3073.37 (34.15)	3345.20 (37.17)	8.84
132	D 244 Cheola	136.80	2834.77 (20.72)	3043.87 (22.25)	7.38
133	D 223 Khadeen	76.00	2310.76 (30.40)	2490.10 (32.78)	7.80
134	D 228 Ambota	86.40	2962.77 (34.29)	3205.52 (37.10)	8.19
135	D 239 Sari Dhar	48.00	4665.79 (97.20)	5039.98 (104.99)	8.02
136	R 56 Parwanoo	124.00	2411.28 (19.44)	2643.23 (21.32)	9.62
137	D 225 Gumma	84.00	1685.37 (20.06)	1840.74 (21.91)	9.22
138	D 227 Annu I	8.00	205.51 (25.69)	225.29 (28.16)	9.63
139	D 165 Maltu IV	41.20	1378.89 (33.47)	1479.77 (35.92)	7.32
140	D 185 Kurla and Johari	94.70	1885.82 (19.91)	2049.78 (21.64)	8.69
141	D 235 Chamgah	52.80	1418.89 (26.87)	1538.04 (29.13)	8.40
142	R 37 Maltu	49.60	1027.15 (20.71)	1095.85 (22.09)	6.69
143	D 162 Maltu I	28.40	795.12 (27.99)	859.27 (30.26)	8.07
144	D 163 Maltu I	11.20	184.96 (16.51)	195.71 (17.47)	5.81
145	D 164 Maltu III	15.60	784.22 (50.27)	846.25 (54.25)	7.90
146	D 166 Dhar	69.60	1667.99 (23.96)	1819.04 (26.13)	9.05
147	D 237 Sherla	16.80	394.14 (23.46)	426.52 (25.39)	8.21
148	D 94 Nandal	8.40	368.39 (43.86)	396.54 (47.21)	7.64
149	D 82 Jawa Rajgarh	43.60	883.84 (20.27)	933.19 (21.40)	5.58
150	D 83 Rajgarh	133.20	3321.10 (24.93)	3624.14 (27.21)	9.12
151	D 230 Jangeshu Kandi	157.20	4684.00 (29.80)	5065.73 (32.22)	8.15
152	D 240 Dochi	104.80	2733.81 (26.08)	2956.05 (28.21)	8.13
153	R 24 Rajgarh	68.80	1520.64 (22.10)	1637.35 (23.80)	7.67
154	D 92 Deora	25.60	532.13 (20.79)	578.04 (22.58)	8.63
155	D 91 Bhawan ki Dhar	11.60	168.05 (14.49)	180.57 (15.57)	7.45
156	D 93 Nandal Nagali	12.40	357.85 (28.40)	384.97 (30.55)	7.58
157	D 80 Seri	20.80	480.15 (23.08)	521.28 (25.06)	8.57

158	D 182 Kalath III	25.60	970.07 (37.89)	1030.33 (40.25)	6.21
159	D 81 Charech	72.40	1571.72 (21.71)	1715.94 (23.70)	9.17
160	D 229 Tiron	32.80	1082.47 (33.00)	1168.82 (35.63)	7.98
161	R 52 Gumma	179.60	3053.55 (17.00)	3283.95 (18.28)	7.54
162	R 49 Gadiar	31.20	799.48 (25.62)	862.49 (27.64)	7.88
163	D 185 Johari	24.30	1300.17 (53.50)	1392.99 (57.32)	7.14
164	D 226 Annu II	30.80	727.04 (23.60)	784.12 (25.46)	7.85
165	D 201 Kalath I	55.60	1484.16 (26.69)	1585.31 (28.51)	6.81
166	R 31 Barog	500.80	11260.12 (22.48)	12138.26 (24.24)	7.80
167	R 30 Chabil ki Dhar	265.20	6909.85 (26.05)	7387.70 (27.86)	6.91
168	D 132 Charar	181.60	4557.99 (25.10)	4930.93 (27.15)	8.18
169	D 130 Chawal	4.00	184.93 (46.23)	198.95 (49.74)	7.58
170	D 129 Rano	18.80	427.97 (22.76)	461.36 (24.54)	7.80
171	D 127 Shashal	82.40	2190.31 (26.58)	2354.34 (28.57)	7.49
172	D 103 Dharot ka Cheon	5.60	112.47 (20.08)	122.19 (21.82)	8.64
173	D 117 Chabil ki Dhar IV	2.40	69.71 (29.04)	76.62 (31.93)	9.92
174	R 29 Kathani	16.00	137.97 (8.62)	146.08 (9.13)	5.87
175	D 69 Palech I	22.40	376.31 (16.80)	404.90 (18.08)	7.60
176	D 68 Hathon	6.00	278.26 (46.38)	303.44 (50.57)	9.05
177	D 133 Koon	10.40	417.38 (40.13)	450.27 (43.29)	7.88
178	D 128 Kali Kufer	91.60	2738.80 (29.90)	2927.42 (31.96)	6.89
179	D 70 Palech II	3.20	180.86 (56.52)	195.32 (61.04)	8.00
180	D 99 Salumna	23.20	585.74 (25.25)	640.28 (27.60)	9.31
181	D 102 Baran ki Cheon	18.80	563.58 (29.98)	608.84 (32.38)	8.03
812	D 78 Karol VIII	4.80	161.82 (33.71)	174.80 (36.41)	8.02
183	D 76 Karol VI	0.80	106.07 (132.59)	114.94 (143.67)	8.36
184	D 75 Karol V	19.20	488.10 (25.42)	527.51 (27.47)	8.07
185	R 23 Karol III	8.00	764.73 (95.59)	827.84 (103.48)	8.25
186	R 22 Karol	12.40	153.16 (12.35)	167.49 (13.51)	9.36
187	D 79 Daid	14.40	422.87 (29.37)	460.46 (31.98)	8.89
188	D 72 Karol II	16.40	796.94 (48.59)	857.72 (52.30)	7.63
189	D 71 Karol I	5.20	501.09 (96.36)	546.86 (105.16)	9.13

190	D 101 Kuroli	19.60	528.08 (26.94)	573.36 (29.25)	8.57
191	D 100 Dharot	34.40	1133.64 (32.95)	1218.73 (35.43)	7.51
192	D 73 Karol III	10.40	317.25 (30.50)	340.95 (32.78)	7.47
193	D 74 Karol IV	5.60	269.16 (48.06)	294.93 (52.67)	9.58
194	D 58 Basha	11.20	234.71 (20.96)	257.81 (23.02)	9.84
195	D 55 Surron I	2.00	87.99 (43.99)	94.48 (47.24)	7.38
196	D 54 Shadial	8.40	165.83 (19.74)	177.98 (21.19)	7.33
197	D 59 Bagetu	2.40	92.13 (38.39)	101.88 (42.45)	10.58
198	D 57 Kamhal	4.80	114.99 (23.96)	121.20 (25.25)	5.40
199	D 56 Surron II	2.80	118.19 (42.21)	126.89 (45.32)	7.36
200	D 110 Raikot	34.80	553.14 (15.89)	598.41 (17.19)	8.18
201	D 113 Sarighat	17.60	408.93 (23.23)	437.12 (24.84)	6.89
202	D 109 Panewa	38.40	848.93 (22.11)	920.44 (23.97)	8.42
203	D 53 Sungal	11.20	301.44 (26.91)	330.24 (29.49)	9.56
204	D 112 Alobra	54.40	1416.63 (26.04)	1547.32 (28.44)	9.22
205	D 111 Thothal	5.20	156.46 (30.09)	168.52 (32.41)	7.71
206	D 62 Bisha	80.00	1456.40 (18.20)	1584.13 (19.80)	8.77
207	D 134 Kothi	87.60	2395.80 (27.35)	2586.35 (29.52)	7.95
208	D 67 Sainj	12.80	408.33 (31.90)	440.06 (34.38)	7.77
209	D 60 Badoon Sikar	28.40	1219.09 (42.92)	1309.20 (46.10)	7.39
210	D 121 Pansora	3.60	196.92 (54.70)	209.18 (58.11)	6.23
211	D 122 Shangari	6.40	524.63 (81.97)	569.43 (88.97))	8.54
212	D 124 Katyara	82.80	1717.99 (20.75)	1846.16 (22.29)	7.46
213	D 61 Danoli Dochi	6.40	626.56 (97.90)	686.79 (107.31)	9.61
214	D 63 Kiari	23.60	621.74 (26.34)	673.80 (28.55)	8.37
215	R 20 Bisha	66.00	2101.52 (31.84)	2275.43 (34.48)	8.27
216	D 66 Kasauli	5.60	166.45 (29.72)	176.53 (31.52)	6.06
217	D 65 Birni Kasauli	7.20	383.72 (53.29)	414.69 (57.59)	8.07
218	D 77 Karol VII	1.20	61.45 (51.21)	68.25 (56.87)	11.06
219	D 106 Naloh	36.80	614.66 (16.70)	663.80 (18.04)	7.99
220	R 21 Karol	279.60	6472.59 (23.15)	6965.88 (24.91)	7.62
221	D 104 Karol	67.20	1993.61 (29.67)	2117.54 (31.51)	6.22

222	D 105 Mathia	48.00	1398.58 (29.14)	1505.03 (31.35)	7.61
223	D 119 Chabil ki Dhar II	26.40	1283.62 (48.62)	1358.27 (51.45)	5.81
224	R 29 Kathani	16.00	821.49 (51.34)	889.47 (55.59)	8.27
225	D 126 Manlog	51.40	1302.95 (25.35)	1400.16 (27.24)	7.46
226	D 107 Dhalain	18.40	345.21 (18.76)	378.13 (20.55)	9.53
227	D 114 Kathani	287.80	7251.49 (25.20)	7815.50 (27.16)	7.78
228	R 51 Gauri ki Dhar	42.00	663.59 (15.80)	719.73 (17.14)	8.46
229	R 46 Jagatgarh	135.90	3234.37 (23.80)	3455.66 (25.43)	6.84
230	D 188 Karalghat	102.80	3180.57 (30.94)	3418.62 (33.25)	7.48
231	D 187 Kalath	8.80	378.27 (42.98)	409.24 (46.50)	8.18
232	D 181 Sirguli ka Tiba	25.20	519.91 (20.63)	559.16 (22.19)	7.55
233	D 212 Halda II	16.00	435.26 (27.20)	470.23 (29.39)	8.03
234	R 54 Karal Dev	151.60	3464.32 (22.85)	3773.42 (24.89)	8.92
235	R 53 Tiron	85.60	2071.89 (24.20)	2219.84 (25.93)	7.14
236	R 48 Kalath	167.60	3854.75 (22.30)	4128.78 (24.63)	7.11
237	D 183 Kalath IV	36.30	751.69 (20.71)	816.59 (22.49)	8.63
238	D 168 Kiard I	9.20	446.17 (48.49)	476.97 (51.84)	6.90
239	D 167 Gaduar	28.20	721.66 (25.59)	781.49 (27.71)	8.29
240	D 144 Chewa Khil Chunjari	5.20	252.46 (48.55)	273.93 (52.68)	8.50
241	R 32 Chunjari	67.60	1605.11 (23.74)	1717.82 (25.41)	7.02
242	R 47 Karalghat	136.80	4395.26 (32.13)	4688.80 (34.27)	6.68
243	D 139 Banjani	4.00	147.21 (36.80)	159.25 (39.81)	8.17

* Some of the compartments were divided into sub-compartments which were located at different locations

* Figures in parenthesis denote carbon density in t ha^{-1}

Appendix VII

ANOVA showing regression between Ring Width Index (RWI) and temperature

Diameter Class		**Sum of Squares**	**df**	**Mean Square**	**F**	**P**
D1	Regression	0.187	1	0.187	9.341	0.005*
	Residual	0.520	26	0.020		
	Total	0.707	27			
D2	Regression	0.446	1	0.446	10.462	0.003*
	Residual	1.107	26	0.043		
	Total	1.553	27			
D3	Regression	0.240	1	0.240	11.765	0.002*
	Residual	0.529	26	0.020		
	Total	0.769	27			
D4	Regression	0.588	1	0.588	18.807	0.000*
	Residual	0.812	26	0.031		
	Total	1.400	27			
D5	Regression	0.888	1	0.888	20.284	0.000*
	Residual	1.139	26	0.044		
	Total	2.027	27			
Average Index	Regression	0.435	1	0.435	22.488	0.000*
	Residual	0.503	26	0.019		
	Total	0.938	27			

* significant at < 0.05

Appendix VIII

ANOVA showing regression between Ring Width Index (RWI) and precipitation

Diameter Class		**Sum of Squares**	**df**	**Mean Square**	**F**	**P**
D1	Regression	0.504	1	0.504	11.097	0.002*
	Residual	1.725	38	0.045		
	Total	2.229	39			
D2	Regression	0.637	1	0.637	14.827	0.000*
	Residual	1.633	38	0.043		
	Total	2.271	39			
D3	Regression	0.206	1	0.206	4.773	0.035*
	Residual	1.643	38	0.043		
	Total	1.849	39			
D4	Regression	0.134	1	0.134	2.510	0.121
	Residual	2.031	38	0.053		
	Total	2.165	39			
D5	Regression	0.070	1	0.070	1.227	0.275
	Residual	2.170	38	0.057		
	Total	2.240	39			
Average Index	Regression	0.269	1	0.269	7.810	0.008*
	Residual	1.309	38	0.034		
	Total	1.578	39			

* significant at < 0.05

Appendix IX
ANOVA showing regression between RWI & temperature and RWI & precipitation

Diameter Class		**Sum of Squares**	**df**	**Mean Square**	**F**	**P**
D1	Regression	0.247	2	0.123	6.702	0.005*
	Residual	0.460	25	0.018		
	Total	0.707	27			
D2	Regression	0.648	2	0.324	8.958	0.001*
	Residual	0.904	25	0.036		
	Total	1.553	27			
D3	Regression	0.306	2	0.153	8.257	0.002*
	Residual	0.463	25	0.019		
	Total	0.769	27			
D4	Regression	0.613	2	0.307	9.735	0.001*
	Residual	0.787	25	0.031		
	Total	1.400	27			
D5	Regression	0.892	2	0.446	9.818	0.001*
	Residual	1.136	25	0.045		
	Total	2.027	27			
Average Index	Regression	0.490	2	0.245	13.656	0.000*
	Residual	0.448	25	0.018		
	Total	0.938	27			

* significant at < 0.05

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