Impact of Forest Degradation on Carbon Density in Soil and Vegetation of *Shorea robusta* (Sal) Forests in the part of Siwalik hills of Dehradun, India, using Geospatial Techniques

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By
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I certify that although I may have conferred with others in preparing for this assignment, and drawn upon a range of sources cited in this work, the content of this thesis report is my original work.
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Disclaimer

Santosh Pal Singh

Abstract

Forest canopy density is one of the indicators of the status of forests and good measure of the level of forest degradation. The study was carried out with objectives to determine the variability of carbon density in soil and vegetation, relationships among soil organic carbon, biomass carbon and forest degradation as well as the potential of carbon sequestration in Sal forests of Thano Forest Range, East Dehradun forest Division, Dehradun, Uttarakhand , India.

The study was carried out by using IRS- LISS III satellite data and ground data collected from stratified random sampling based on homogeneity map of forest strata. The best correlation of aboveground biomass with NDVI has been used for mapping aboveground biomass and carbon from plot level to the area of Sal forests. The validation indicated good prediction of the model.

The study overall revealed decrease in soil and vegetation carbon with decreased forest density classes. Comparison analysis indicates deceasing trend of vegetation carbon is more pronounced in Pure_Sal as compared to other categories of Sal forests. The highest vegetation carbon density was found in Pure_Sal with >80% density (291.04 ± SE 13.57 t/ha) and minimum in Sal forests on hills with 10-40% density (57.50 ± SE 16.23 t/ha). As expected, the contribution of tree layer in aboveground vegetation carbon was found highest among all layers which varied from 97-99% of the total aboveground vegetation carbon among different forest strata. Further analysis indicated variable trends of carbon in different component layers of aboveground biomass, indicating complex interaction of forest degradation with other factors such as terrain, forest composition, anthropogenic pressures etc.

Soil organic carbon density in each soil depth classes has shown decreasing trend with decrease of forest density class in all categories of Sal forests. The maximum soil organic carbon density in top 30 cm soil depth class (61.16 ± SE 3.96 t/ha) was found in Pure_Sal with >80% density and minimum in Sal mixed Teak forest with40-60% density (25.64 t/ha) and Hill_Sal with 10-40% density (27.30 ± SE 2.86). Similarly, the total SOC density in a meter soil depth was estimated maximum in Pure_Sal with >80% density (179.05 ± SE 11.20 t/ha) and minimum in Hill_ Sal with 10-40% (68.98± SE 11.38). This confirms that forest degradation adversely impact carbon sequestration also in all soil depth classes. The open to moderately degraded Pure_Sal forests have been to be the most potential area for C- sequestration.

Thus, this study proves that forest degradations decrease soil and vegetation carbon density however, its impacts are variable in different components of biomass as well as in soil depth classes, depending upon complex interactions with other factors as well.

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1. Introduction

1.1. Background

Carbon mitigation through forests has recently been recognized as one of the most important ecosystem services with specific reference to global warming and implication of Kyoto- Protocol. Forests are crucial for ecological functions, by regulating the climate and water resources. They play a critical role in global carbon cycle and offer significant potential to capture and hold carbon (C). Forest ecosystems store nearly two third of terrestrial C and have a larger C density (C mass per hectare) than any other land uses (Zhou *et al*., 2008). Forests hold 20-25 times more C ha^{-1} than cleared lands and 100-200 Mg C ha^{-1} may be lost as a result of deforestation (Houghton and Hackler, 1995).

Terrestrial ecosystems are an important component of the global C budget through photosynthesis, respiration, decomposition and biomass combustion. Forest biomass constitutes the largest terrestrial C-sink and accounts for 90% of all living terrestrial biomass (Tan, *et al*., 2007; Zhao and Zhou, 2005) The substantial C is transferred from terrestrial reservoir to the atmosphere as a result of change of biomass caused by deforestation and degradation. The anthropogenic actions and natural disturbances such as pests, fire and climate change cause forest degradation and reduction in the productivity which inevitably reduced the potential for C- sequestration. C- density is a critical parameter in determining the extent of human activity on ecosystem. Iverson *et al.,* (1994) introduced a forest degradation ratio which defined as the actual biomass density divided by the potential biomass density and found a logarithmic model to fit the relationship of forest degradation to anthropogenic population density at a significant level. The C- loss and C- dynamics in relation to degradation of natural forests is an important area in understanding forest ecosystems C cycle. Land cover change involving deforestation and land degradation is a significant global concern due to loss of biomass and its corresponding carbon stocks. At the same time, changes in vegetation lead to modification of the physicochemical characteristics of the soils, which can also induce changes in the soil reserves. Wang *et al*., (2001) studied on the impact of human disturbances on vegetation C- storage in forest ecosystem in China, concluded that, apart from change in land use, forest degradation can also cause significant C release from existing forest ecosystem. However, if a more effective management system can be applied to degraded forests, C sequestration by these forests will increase significantly. Land-use change, mainly forest burning, harvest, clearing for agriculture may compose 15-40% of annual human-caused emissions of carbon to the atmosphere and terrestrial ecosystems (Houghton, 2003).

1.2. Forest degradation

Forest degradation is considered as the quantitative and qualitative loss of vegetation cover over a long period of time within the forests and thus gradually reduced productivity (FAO, 1993). It is not a one time process, but ongoing process due to continuous anthropogenic pressures for exploitation of forest products. Degradation is a critical environmental problem which has significant impact on depletion of biomass, loss of economic opportunities and increase in social problem in addition to the global warming. Forest degradation is critically reducing the potential of land for C-sequestration in the long run and therefore, considered a serious hazard to the environment. Degradation processes can be assessed in terms of crown cover, tree density, biomass density, biodiversity loss, soil quality and erosion. It causes land degradation and ultimately leads to loss of productivity because of poor soil conditions, loss of nutrients and soil organic matters. Forests degradation, as a result of unsustainable human activities, affects an even large area of forests per annum than deforestation (De Gier, 1996). The forests are largely degraded by mining, overgrazing, lopping, over-harvesting of wood and non-wood forest produces, linked with underlying causes of demographic, socio-economic, population growth, agriculture, urban development and political factors of the region. The natural forests once exposed to such overexploitation of the resources develop physiological stress in vegetation and become more susceptible to the natural hazards such as fire, pests, diseases, adverse edaphic and climatic factors. Such impacts of human activities aggravate forest degradation. The degradations reduce the potential of forest to function as regulator of the environment, natural regeneration, soil and water conservation, and lastly serious impacts on C-dynamics. The magnitude of forest degradation with respect to C- dynamics is still not well understood. The estimation of changes in forest C pool is useful for understanding C storage associated with various level of degradation in various forest types**.**

1.3. Deforestation

Deforestation is considered as "the removal of forest stand where land is put to a non forest land-use" (Helm, 1998). Good Practice Guidance for Land Use, Land-Use Change and Forestry (LULUCF), (IPCC, 2003) defined deforestation as the direct human- induced conversion of forested land to non-forested land. The conversion of forests for other land use is broadly for agriculture, pastures, shifting cultivation, plantations etc. Most of these changes affect the vegetation and soil and thus change the amount of C held in forest land. Deforestation is one of the single biggest threats to the terrestrial C sink and climate change along with soil management practices influence sink capacity of the soils (Reay, 2007). The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) indicates that the forestry sector, mainly through deforestation, accounts for about 17% of the global greenhouse gas emissions which is the second source after energy sector. Recognizing this, the support to reduce emissions from forest deforestation and forest degradation (REDD) has been adopted in Bali Action Plan of United Nations Framework Convention on Climate

Change (UNFCCC) at the 13th session of Conference of Parties(COP 13) in Bali, Indonesia, 2007. The REDD is considered as a relatively low cost green house gas mitigation option and also now emerged as one of the key areas for fighting against global warming (FAO, 2009). As pointed out by the IPCC (1996) global estimate of C emission from deforestation has remained highly uncertain and show high geographical variability, needs to be further studied.

1.4. Forest canopy density

Forest canopy density is one of the indicators of the status of forest and good measure of the level of forest degradation. Forest canopy refers to the proportion of the ground covered by vertical projection on to it of the overall vegetation canopy (Howard, 1991). Forest canopy density is directly or indirectly related to severe problem caused by high biotic pressure, degradation, soil erosion and encroachment on forest land for agriculture and settlement. Canopy density is a dynamic process, usually opened by removal of trees or vegetation. The created gaps are generally filled up by new vegetation or co-dominant vegetation, depending upon edaphic, climate, disturbances factors etc. The anthropogenic interventions like fire, illegal felling, fuel-wood collection, lopping, grazing etc. in the natural forests adversely affect canopy closure and continuous disturbances may not allow to recover canopy closure to its original potential. Canopy disturbances are not a random process because certain areas are more persistently and more frequently disturbed than other areas. It has also been reported that high biotic pressure on Sal forests of Chitwan district of Nepal caused forest degradation and leading to thinning of canopy density proportionate to the biotic pressure (Panta, 2003). Bharti (1999) has also reported the loss of canopy closure in Sal forests of Dehradun, adjacent to human habitation due to high biotic pressure for lopping, grazing, firewood and timber collection which is the indicator of forest degradation.

1.5. Carbon Storage in forest ecosystem

Carbon storage in forest ecosystem involves numerous components including biomass C and soil organic carbon (SOC). Biomass is the organic material and includes both above-ground and below-ground biomass. Above-ground biomass includes all vegetation biomass above the soil including stem, stump, branch, bark, seed and foliage while below-ground biomass includes all live roots; fine root of less than 2 mm diameter are sometimes excluded because these often cannot be distinguished empirically from soil organic matter or litter (IPCC, 2003). Plants are the main source of the SOC, either from the decomposition of aerial plant parts or underground plant parts. Soil is considered as an important sink for the carbon storage in the form of SOC (Kumar *et. al*., 2006). Interest in SOC has greatly increased in recent years because terrestrial organic C can be a key factor in understanding the effect of C emission on global climate change. Whether soil is a source or sink of terrestrial C depends on the balance between the oxidation and humification processes. The biochemical oxidation of SOC can lead to emission of CO_2 into the atmosphere C, while the humification process leads to sequestration of organic C. Emission of CO_2 from oxidation of soil organic matter or from respiration of the above ground biomass is still the largest source of CO_2 in the atmosphere (Schesinger, 1991; Lal *et al*., 1998).

Deforestation and degradation causes perturbation in the ecosystem and can influence the dynamics of C stocks both in biomass and soil. The SOC stock is attributed with numerous factors including biomass change, moisture and temperature regime of soil, forest management etc. Estimating the effect of degradation on SOC dynamics are critical to predict the overall impact on carbon density in the forests, including biomass C density. Considering this, the study on the effect of degradation on both biomass C and SOC was envisaged.

Recent studies on Indian forest biomass, phytocarbon and SOC pools are available at macro level, mostly with the available data (Ravindranath *et al*., 1997; Dadhwal *et al*., 1997; Haripriya, 2000; Chhabra et *al*., 2002; Chhabra *et al*. 2003; Ramachandran *et al*., 2007). As per survey of the literature, it is revealed that studies on C density changes in above and below ground biomass, and SOC with respect to degradation of ecological fragile natural forests, having dominance of one tree species are lacking. Such kind of micro-level studies would be very useful in better understanding C dynamics of fragile forest ecosystem and for sustainable forest management, especially in country like India, where degradation had been caused by anthropogenic activities and various forest management practices adopted from time to time to meet the local and national need. In addition to this, such studies would also provide useful information to explore the potentiality of C- sequestration of such forests which can be considered as one of the significant parameter for Environment Impact Assessment (EIA) studies and overall quantification of ecosystem service available from such forests. Considering this, the present study on impact of degradation on *Shorea robusta* (Sal) forests in part of Siwalik hills of Himalaya in Dehradun, India was proposed.

1.6. Problem statement

The Sal (*Shorea robusta*) forests occurring in the study area are the natural forests. These forests were worked under various silvicultural practices prescribed in the working plan of the Forest Department (Bharti, 1999). The past management history revealed that these forests were managed with an objective to enhance productivity of Sal trees for harvesting maximum timber, usually on the principle of sustainable forest management till 1990s. Various silvicultural systems were applied from time to time in order to improve the productivity of Sal trees and increase their natural regeneration. However, these forests could not withstand against heavy biotic pressure of overgrazing, lopping, overexploitation of non-wood forest produces, urbanization etc, resulting failure of natural regeneration and land degradation. After formulation of India Forest Policy (1988), the emphasis of the management of such forests was shifted from production forestry to biodiversity conservation, ecological functions and meeting the need of the local people. As per provision of this policy, the natural forests should not be replaced by other land-use. The only options available are to maintain them or making efforts for restoration of the degraded forests by natural vegetation. The later option would provide better opportunities of maximum utilization of scarce land resources for carbon sequestration in the perspective of both ecology and mitigation of global warming. However, this needs to be supported by studies related with impact of degradation on carbon storage and also the potential of such forests if reforested. In addition to this, the proper assessment for EIA studies is also required for justification in the investment for restoration of these forests, duly supported by substantial information on the relationship of changes in carbon pools of vegetation and SOC with respect to various level of degradation. Therefore, the present study was proposed to generate data on such information in order to strengthen the management practices for restoration as well as preventing further degradation of Sal forests in Doon valley.

1.7. Objectives

1. To determine the variability in SOC and vegetation carbon in different forest density classes of Sal forests.
2. To estimate carbon density of existing Sal forests v/s potential of carbon sequestration with respect to forest degradation.
3. To study relationship among SOC, biomass carbon and forest degradation.

1.8. Research questions

1. What is the impact of forest degradation due to anthropogenic activities on soil and vegetation carbon density?
2. How is SOC changing in surface and subsurface layers in different forest density classes of Sal forests due to anthropogenic pressures?
3. What is the total potential of C sequestration in terms of vegetation and SOC in Sal forests of study area?
4. What is the relationship among biomass C, SOC and forest density classes and /or degradation?
5. What is the relationship between above ground biomass related C density and spectral reflectance?

1.9. Hypotheses

1. Forest degradation reduces the potential of carbon sequestration due to reduced foliage and productivity of Sal forests and regeneration failure.
2. There is a relation among forest degradation, biomass C and SOC, which can be used to predict loss or gain of C sequestration.

1.10. Structure of thesis

The thesis comprises of 8 chapters starting with the present one which throws light on background, problem statements, objectives, research questions and. hypotheses. The chapter 2 deals with review of literature explaining the basic concepts on related issues of research and the previous works. Chapter 3 gives a description of the study area mentioning its selection criteria, location, road network, physiography, geology, soils, climate, vegetation and other features of the area. Chapter 4 explains research approach to methodology and materials needed in order to answer the research questions and achieve objectives. Chapter 5 summarizes the results obtained followed by interpretation of finding through discussions. The conclusions and recommendations are given in the chapter 6. Chapter 7 includes references and Chapter 8 consists of appendices.

2. Literature review

2.1. Variability of C- stock in different land-use land-cover classes/changes

Land use land cover (LULC) change is the second most important source of CO_2 emission (IPCC, 2001) as forest areas are rapidly changing into other land use and causing forest degradation. The literature survey indicated that a number of studies are available on the estimation of the C stocks in vegetation and soil in different LULC classes and also changes occurred in C stock with respect to conversion of forests in other land use. These studies have supported the hypothesis that land use changes from forests to agriculture and other usage causes tremendous losses of terrestrial C that reduce the potential for land sustainability. Therefore, it is clear that because of overexploitation and continuous land conversion, LULC changes have become a net source of C to the atmosphere (Houghton, 1990; Brown and Lugo, 1990; Sharma and Rai, 2007). Forests vary considerably in their capacity to absorb and store C. Factors which influence C absorption rate include temperature, precipitation, stocking, soil, slope, elevation, site condition, growth rate and range. Generally speaking, close forests have a greater capacity to store more C than open forests and woodlands. Undisturbed forests store more C than degraded forests; similarly, wet forests store more C than dry or semiarid forests and mature forests store greater quantities of C than do young forests (Negi and Chauhan, 2002).

Some studies are also available on the changes in C stock after reforestation of degraded/open lands with various types of crops/ type of forest trees, it was found that there is overall increase in stock, depending upon soil types, climate type of tree species etc used in reforestation program. Zhou *et al*. (2008) showed that over the 10 years period, the reforestation in Guangdong, China has increased forest C- density by 1.58 Mg C ha^{-1}. Total C storage in tree layer was the greatest among all layers studied. C storage in litterfall and understorey amounted to 38-44% of the total C storage, demonstrating that these layers are also significant in estimation of total C storage. The analysis also showed that C accumulation in broad leaved forests was the highest (0.19-1.36 Mg ha^{-1} $year^{-1}$) among all the key reforestation forest types in Guangdong, indicating that selection of tree species also play vital role in C sequestration.

2.1.1. Soil organic carbon

Soil is a major store of organic C, especially the forest soils, because these contain higher soil organic matter in comparison to any other land use. It may be because of continuous extensive litter fall and its decomposition, which releases the organic C (Jha *et al.*, 2003). Global warming, atmospheric deposition and increase in atmospheric CO_2 concentration are the primary atmospheric factors which may have impact on forest soils (Josline and Johnson, 1997). The conversion of land from its natural state to other land use like agriculture generally leads to losses of SOC. The decline in total organic carbon in the agro-ecosystem was reduced two times faster than that of the soil carbon storage in the sub humid woodland forests and plantations. The tropical rain forests are usually closed ecological system which represents a highly efficient production form and a considerable quantity of organic litter falls into the soil surface and decays, providing food for a highly active soil flora and fauna which ultimately stores more organic carbon than cultivated land (Swarup *et al*., 2000).

The soil in equilibrium with natural forest ecosystem have high C density than any other land-use including cultivation. The cultivation disturbs the natural organic carbon equilibrium. Land-use change, particularly, conversion to agriculture ecosystem depletes the soil C stock. Thus, degraded agriculture soils have lower SOC stock than their potential capacity. Consequently, afforesting of agriculture soil and management of forest plantations can enhance SOC stock through C sequestration. The rate of SOC sequestration, and the magnitude and quality of soil C stock depend on complex interactions between climate, soil, tree species and management, and chemical composition of the litter as determined by the dominant tree species (Lal, 2005). Swarup *et al*.(2000) have also documented that the agricultural soils of northwest of India have lost about one half to two third of their original organic carbon content. The literature search also support that SOC can be increased manifold in degraded forests after reforestation over the original soil.

SOC equilibrium is governed by a number of interacting factors such as temperature, moisture, texture, quality and quantity of organic matter, methods of application, soil tillage and cropping systems. Low level of SOC is also attributed to soil mining, tillage and severe soil degradation, while undisturbed soil, the SOC concentration of most of the soil is high (Jenny and Raychaudhuri, 1960). Lal (2005) also concluded that SOC stock is attributed to numerous factors, including the amount of above and below ground biomass returned to the soil, change in soil moisture and temperature regime, high decomposition due to difference in C:N ratio and lignin content, decrease in soil aggregation and reduction in physical protection of the soil Organic matter and increase in soil erosion. Afforestation of land can reverse some of the degradation processes and cause enhancement of SOC stock. Besides other factors, anthropogenic factors, which may affect SOC in forests, include forest management activities, deforestation, degradation, reforestation etc. Management systems that maintain a continuous canopy cover and minimize regular natural forest disturbance are likely to achieve the best combination of high yield and C storage. Further, Lal (2004) reported that low SOC pool in soil of India is partly due to the sever problem of soil degradation and the main causes of decline in SOC pool in degraded soil is reduction in biomass, accelerated soil erosion and runoff.

Dinakaran and Krishnayya (2008) studied the influence of different vegetal covers, changes in land use pattern and heterogeneity of physical fractions of SOC pool on soil carbon. SOC was much higher in soils with natural tree cover. Difference in vegetal cover not only influenced SOC content of the top layer, but also of deep layers. Changes in land use pattern severely reduce sink capacity of soils. It appears that land-use change is a dominant factor in accounting the sources and sinks of C (Houghton and Goodle, 2004). Many studies have shown significant reduction in soil organic C following conversion of natural forests into cultivation or pasture (Fearnside *et al*., 1998; Solomon *et al*., 2002). Detwiler (1986) and Detwiler and Hall (1988) indicated that the stock of soil carbon in a 40-cm profile in the tropics could be reduced by 20% by conversion of primary forests to pasture. In some cases, increase in SOC reported when forests are converted into pasture which indicates that SOC is a complex phenomenon depending on number of factors including management practices (Fearnside *et al*. 1998; Guo and Gifford, 2002).

Ordonez *et al*. (2008) analyzed soil carbon content at different depth layers (0-5, 5-15, and 15-30 cm) in 10 different LULC classes. C- content in each layer was estimated and found highest in oak forests and lowest in case of degraded forests; similarly total SOC was reported highest in oak forests (116.4 Mg C ha $^{-1}$) and lowest value in degraded forests (72.8 Mg C ha $^{-1}$).

For land use change involving re-establishment of woody vegetation (e.g. forests to plantation, reversion to agriculture land to forests), effect on C soil also depend on vegetation type, age of new vegetation, input rates and decomposability of litter and roots and vertical distribution of C inputs throughout the soil profile (Post and Kwon, 2000; Guo and Gifford, 2002; Kasel and Bennett, 2007).

2.1.2. Vegetation carbon

Literature search concluded that the biomass C is also affected by the deforestation and its conversion to other land-use types such as pasture, shifting cultivation, cropland etc. Sharma and Rai (2007) reported that the conversion of forests into other land uses resulted in a remarkable decline in the C density and significantly increased C flux relative to storage. However, the impacts of deforestation and degradation on the relationship of changes in above and below ground carbon pool and SOC pool need to be studied in different forest ecosystem.

Fitsimmons *et al*. (2004) studied the effects of deforestation on ecosystem C density in aboveground biomass and SOC to 45 cm depth in central Saskatchewan, Canada. The C density for forested was significantly higher (158 Mg C ha $^{-1}$) ($P<0.05$) than for pasture (63 Mg C ha $^{-1}$) and for cultivated fields (81 Mg C ha $^{-1}$). However significant differences were not detected between forested and deforested sites for SOC alone. Differences in ecosystem C densities between forested and deforested sites were primarily the result of differences in vegetation biomass. The differences in vegetation C between forested and deforested sites in the study area were estimated to vary between 30 to 75 Mg C ha $^{-1}$ on account of disturbances process of forest fire etc. it was also estimated that the vegetation in study area if reforested along with legislative protection has the potential to sequester 30 -75 Mg C ha $^{-1}$ over the next 50 -100 years.

Zheng *et al*. (2007) studied the C- dynamics in forest ecosystem as affected by different forest management practices. The assessment of the overall impact of different reforestation types on C – storage was done through quantification of above ground biomass and below ground biomass C-pools. It was found that soil surface disturbances during forest management practices was one of the main factors in reducing the soil and under-storey C-storage of tree plantation stands and concluded that the natural restoration of the forest is a superior approach for increasing C- storage potential.

Studies on land use change and corresponding forest re-growth after agriculture land abandonment was also carried out and considered as the main mechanism for the conterminous U.S. carbon sink (Huntington *et al*., 1995; Houghton *et al*., 1999; Houghton and Hackler., 2000; Pacala *et al*., 2001; Hu and Wang, 2008) Pacala *et al*. (2001) estimated that half of C sink (0.30-0.58 Pg C yr^{-1}) conterminous US from late 1970s to the early 1990s was due to forest re-growth on abandoned croplands.

Ordonez, *et al*. (2008) estimated C content in vegetation, litter and soil under different 10 classes of LULC in the central highland of Mexico. These areas are subject to rapid degradation and deforestation by human pressure. Forest classes showed highest total carbon stock, followed by degraded forests, plantations, grassland and agriculture, indicating the vulnerability of land-use change process.

Rautiainen (2009) carried out study on C-gain and recovery from degradation of forest biomass in European Union during 1990- 2005, by analyzing international data. The net gain was estimated at 360-400 Tg CO_2 $year^{-1}$. This C-sequestration was driven by recovery of ecosystem from human induced degradation.

Upadhya *et al*. (2005) reviewed C sequestration as affected by land use change and forest/soil degradation. Land-use changes, caused by deforestation and conversion to agriculture and degradation, have a strong influence on C- emission to the atmosphere. They concluded that there is a high potential for enhancing the C sequestration in Himalaya region through improved management of degraded lands.

Lal (1995) reported that overall, forest ecosystem store 20-100 times more carbon per unit area than crop lands, hence, play a critical role in reducing ambient CO_2 level, by sequestering atmospheric C in the growth of woody biomass through process of photosynthesis and thereby increasing the SOC content. The restoration of degraded forests and soil has a globally a potential for sequestrating C in terrestrial ecosystem corresponding to 50-75% of the historic loss (Brown and Pearce, 1994).

2.2. Biomass estimation

FAO (2005) has defined biomass as “the organic material both above and below the ground, and both living and dead, trees, crops, grasses, dried litter, root etc.” Aboveground biomass include all living biomass above the soil, while belowground biomass includes all biomass of live roots, exceeding fine roots (<2mm dia).

2.2.1. Above ground biomass (AGB) estimation

Literature survey revealed that different approaches, based on field measurement and Remote Sensing (RS) and Geographic Information System (GIS) are available for AGB estimation. RS does not measure biomass directly, but rather it measures other parameter of forest characteristic like spectral reflectance and therefore, ground data is necessary to develop the biomass predictive models and its validation. A sufficient number of field measurements are a prerequisite for evaluating AGB estimation results. Biomass assessment is usually carried out by collecting field inventory data from sample design. The existing species specific volume/ biomass regression equations, specific gravity and biomass expansion factors are used to calculate biomass of the sample design, followed by the extrapolation to the entire area for total biomass (e.g. Zianis, *et al*., 2005; Deo, 2008; Srivastava, 2009, Dadhwal, *et.al*., 2009).

2.2.1.1. Allometric regression equations

The allometric regression equations and expansion factors (EF) for a range of tree species and forest types have been developed and used for converting inventoried forest volume to above ground biomass for C-estimation in large number of studies, considered a reasonable standard method of biomass C estimation. (e.g. Negi, 1984; Hall and Uhlig, 1991; Kauppi *et al*., 1992; Fang *et al*., 1992; Dadhwal *et al*., 1997; Haripriya, 2000; Hu and Wang, 2008; Kun, and Dongsheng,2008; Zou *et al*., 2008; Srivastava, 2009; Dadhwal, *et.al*, 2009; Kale *et al*., 2004).

Chave et al. (2004) pointed out that there are four types of uncertainties to be considered. The presence of uncertainty at each step can lead to error propagation in estimated AGB. These uncertainty errors are due to tree measurements, choice of allometric equations, sampling usually related to plot size, and representative of small measurement plot networks across large forest landscape. Among these, the allometric equation is considered the most important source of error. In order to estimate AGB in tropical forests, the use of species specific allometric equations should be preferred due the fact that different species have different tree structure and wood density (Ketterings et al., 2001, Nunung, 2006). The 'Good Practice Guidance' IPCC, 2003 has also given priority for the selection and use of species specific or similar species allometric equations in the priority order of local to national to global scale in biomass calculation. In the present study, the species specific volume allometric equations of the local area developed and compiled by FSI, 1996 was used in all tree species except Sal trees. In case of Sal trees, the allometric biomass equation of local area developed by Negi (1984) was used to minimize the uncertainty error as far as possible.

2.2.1.2. Expansion ratio

Expansion ratio (ER) is applied to account for the non-stem biomass such as twigs, foliage etc which is not accounted for during volume/biomass estimation (Cannell, 1982). Haripriya (2000) used expansion ratio of 1.59 for broad- leaved species, 1.51 for conifers and 1.55 for hardwoods mixed with confers. Lal and Singh (2003) used expansion ratio of 1.16 for Sal, 1.34 for Teak, 1.25 for conifers, 1.40 for broadleaved species and 1.32 for hardwood mixed with conifers for obtaining total volume of aboveground biomass which were determined on the basis of earlier studies in India, Nepal and Bhutan (Cannell, 1982). In the present study, the available ratio of 1.34 for teak and 1.40 for other broadleaved species except, Sal were used. Since biomass allometric equation for Sal trees developed by Negi (1984) included all the components of AGB and therefore, the use of expansion ratio was not needed.

2.2.2. Below ground biomass (BGB) estimation

Measuring AGB is relatively well established, however, BGB is difficult and time consuming to measure in all forest ecosystem and methods are not standardized. AGB is often estimated from root shoot ratios(R/S). Based on number of studies covering tropical, temperate and boreal forests the mean R/S reported by Cairns et al., 1997 was 0.26 with range from 0.18 to 0.30. It is also reported that R/S did not vary significantly with latitudinal zone, soil texture or tree type. Negi (1984) reported that the root biomass of Sal trees increased with increasing AGB, but the percentage contribution of BGB decreased from 38 % to 22% with increasing diameter and AGB. Similar trends were also observed in case of total biomass where the corresponding percentage contribution of root biomass decreased from 27% to 18%. Similar results were also reported by Misra (1969) for Sal trees plantations. In the present study, the mean R/S (0.30) for Sal tree was taken as per findings of Negi (1984) while, 0.26 was considered for other tree species.

2.3. Remote sensing for biomass and carbon mapping

The remote sensing technique has been widely used in many studies on biomass assessment (e.g. Kale *et al*., 2002; Zheng *et al*., 2004; Srivastava, 2009; Dadhwal, *et.al* 2009; Kale *et al*., 2009) The advantage of remote sensing data and high correlations between spectral data and vegetation make it useful for large scale AGB mapping. The biomass measurement from sample plot can be integrated into the remote sensing technique to get cost effective and large spatial information on AGB distribution (Deo, 2008). However, remote sensing based AGB estimation is a complex procedure in which many factors such as atmospheric conditions, mixed pixel, data saturation complex biophysical environments, insufficient sample data, extracted remote sensing variables and selected algorithms may interactively affect AGB estimation (Luther *et al*., 2006).

2.3.1. Vegetation indices

Vegetation indices (VIs) are the quantitative measure of measuring biomass or vegetation vigour, usually formed by a combination of several spectral bands, whose values are added, divided or multiplied in order to yield a single value that indicates the amount or vigour of vegetation. A variety of VIs have been developed, with most commonly using red and near infrared regions of the spectrum to emphasize the difference between strong absorption of red electromagnetic radiation and the strong scatter of near infrared radiation. The simplest form of vegetation index is a ratio between near infrared and red reflectance and it is high for healthy living vegetation. Literature survey revealed wide disagreement regarding the biomass and VIs relationship. Many studies report a significant positive relationship (e.g. Boyad *et al*., 1999, Zheng *et al.,* 2004;; Dadhwal *et al*., 2009) while some results showed poor relationship (Foody *et al*., 2003, Schlerf *et al*., 2005).

The Normalized Difference Vegetation Index (NDVI) is one of the most commonly used VIs in many applications relevant to analysis of biophysical parameter of forests. Over past two decades its utility has been well demonstrated in satellite assessment and monitoring of global vegetation cover (Huete and Liu, 1994; Leprieur et al., 2000). The strength of NDVI is in its rationing concept which reduces many form of multiplicative noise present in multiple bands. However, conclusions about its value vary depending on the use of specific biophysical parameters and characteristics of the study area. (Deo, 2008). It is computed by the product of the ratio of two electro-magnetic wavelengths (near infrared – red) / (near infrared + red). 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 and the value of NDVI tends to one. In contrast of this, clouds, water, snow etc. have a high red reflectance than near-infrared reflectance and these features yield negative NDVI value. Rocks and bare soil also have similar reflectance and usually zero value of NDVI.

The saturation of the relationship between biomass and NDVI is also a well known problem. This can be explained by the fact that as canopy increases, the amount of red light that can be absorbed by leaves reaches a peak while near-infrared (NIR) reflectance increases because of multiple scattering with leaves. The imbalance between a slight decrease in the red and high NIR reflectance results in a slight change in the NDVI ratio and thus, yield poor relationship with biomass (Tenkabail et al., 2000). Further, Rauste (2005) observed that saturation level is also dependent on the tree species, forest types as well as the ground surface types. Therefore, a suitable relationship of VIs and biomass is crucial in assessment of biomass in different circumstances and a matter of more research work. The usefulness of remote sensing in such work depends on the strength of the relationships developed with respect to a particular type of forests and its geographical location.

2.4. Studies on Sal forests

Though a number of studies on Sal forests related with biomass and productivity assessment were carried out (Misra *et al*., 1967; Raman, 1975; Kaul *et al*., 1979a; Chaturvedi and Sharma, 1980) but study related with variability of vegetation and soil organic C is lacking with respect to various level of forest degradation. Negi (1984) estimated total biomass and compared net primary productivity per unit area in plantations and natural Sal forests, developed a set of regressions between dry matter tree components (stem, bark, leaves, root and total biomass) and measurable parameters like diameter at breast height (Dbh), height etc. to be applied to establish volume/dry weight relationship and concluded that D^2 H gave the best results for predicting the biomass in managed natural forests of Dehradun. The allometric regression equation developed for Total AGB/D^2 H is as follows:

$$\log y = (-1.78825 + 1.04848 \log x)$$

where, y = Total aboveground biomass; x = D^2 H (Dia. in cm & Height in m).

The above mentioned allometric equation was also used in this study for estimating the total AGB of Sal trees. Negi *et al*. (1988) compared biomass estimates obtained by using various methods (mean tree technique, stratified technique, basal area proportion and regression method) in *Shorea robusta* stand and obtained the best results by regression methods after the stratified tree technique. It was also reported that stratified tree technique is undoubtedly more expensive and time consuming and therefore, regression equations are most useful for wide applicability. They have also assessed the effect of plot size (100m^2, 200m^2, 400m^2 and 1000m^2) on the variability of stand parameter for biomass estimation and indicated that stand biomass was substantially affected by the plot size less than 200m^2 and suggested for using larger or more plots for better estimation of biomass. In view of these facts and time constraint, plot size of 500m^2 was considered for the present study. Negi and Chauhan (2002) studied green house gases mitigation potential by Sal forests in Doon valley and found that increase in temperature followed by the increased rainfall ultimately provide the favorable condition for fast decomposition and mineralization resulting in high productivity and subsequently high carbon sequestration. The total biomass and C – storage in standing crop Sal tress of various age was computed. The total biomass varied from 182-777 t/ha depending on stand age and density, similarly C-storage in total biomass varied from 91.0- 388.45 t/ha. C- Storage in soil showed the variation from 31.0-62.9 t/ha in the top 30 cm soil depth. The highest quantity of C i.e. 61.7 t/ha was found stored in the soil of Lacchiwala Sal forests growing on flat areas.

A number of studies other than biomass and productivity available on Sal forests were not considered for review under the present study.

Conclusion of review of literature

The summary of literature review concluded that forest degradation and deforestation are the most important source of CO2 emission and cause loss of SOC and vegetation C pool. A good number of studies are available on the assessment of total loss of C and its variations in SOC and vegetation carbon with respect to different land-use, land –cover classes and, changes occurred on conversion of forests into agriculture and other land uses. However, studies related with impact of various level of forest degradation on the process, relationship and variability occurred in SOC in different soil depths and vegetation C losses are very limited and therefore, these concepts are not well understood, hence the present study on impact of forest degradation on C density in soil and vegetation of natural forest of *Shorea robutsa* was undertaken.

3. Study area

The Thano Range of East Dehradun Forest Division was selected on the basis of fulfilling of the following criteria.

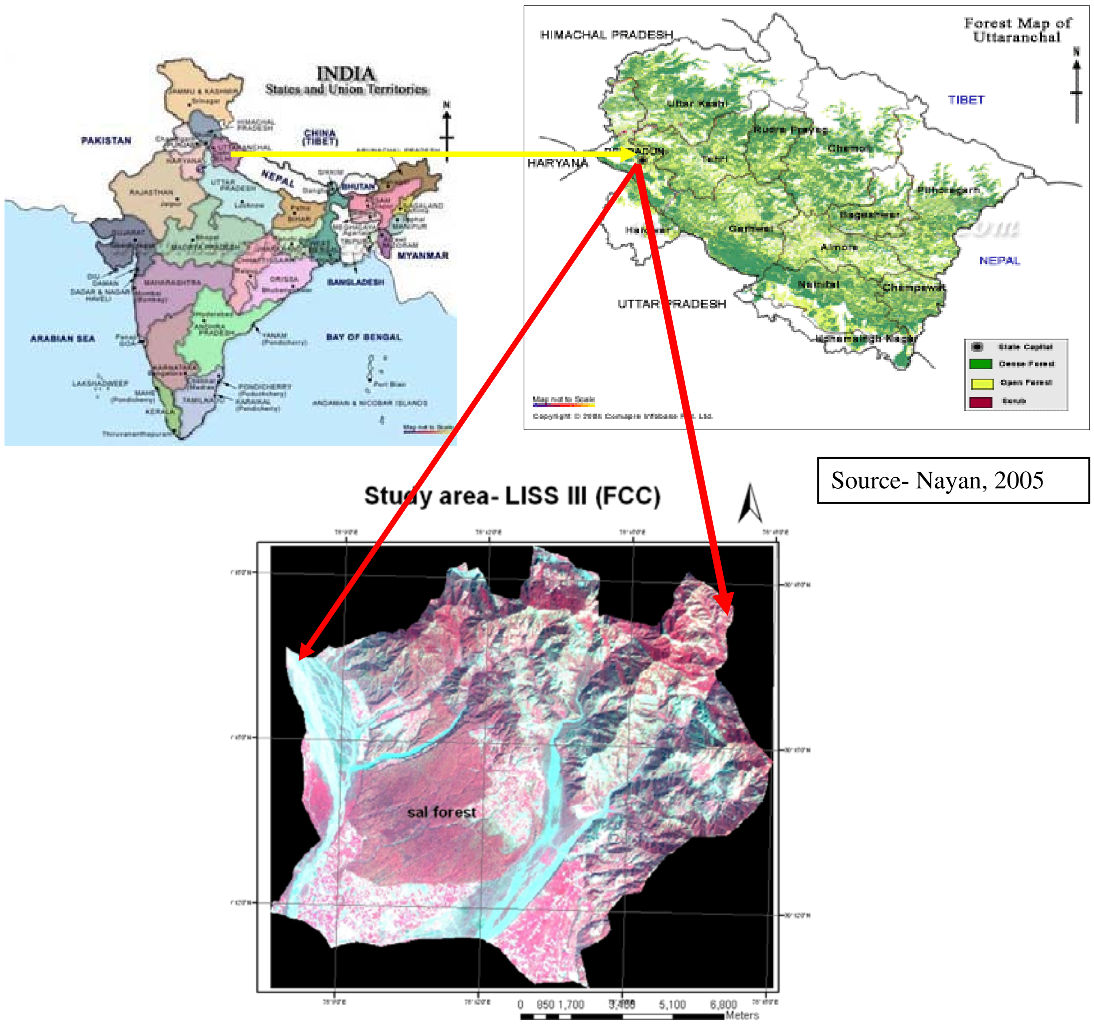
- The area consists of a number of forest density classes indicative of various levels of degradation stages due to anthropogenic pressures.
- The area comprised of the natural forest ecosystem predominantly pure Sal and Sal dominated forests which is highly fragile and highly threatened from biotic pressure as well as management practices.
- The area falls within one bio-geographic zone, Himalaya (Rodgers and Panwar 1990) with more or less having similar topography, soil formation, weather- range of temperature and rainfall.
- The area is accessible for collection of field data on vegetation and soil samples as well as for ground- truth verification.
- The area has different physiographic units.

3.1. Location

The study area lies between geo-coordinates 30° 10’ 00” to 30° 18’ 36” north latitude and 78° 07’ 48” to 78° 18’ 00” east longitudes in the district of Dehradun (Figure 3.1). The study area comes under administrative boundaries of East Dehradun Forest Division, Dehradun in the state of Uttarakhand, India. The area is surrounded by human settlements and agriculture land along with adjacent forests of Barkot Forest Range in South, Lachhiwala Forest Range in west, Malsi Forest Range in north and Pauri Garhwal and Tehri Garhwal hilly forests in east. A number of human settlements and agriculture fields are interspersed with Sal forests of the study area, putting anthropogenic pressure on forests. The area of Thano Forest Range covers a total area of 11775 hectares, out of which Sal forests and Sal dominated forests are roughly occupying 3000 hectares of land.

3.2. Road networks

The area possesses a good network of metalled roads maintained by Public Works Department (PWD), fair weathered forest motor roads and fire controlled roads maintained by Forest Departments. The main metalled roads crossing from north to south and south-west are Raipur-Thano Ranipokhari and Thano-Jollygrant roads respectively. In addition to this, a number of link roads also exist to various villages in and around the study area and thus provide good accessibility to the interior areas.



Source- Nayan, 2005

Figure 3.1 Location of the Thano Forest Range (study area)

3.3. Physiography

The central and southern-eastern side of the study area is characterized by piedmont-zone flat and gentle to moderate slopes and valleys, occupying with Sal and Sal dominated forests. The area facing towards on northern and western side comprises of gently to moderate and steep hills and valleys and covered with northern tropical deciduous forests of miscellaneous species. The gentle slopes in southern part of the area has piedmont zone. This zone can be further characterised as upper, middle and lower. There is a network of shallow, dry and boulderly seasonal streams locally known as ‘rau’, which come down from the upper slopes and carry their discharge into Song river boarding on eastern side and into Jakhan river on the western side of study area. These two main rivers provide drainage pattern through the network of ‘raus’ and streams which carry immense volume of turbulent water loaded with loose boulders and gravels during monsoon. The beds of these rivers along with majority of streams are very wide and shallow and remain dry most part of the year. The river beds are also intermixed with patches of riverine forests and grasslands, highly suitable habitat for herbivores wildlife. The DEM overlaid IRS LISS III FCC of the study area is shown in figure 3.2.

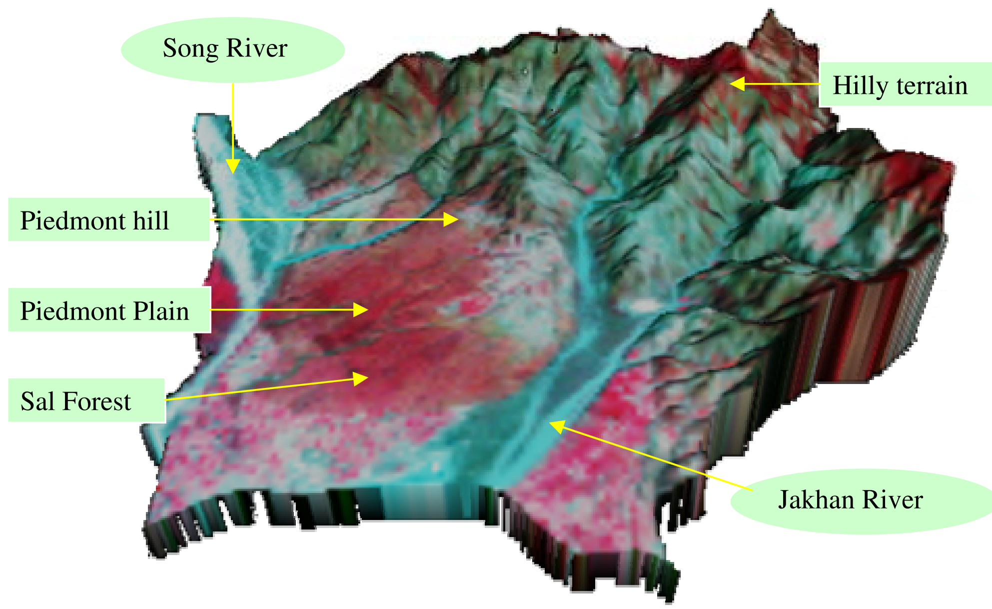


Figure 3.2 showing 3- D View of the study area.

3.4. Geology

The study area is a part of Dehradun valley which belongs to the synclinical rocks filled with Doon gravels. Doon valley is covered by unstratified and unasserted pebbles and boulders belonging mainly to the upper siwaliks with a very little matrix known as Doon Gravels. These gravels are generally loose and highly pervious with little or no clay and form a poor water reservoir. The permanent water table is generally deep in Doon Valley. The oldest Doon gravel are formed from partly of crushed upper Siwaliks cobbles, angular pebbles of quartzites, slate and shales, lime stone pebbles alternating with clay, sand, gravel and large boulders. The younger Doon Gravel are characterized by very large boulder present in debris flow and river deposits, comparatively less weathered and in incipient stage of soil formation.

3.5. Soils

The variations in soil characteristics, especially texture, depth, stoniness. colour, drainage, moisture status, organic matter content etc. is reported to be due to variations in topography, intensity of soil erosion, parent material and other factors in the Doon Valley. The forest soils of the Doon valley mainly belong to the orders Inceptisol, Molilisol and Alfisol. The soils under Sal forests are generally classified to coarse loamy thermic flueventic haplumbrept, having acidic to near neutral reaction and texture from loam to loamy sand throughout the depth with embedded gravels and pebbles. The high organic matter content indicates a high fertility status but the presences of high amounts of gravels with some stones reduce the effective soil volume (Sharma, *et el*., 1995).

3.6. Climate

The climate of the area varies from sub-tropical to temperate depending upon the altitude, with distinct seasons of monsoon, winter and summer periods. The mean annual temperature of the area is 20^0 C with maximum and minimum temperature of 38.20^0 C and 30^0 C respectively (Gautam, 2005). The hottest months are May and June and coldest are December and January. The mean annual rainfall of the area is about 2080 mm and bulk of it occurs during in July- September which is preceded by a few premium showers and followed by short winter rainfall from December to March. The torrential rains cause substantial soil erosion in the area.

Frosts are common on winter night. Sever frosts occur in January and February which causes damage to young Sal regeneration.

3.7. Vegetation

The heterogeneous landscape of the study area is supported by variety of forest vegetation types occurring in different altitudinal zones. Sal (*Shorea robusta*) is the characteristic tree species. The whole study area is interspersed by a number of small patches of rural settlements, agricultural fields, grasslands and orchards. Open/ scrubs are mostly occurring on the surroundings of the settlements, steep and precipitous slopes and poor sites, mostly affected by high degree of biotic interference.

According to the classification by Champion and Seth (1968), three subtypes of Sal forests have been recognized:

- Moist Siwalik Sal Forests (3C/C2a)
- Moist Bhabar Dun Sal Forests (3C/C2b(i))
- Dry Siwalik Sal Forests (5B/CIa)

The Sal forests of this study area is predominantly belongs to 3C/C2a subtypes, followed by 3C/C2b(i) and few patches of Dry Siwalik forests on the higher slopes and ridges in the south-western aspects. Sal of 5B/CIa subtypes is usually stunted due to very poor moisture receptivity and the ground flora consists of thorny bushes of ‘karaunda’ (*Carissa opaca*) and ‘kathber’ (*Zizyphus glaberrima*) The quality of Sal is usually poor and is generally III/IV quality. The Sal in other two subtypes is usually II/III quality and forming nearly pure stands. Its typical associates are *Terminalia alata, Anogeissus latifolia.* Other important associates are *Haldina cordifolia, Kydia calycina, Lannea coromandelica, Syzygium cumini, Terminalia bellerica.* The underwood is usually light and consists of *Mallotus phillippinensis, Cassia fistula, Ehretia laevis, Bauhinia variegata, Ougeinia oojeinensis, etc.*

The undergrowths in various proportions are *Murraya koenigii, Clerodendron viscosum, Adhatoda vasica, Woodfordia fruticosa, Milletia auriculata, Bauhinia vahlii etc.* The common grasses are *Eulaiopsis binata, Imperata cylinderica, Chrysopogon fulvus* etc (Bharati, 1999). The study area is also heavily infested by undergrowth of *Lantana camara, Cassia tora,* and *Ageratum conizoides* in degraded sites of Sal forests (Figure.3.3).

Besides Sal forests, the Thano forest range is also comprised other types of forests, namely Northern dry deciduous, Dry deciduous scrubs, Khair- sissoo, and subtropical pine forests occurring in different altitude zone, aspects and slopes of the study area. The Khair- Sissoo is the riverine forests of the area, occupying along the riversides in patches.

3.8. Other features

Sal forests are unique with respect to their economic, biodiversity and ecological values. These forests have been suffering heavily from biotic pressure for lopping, grazing, fuel-wood, timber and extraction of minor forest produce like oleoresin, locally known as 'Ral', used in paints and varnishes and as incenses in religious ceremonies, fat from Sal seeds used for soap manufacture, leaves for fodder and bedding material in cattle shelters and ultimately organic manure for agriculture.

The Sal heartwood borer, *Hoplocerambyx spinicornis* (Coleoptera: Cerambycidae) is most injurious pest affecting Sal forests, its larvae girdling and forming large tunnels in heartwood and killing trees. The damage assessment carried out by Pant *et al*. (2002) has shown considerable increase in pest population from 1990 onwards. The recent epidemic of borer attack occurred in 1998. The infested trees are regularly felled by the forest department for keeping pest population under manageable level and in some places teak (*Tectona grandis*) plantations have been raised within opening of Sal forests. These teak plantations are responsible for further soil degradation and decrease in quality of forests in terms of biodiversity due to poor undergrowth. The infestation of weed, particularly *Lantana camara, Adhatoda vasica, Cassia tora* are spreading at faster rate in degraded open Sal forests, causing inhibition of natural Sal regeneration Thus Sal forests of study are more prone to degradation due to both biotic interference and pest infestations (Nayan, 2005).

The various kinds of anthropogenic pressures and its impact on species composition and forest density are depicted in figure 3.3.

Undergrowth-overexploitation

Agriculture

Weed infestation

Lopping

Grazing and removal of trees

Soil erosion

Figure 3.3 Anthropogenic pressures and its impact on forests.

4. Materials and methods

4.1. Materials

4.1.1. Satellite data

The detail of satellite data used in the present study are furnished below

Sr.no.	Data	Path /row	Date of acquisition	Spatial resolution (m)	Swath(km)
1	IRS-P6 LISS_III	96/49	21.3.2008	23.5	141
2	LANDSAT ETM+	146/39	25. 11.2008	30	185
3	ASTER DEM		2009	30	

4.1.2. Ancillary data

- Survey of India (SOI) topographic sheets (No 53J/3, J/4, J/7, and J/8) on 1:50,000 scales.
- Forest management plan along with digital maps of boundary, compartment & block and historical data of the study area available with State Forest Department, Uttarakhand.

4.1.3. Instruments

The details of instruments used during the field work are given in the table given below

Table 4.1 Details of instruments used in collection of field data

Sl. no	Instruments	Purpose
1	Garmin GPS 12 Channel	Geospatial location of sample plots
2	Hypsometer	Measurement of tree height and slope of sample plots.
3	Magnetic compass	Aspect of field sample plots.
4	Caliper	Measurement of diameter of shrubs in sample plots
5	Measuring tapes	Laying sample plots and other distance measurements.
6	Metallic tapes	Measurements of Dbh of trees in sample plots. Measurements of depth of Soil profile in soil samples
7	Electronic balance	Fresh weight of tillers of shrubs, herbs, litter and Humus collected from sample plots
8	Sample collecting bags, Field knife and marking pen	Collection of vegetation, litter, humus and soil samples
9	Digging equipments	Digging pits for soil samples
10	Munsell soil color chart	Determination of colour of soil profile in soil samples.
11	Digital camera	Photographs of study area on various locations.
12	Field-books and Performa	Recording field measurements and observations.

4.1.4. Software

The following softwares were used for satellite database creation, image processing, geospatial and GIS analysis

- ERDAS Imagine 9.0 for image analysis.
- ArcGIS 9.2 and ArcView 3.2a for database creation and geospatial analysis.
- FCD mapper for forest canopy density classes analysis.
- Microsoft Excel for field and laboratory data analysis.
- Microsoft- Word 2003 and MS- Power Points for report preparation and presentations.

4.1.5. Chemicals

Potassium dichromate solution ($K_2Cr_2O_7$), concentrated sulphuric acid ($H2SO_4$), ferrous ammonium sulphate ($FeSO_4.(NH_4)2SO_4.6H_2O$), diphenylamine indicator, sodium fluride, distilled water were used in the Soil laboratory of IIRS for analysis of soil to determine soil organic carbon in soil samples.

4.2. Methods

4.2.1. Research approach

The research approach (conceptual framework) was used as guidance all along the completion of this study. An extensive literature review was conducted on soil and vegetation carbon with respect to forest degradation, deforestation, Land-use changes, methodology of biomass and carbon estimation, role of remote sensing in biomass and carbon mapping, basic concepts on various factors governing C- sequestration in soil and vegetation etc. The research work can be divided into three phases, pre-field work, field work and post field work. The pre-field work included preprocessing of satellite data, visual interpretation for generating forest density map, type map and homogeneity map. The field work was related with sampling inventory for all component of above ground biomass, and soil samples homogenous strata-wise. The post field work comprised of laboratory analysis for estimating soil organic carbon, processing field and laboratory data, spectral reflectance analysis for developing relationship with biomass and carbon.

The research steps showing the estimation of carbon and its relation with biomass and spectral reflectance (NDVI) are given in Figure 4.1.

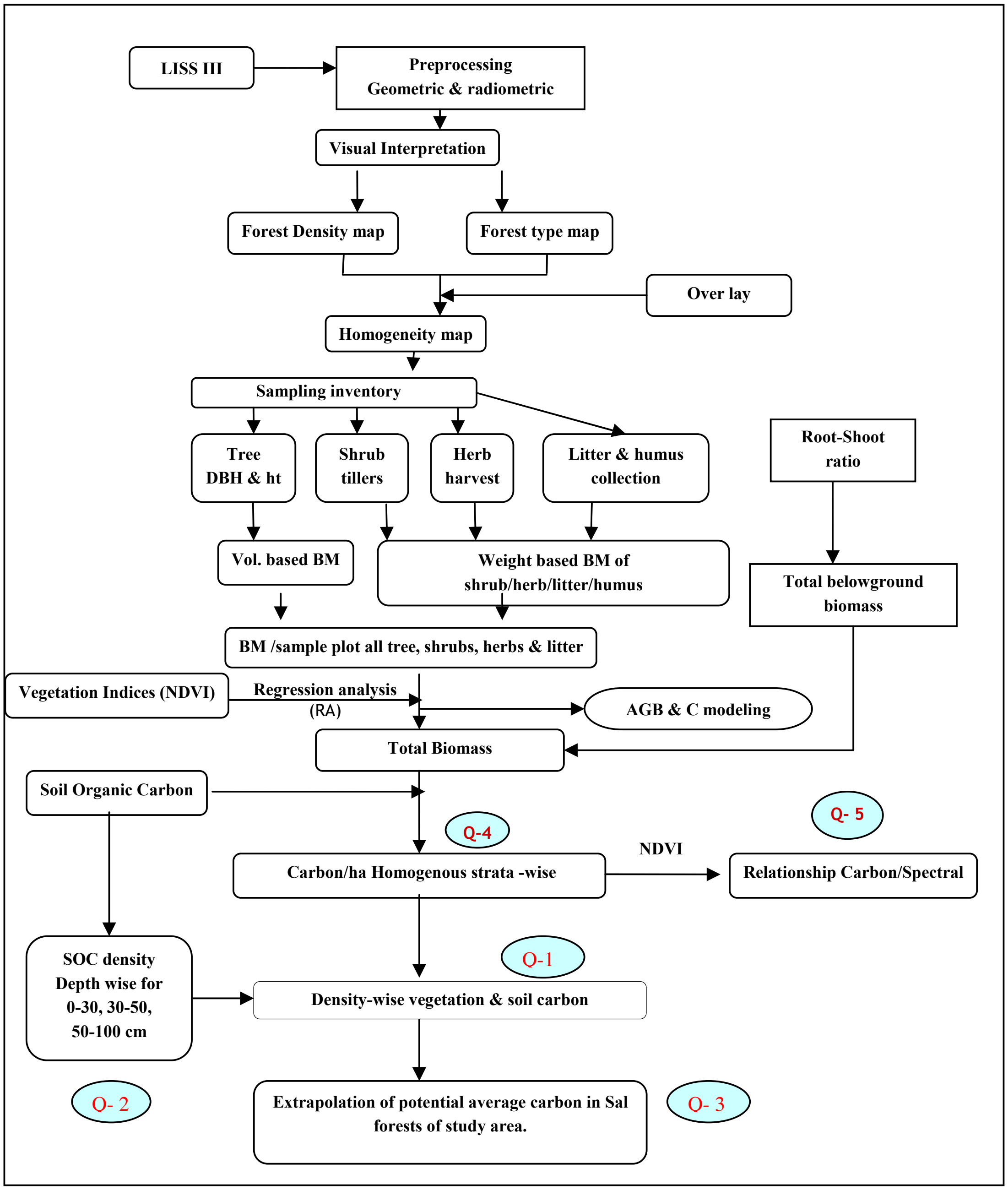


Figure 4.1 Research approach steps

4.2.2. Pre-field work

Research project planning was carried out after literature survey and collection of ancillary data. Following this, the satellite images of LISS III, LANDSAT ETM+ ASTER data of the study area were obtained from the digital library of IIRS. Raw images were rendered to geometric and radiometric corrections.

4.2.2.1. Geometric and radiometric corrections

Image to image registration was carried out using orthorectified geotiff image of Landsat ETM+ as a master image. Well distributed ground points were chosen throughout the imagery and re-sampling of the image was done using first order polynomials and nearest neighbourhood algorithm in ERADAS Imagine software. Image registration was carried out with UTM 44 N projection, WGS 84 spheroid and WGS 84 datum. Radiometric and contrast corrections was applied for radiometric defects and for improving visual impact of false colour composites (FCC). After geometric and radiometric corrections and image to image co-registration, the area of interest (AOI) i.e. Thano forest range was extracted by overlaying the shape file of boundary of study area obtained from state forest department, Uttarakhand, Dehradun.

4.2.2.2. Preliminary Interpretation

Preliminary interpretation of LISS III satellite image for forest and non-forests and other land-use/ land cover map of the study area has been done both by visual interpretation method. Standard methodology using image elements such as tone, texture, shape, association, etc were used for visual interpretation in Arc View 3.2a. Re-Reconnaissance field visits were conducted to collect information about land cover/ land use in the area. The Sal forests and dominated Sal forests were delineated from the extracted map of forests/nonforests in Arc GIS. The Sal forests and Sal dominated forests having more than 70% dominance of Sal species were considered for the purpose of this study. The further study was confined to delineated Sal forests and Sal dominated forests. These forests were classified into four subtypes based on the basis of terrain and relative dominance of the composition of species as shown in Table 4.2.

Table 4.2 Sal forests and dominated Sal forests (SDF) subtypes

Sl. no	Sub-types	Relative dominance of tree species	Terrain
1	Hill_Sal	Sal >80%, others < 20%	Hilly, usually slope $>5^0$
2	Pure_Sal	Sal >80%, others < 20%	Flat, or gentle/moderate slope $< 5^0$
3	Sal_Teak	Sal>50%, others<15%, Teak >35%	Flat, or gentle/moderate slope $< 5^0$
4	Sal_Mixed	Sal > 60%, others < 40%	Flat, or gentle/moderate slope $< 5^0$

The sub-types classes of SDF were delineated from SDF maps through ground truth verification. Based on visual interpretation and field reconnaissance, the following classification scheme for Sal forest density mapping was considered for the purpose of this study (table 4.3). The photographs at figure 4.2 depict the canopy density classes as mentioned below in the table.

Table 4.3 Classification scheme for canopy density classes of SDF subtypes.

Sl. no	Canopy density class	% age of canopy density
1	Very dense forests	> 80 %
2	Dense forests	60-80 %
3	Average dense forests	40-60 %
4	Poor dense forests	10- 40 %

Forest Cover density (FCD) mapper (semi-expert system), which computes remote sensing reflectance values of vegetation, bare soil, thermal and shadow indices was used to classify canopy density using Landsat ETM+ images in percentage for each pixel. Since FCD only support BSQ, BIL, Bitmap(BMP) format., all seven bands of Landsat images were converted to BMP format and were used in FCD mapper. The LISS III image was not used as it was not compatible with FCD mapper due to lack of thermal band. The FCD map was generated at 10% class interval of canopy density which was merged into 20% class interval for better interpretation as per the scheme (Table 4.2). This map was used as ancillary information in visual interpretation of LISS III image for delineation four canopy density classes of SDF (Figure 4.3).

Figure 4.2 Showing different forest density classes

4.2.2.3. SDF types, density and homogenous strata mapping

Different SDF types were visited for ground truth collection and verification. The LISS III image was on screen visually interpreted to classify SDF types and its density. The interim maps were field verified and corrections, wherever necessary, were made. Different strata of types and density were finally delineated using image elements, base map of canopy density prepared through model of FCD mapper and ground truth. After that, all the concerned attributes were assigned to each cover class in ArcView. The final SDF types map and forest density map were overlaid in GIS domain to generate SDF homogenous type & density strata map (homogeneity map), followed by merging of insignificant strata class in terms of pixel value into adjacent strata. The homogenous type and density map with 12 strata was generated. The concerned strata were given attributes, proper colours and legends and stored in GIS for further analysis. The methodology for preparation of homogenous is shown in figure 4.4.

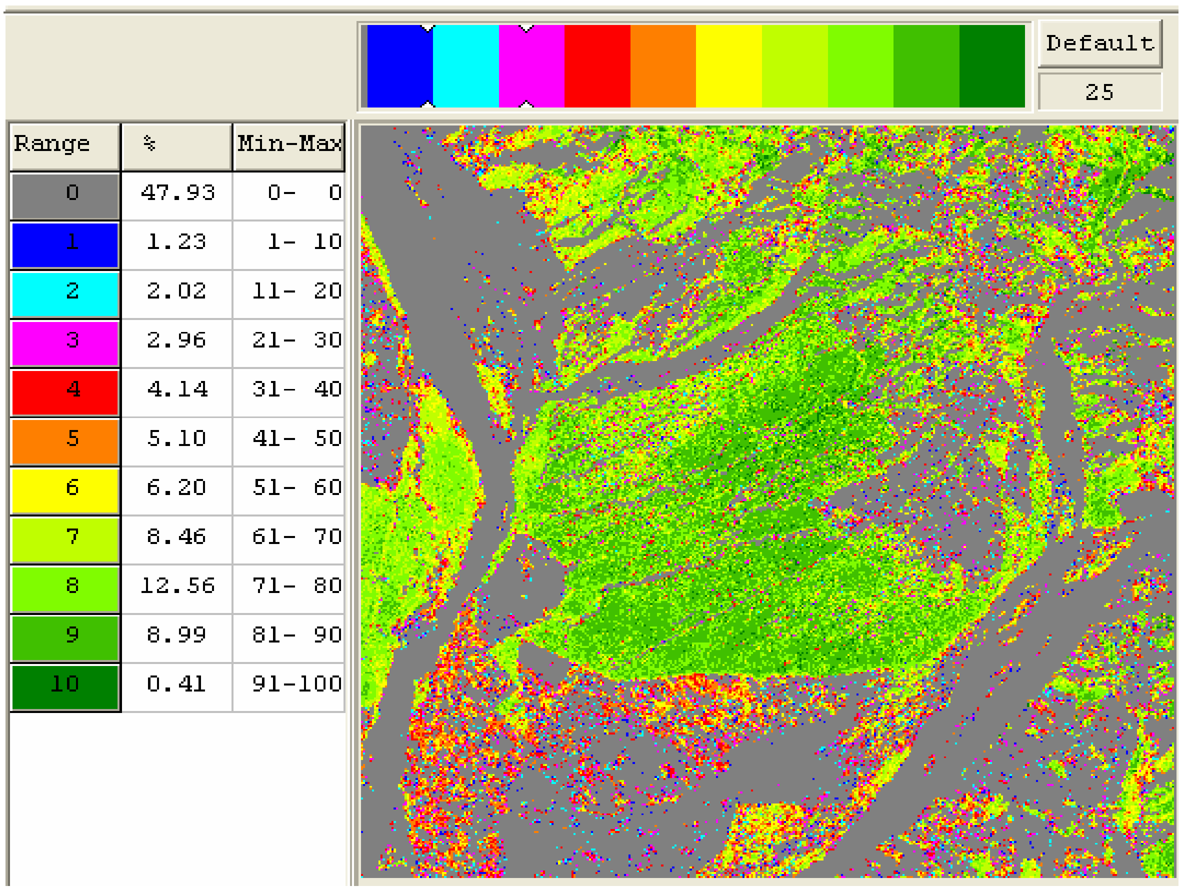


Figure 4.3 Forest density map generated by FCD cover mapper on Landsat ETM data.

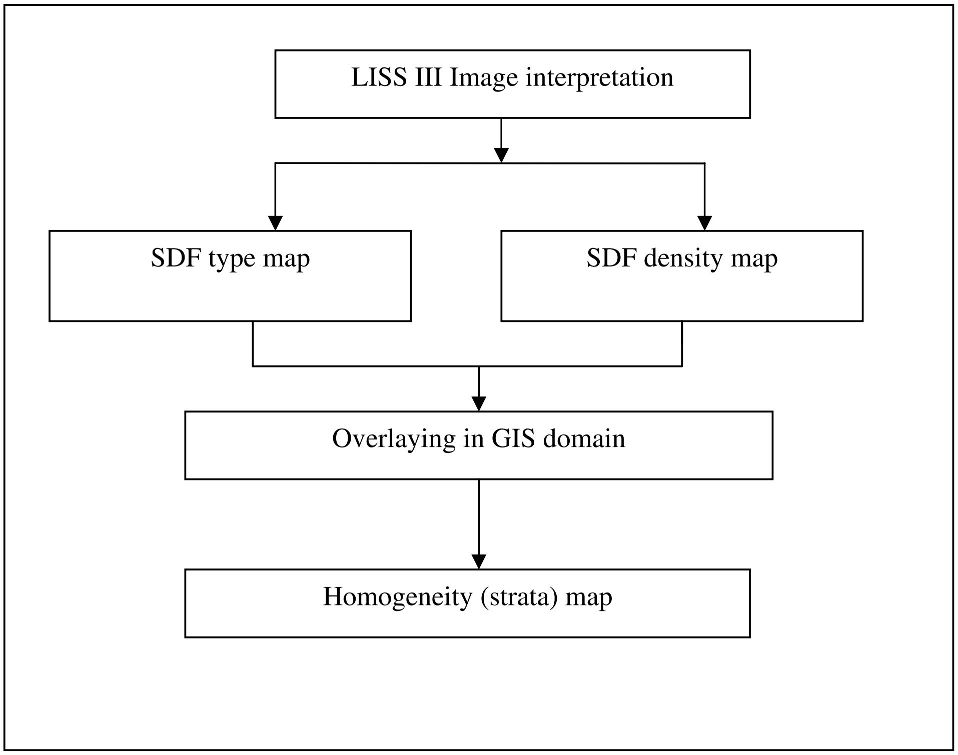


Figure 4.4 Methodology for preparation of homogenous strata

4.2.2.4. Sampling design

The precision in the sample estimation does not only depend on sample size, but also on the variability in the population. In order to reduce the variability in sample population, stratified random sampling with probability proportion to size (PPS) to the homogenous strata was adopted for sampling design (Husch, *et el.*, 1972). In the present study, it was envisaged to do sampling of 0.01% of the area, keeping in view of variability of population, accessibility, limited time frame and extend of task sampling. This sampling strategy resulted into laying out of 60 plots randomly PPS distributed in different homogenous strata depending on the accessibility of location. The location of sample plots is shown in figure 4.5 and number of sample plots laid in each stratum is given in table 4.4. Out of these, forty sample plots selected on the basis of stratified random sampling were used for estimation of biomass / carbon and developing spectral models. Fifteen plots are used for validation the results. Five plots were not found suitable for developing model and validation and therefore rejected for all purposes.

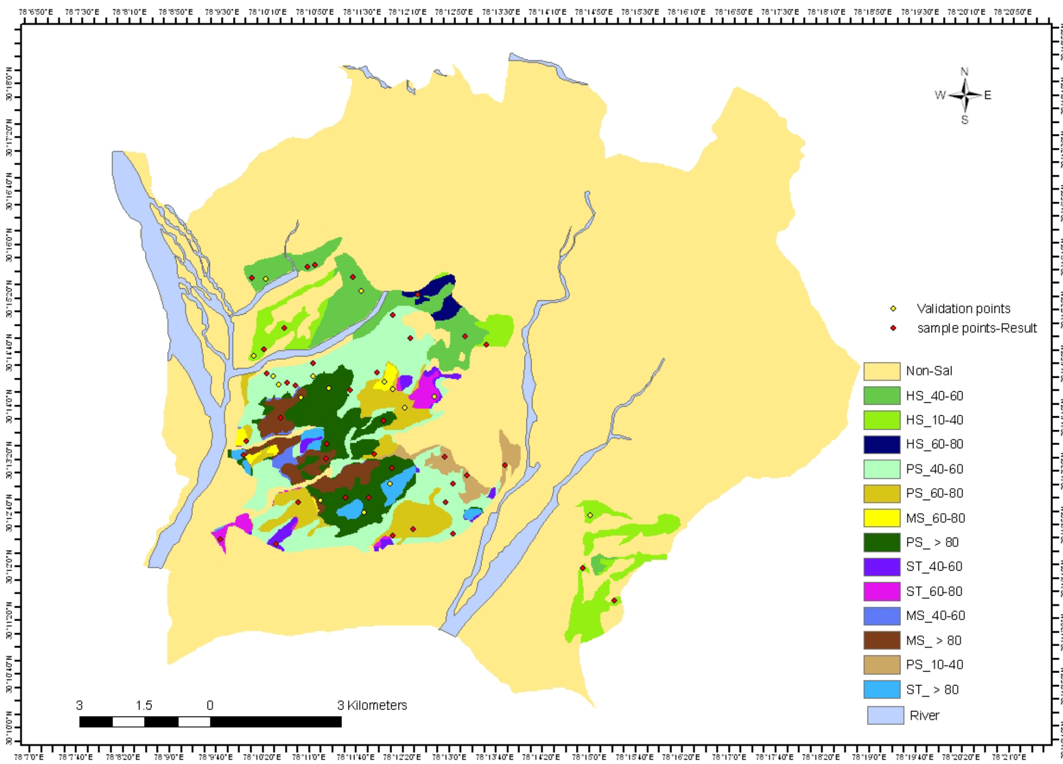


Figure 4.5 Showing location of sample plots on homogeneity map

4.2.3. Field- work

4.2.3.1. Dimensions of Sample plots

The layout of all sample plots for both vegetation and soil data collections were taken as circular in shape. The circular plot of 12.62 m in radius (500 m^2 in size) was taken for tree inventory. Sample plot of 2.52 m in radius (20m^2 in size) for shrubs inventory and 0.5 m in radius (0.80 mt^2 in size) for herbs, litter and humus were taken. The plots for shrubs, herbs, litter and humus were taken within plot of tree inventory. The standard conversion factor for slope was applied, wherever is required.

Table 4.4 Numbers of sample plots laid in each homogenous stratum

Sl.no	Stratum-name	Stratum code	Stratum area (ha)	Sample-numbers
1	Pure_Sal (10-40%)	PS_10-40	106.86	4
2	Pure_Sal (40-60%)	PS_40-60	833.68	16
3	Pure_Sal (60-80%)	PS_60-80	334.77	6
4	Pure_Sal (> 80%)	PS_ > 80	448.10	8
5	Hill_Sal (10-40%)	HS_10-40	391.16	7
6	Hill_Sal (40-60%)	HS_40-60	445.06	8
7	Hill_Sal (60-80%)	HS_60-80	51.74	1
8	Sal_Teak (40-60%)	ST_40-60	60.14	1
9	Sal_Teak (60-80%)	ST_60-80	70.74	2
10	Sal_Teak (> 80%)	ST_ > 80	88.08	2
11	Sal_Mixed (60-80%)	MS_60-80	61.91	2
12	Sal_Mixed (> 80%)	MS_ > 80	183.73	3

Shrubs were considered those plants who attain a maximum height of about 3(-5) mt at maturity. The shrubs inventory also included seedlings and saplings of tree plants. The plants with 3 to 10 cm circumference were treated as saplings and below 3 cm were taken as seedlings.

4.2.3.2. Sampling procedure

4.2.3.2.1 Vegetation sampling

GPS in conjunction with topo map was used to locate the site of various samples on the ground randomly. The circular plots of 12.62 m in radius were laid with help of measuring tapes for tree inventory. The circumference at height of 1.37 m and height of all trees in the plot were measured with help of tapes and hypsometer respectively. The circular plot of 2.5 m in radius was laid for shrubs inventory. The number of bushes, saplings and seedling species-wise were counted. The number of tillers of average girth class of thick, medium and thin as prescribed in detail in the proforma (Appendix-A) were counted for representative bushes of each species. The diameter at 30 cm from base of the tillers with help of caliper, height and fresh weight of representative tillers of each category species-wise were taken in the field. For herbaceous layer, harvesting of the plant material of plot in 0.5 m in radius laid within tree sample plot was taken. Similarly, the litter and humus were also collected in polythene bag from the same plot. The fresh weight of harvested herbs, litter and humus were taken with help of electronic balance in the field. The additional information on crown density, slope, aspect, storey layers, and accessory information related with evidence of disturbances, level and kind of biotic interference, forest working management system etc. were also recorded. The details of field data collected for vegetation sampling is given at Appendix- A. Some photographs of field data collection are given in figure 4.6.

4.2.3.2.2 Soil sampling

Soil samples were taken randomly within tree inventory plot. For this purpose, the pit was dug 1 m in depth and soil samples (approximately 500 gm) were collected for each soil profile in polythene bag. The depth, colour with help of Munsell soil colour chart, and coarse fragments using visual estimation were recorded for each soil profile. Since high deposition of litter and humus and high biological activity occurring in the top layer of forest soil, likely to have more variability in organic carbon, two additional soil samples were collected from top soil profile by digging separate pit within the same tree inventory plot. A clod of soil sample of medium size (3-5 cm in diameter) from each profile was collected for estimation of bulk density estimation. The detail field data were recorded as prescribed shown in the performa (Appendix-A). The general guidelines for collecting soil sample given in the Project Manual – spatial assessment of soil carbon pool of India, IIRS, Dehradun (Anonymous, 2009) were followed.

Data collection on trees

Readings for tree height

Measurement of slope

Collection of herb sampling

Data collection on shrubs

Soil data collection

Figure 4.6 Photographs showing field data collection

4.2.4. Post field-work

4.2.4.1. Organization of field database

The entire field database was organized in Microsoft excel for processing of biomass and carbon estimation in above ground vegetation and soil. The necessary parameter like volume equations, specific gravity, conversion factors etc. were added in database for further processing. The detail processing of database is explained in the respective para of biomass estimation and soil organic carbon estimation.

4.2.4.2. Above ground biomass (AGB) estimation

The above ground biomass for different components e.g. trees, shrubs, herbs, litter and humus was calculated for each plot-wise.

4.2.4.2.1 Tree biomass estimation

The biomass regression equations for total above ground biomass (AGB) developed by Negi (1984) for Sal trees were used. Since such regression equations were not available for other tree species of study area and therefore, volumetric equations developed and compiled by FSI (1996) were used in case of other tree species which considers volume of the individual trees for Dbh >10 cm. Tree volume was multiplied by respective specific gravity as given in appendix and followed by multiplying with expansion ratio (Cannell, 1982) to obtain total AGB. The various parameter as required by different volumetric equations like Dbh, radius, radius^2, sqrt of volume, log diameter^2 * height, etc. were calculated. These volumetric equations are developed for trees having girth > 30 cm and not applicable for trees having girth 30 cm and less than 30 cm. The estimation of biomass for trees >3 to $\leq$ 10 cm diameter has been calculated by relating of basal area and biomass of trees in each plot as per step given below (Dadhwal et *al*., 2009).

- biomass of all trees having dia > 10 cm dia of each plot (500 m^2) was estimated by using biomass equation for Sal trees and volumetric equation, specific gravity and expansion ratio (ER) for rest of trees.
- Correlation between biomass (t/ha) and basal area (m^2) of >10 cm dia was established for each plot and coefficient generated for further processing (Figure 4.7).
- The plot-wise regression coefficient thus obtained above was applied on data with basal area of all trees and basal area with Dbh > 10 cm trees to obtain biomass for all trees and biomass of trees having Dbh <10 cm separately. The linear model is as follows.

$$\mathbf{Y = \alpha + \beta * x}$$

where, Y= biomass(t/ha), α and β are coefficient , X= basal area of trees.

- After getting biomass of all trees and biomass of trees having Dbh > 10 cm separately, the biomass of trees with ≤ 10 dia was obtained by subtracting biomass of all trees from biomass having trees with >10 cm dia.
- The biomass of trees of ≤ 10 dia was added with biomass of trees >10cm dia obtained using biomass equation for Sal trees and volumetric equations used for other species trees. This process enabled to get the total AGB of the plot, including trees having ≤ 10 dia. Class.

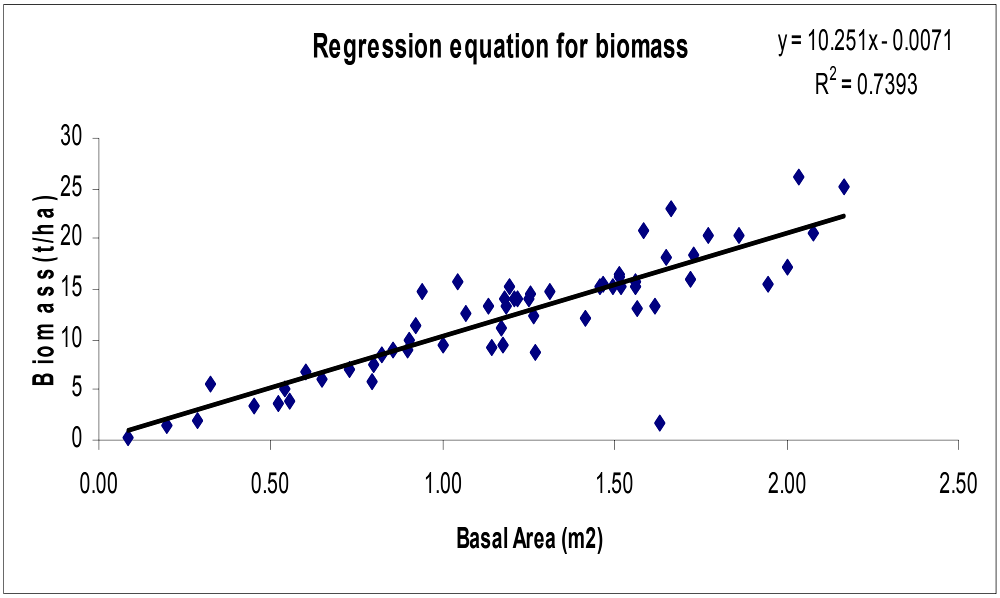


Figure 4.7 Regression analysis between biomass and basal area.

4.2.4.2.2 Shrub biomass estimation

Shrubs are considered those plants usually not exceeding 3 m in height with woody stem. The number tillers of the shrubs were enumerated as thick, medium and thin. The sample tiller of shrubs each collected from the field were kept separately inside oven at 75^0 C till constant dry weight. This was done in order to obtain dry weight of the tillers. The average dry weight of each girth class of tillers was multiplied with respective number of tillers in each girth class of bush of the species. The dry weight of all girth classes of tillers of bushes were added to obtain biomass of bush of the each species which was multiplied with respective number of bushes of the species in the plot. The sum of dry wt of all bushes was taken the biomass of shrub layer per plot. The detail procedure of calculating biomass of shrub layer is given in Fig 4.8.

4.2.4.2.3 Herbs, litter and humus biomass estimation

Herbs are taken those plants usually not exceeding 1 m in height with soft stem. Litter is the undecomposed organic matter (leaves, twigs, branches etc.) on ground bed and distinguishable from humus which is considered the decomposed organic matter (FSI, 2000).

The sample of herbs, litter and humus collected from the field were kept separately inside oven at 75^0 C till constant weight. The dry weight of samples were converted into t / tree plot (500 m^2) and then, t/ha strata-wise.

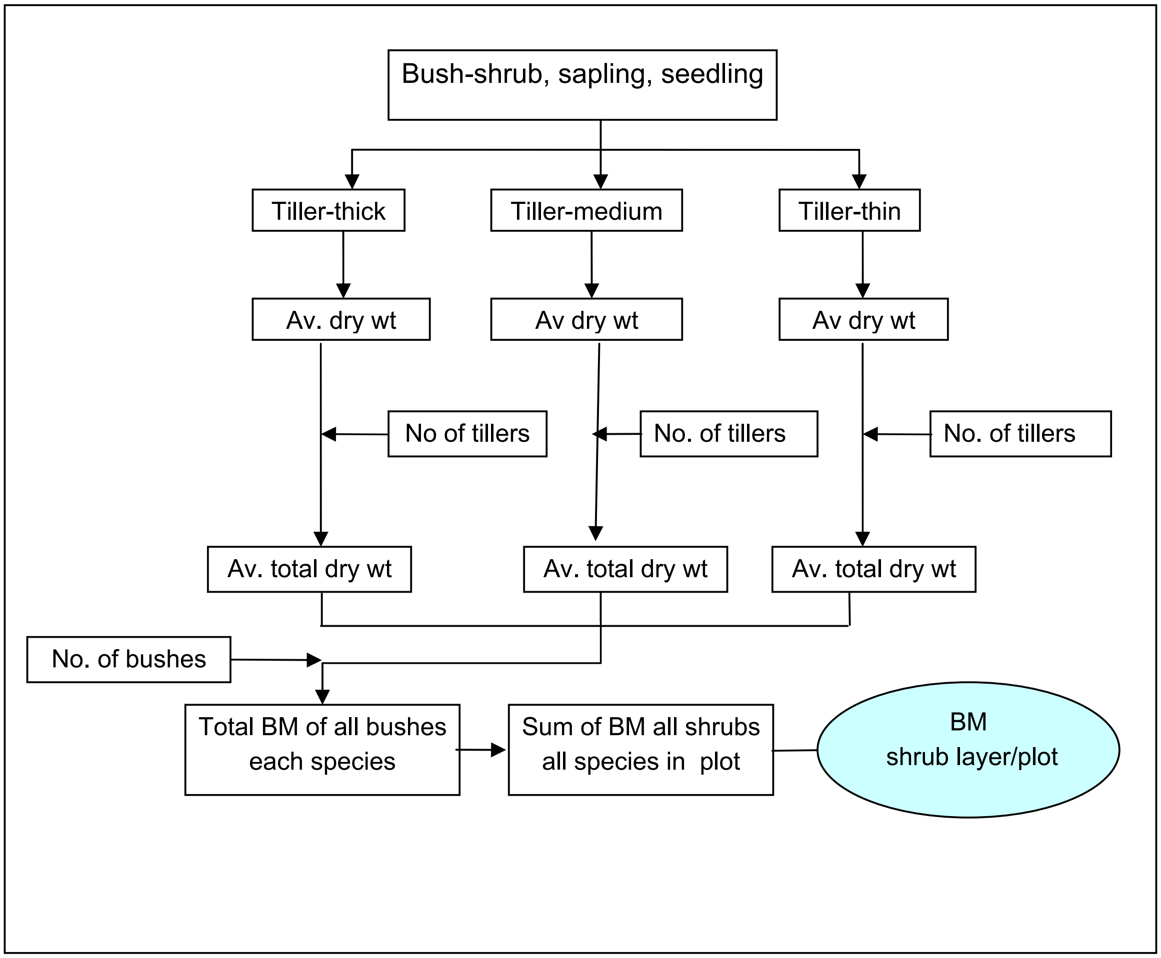


Figure 4.8 Procedure steps for estimation of biomass (BM) of Shrubs

4.2.4.2.4 Total above ground biomass (AGB)

The sum of tree, shrubs, herbs, litter and humus layer biomass (t/ha) were taken as total AGB of the plot and strata-wise.

4.2.4.3. Below ground biomass (BGB)

The BGB of trees was determined by indirect method using root/shoot ratio available from existing studies. The R/S ratio of 0.30 for Sal trees (Negi, 1984) and 0.26 for other trees (Cairns et al., 1997) were used.

4.2.4.4. Vegetation carbon estimation

The multiplication of biomass with the conversion factor of 0.47 represents the average carbon content in biomass (Westlake, 1963). The above ground carbon (AGC) and below ground carbon (BGC) for each substrata class was calculated by multiplication of conversion factor with concerned AGB and BGB of the substrata class. A carbon map was also generated to show total biomass carbon (t/ha) in each homogenous forest strata.

4.2.4.5. Soil organic carbon estimation

Soil organic carbon was estimated by using Rapid Titration method (Walkley and Black, 1934). Samples were oxidized with mixture of potassium dichromate in presence of concentrated sulphuric acid, utilizing the heat of dilution of sulphuric acid. The samples were allowed to cool for minimum 30 minutes. The unused potassium dichromate not reduced by organic carbon was titrated back against standard solution ferrous sulphate in presence of sodium fluoride and orthophosphoric acid as flocculating agents. Diphenylamine was used as indicator and end point of titration was recorded based on visual colour change for blue-violet to green. Subsequently, organic carbon (%) was calculated as follows:

Organic carbon (%) = (10(B-T)/B) * (0.003*100/wt of soil (gm))

where,

B=Volume of ferrous sulphate solution required for blank titration.

T = Volume of ferrous sulphate solution needed for titration of soil sample.

Since, there is incomplete oxidation of organic matter in this procedure. The organic carbon (%) was multiplied by 1.3 on the assumption that there is 77% recovery.

Bulk density was estimated by clod method, as given in Project manual-spatial assessment of soil carbon pool of India, IIRS, Dehradun (Anonymous, 2009). Soil clods collected from the field were oven dried at 105^0 C till constant weight, The final weight was taken as the mass of clod (gm); the clod was tied by a thread and dipped into melted wax (about 55^0 C) and removed immediately to have a fine coating of paraffin wax and allowed the wax coating to solidify. The volume of the clod was measured by recording the displaced amount of water by wax coated soil clod in a water filled cylinder of 500 ml capacity. The bulk density of clod without coarse fragments (CF) was calculated as follows:

Bulk density = mass of clod (gm) / volume of clod (ml).

Since, a large number of clods collected from the fields were having coarse fragments. In these cases, the clod was grinded and sieve it using 2 mm sieve, washed CF with water, oven dry it and weighed CF. Bulk density of clods contained CF was calculated by the following formula;

Bulk density = (mass of clod - mass of CF) / (volume of clod (ml)- volume of CF).

The volume of CF was obtained by dividing mass of CF by 2.65 (density of CF) .The researcher could not get clod in some of the samples, where in bulk density of the adjacent plot was taken for the purpose of calculation. Figure 4.9 shows the analysis for the above process being carried out in the laboratory.

Figure 4.9 Laboratory analysis of the soil samples.

4.2.4.5.1 Estimation of organic carbon stock

The soil organic carbon stock in a soil layer or sample level was calculated by the formula given by Batjes (1996) which is as follows:

OC (t/ha) = (OC fraction *depth- soil layer (mt)* BD * volume fraction of CF)* 10000.

The carbon stock (t/ha) for the depth of 0-30, 30-50 and 50-100 cm was calculated by the method of weighted average of carbon stock in soil layer for each strata classes.

where, OC= organic carbon, BD = bulk density.

4.2.4.6. Regression analysis and spectral modeling

The remote sensing data LISS III image and ground AGB data were used to develop correlation with biomass and spectral properties. The linear, logarithmic, exponential, and power functions were attempted to obtain best fit correlation coefficients with different values of red, infrared, NDVI and NDVI $_{3*3}$ with values of AGB/pixel of sample plots. Correlation coefficients of best fit models were used to model biomass in the study area. Similarly, regression analysis was also done with respect to SOC in order to know the relationship of AGB, SOC and spectral reflectance.

4.2.4.7. Total potential of C- sequestration estimation with respect to forest degradation

The following assumptions were considered for estimation of total potential of vegetation and soil carbon

- That the forest degradation reduces the potential of C- Sequestration.
- That C- sequestration in less in dense/degraded forests can be enhanced maximum to the capacity of highest density class of particular SDF subtypes, if the existing anthropogenic pressures are removed and provide suitable protection and management measures to the less dense /degraded forests.
- That the area lies in similar ecological conditions and therefore, forest growth would be in the same proportion in particular SDF sub types.

Based on these assumptions, the total potential of the existing Sal forests was extrapolated by taking into account of C density equivalent to 80% density class in case of Pure_Sal, Sal_Teak, Sal_mixed and 60-80% density class in case of Hill_Sal of SDF subtypes.

4.2.4.8. Validation of the model

The linear relationship between NDVI and aboveground biomass and carbon density was established and used to generate biomass and carbon density maps. 15 additional sample plots were also observed in the area to validate the observed and predicted biomass and carbon distribution in the study area. Three statistical methods have been used to assess the performance of model) namely coefficient of efficiency or model efficiency (CE), root mean square error (RMSE) and coefficient of determination (R^2) (Nash and Sutcliffe, 1970).

5. Results and discussion

5.1. Delineation of Sal forests and dominated Sal forests

The area of the Thano Range was classified into forest and non forest through visual interpretation and ground truth verification to prepare forest and non-forest map covering Sal and Sal dominated forests (SDF) (Figure 5.1). This map was used as a base map for further extraction of Sal and Sal dominated forests from the forests area of study area as well as reclassification of SDF cover subtypes mapping in ArcGIS. The rest of the forests of the study area is non-Sal belong to different types such as miscellaneous, Sissoo- Khair, and Pine forests in high altitude. The map showing Sal forests is given in Figure 5.2.

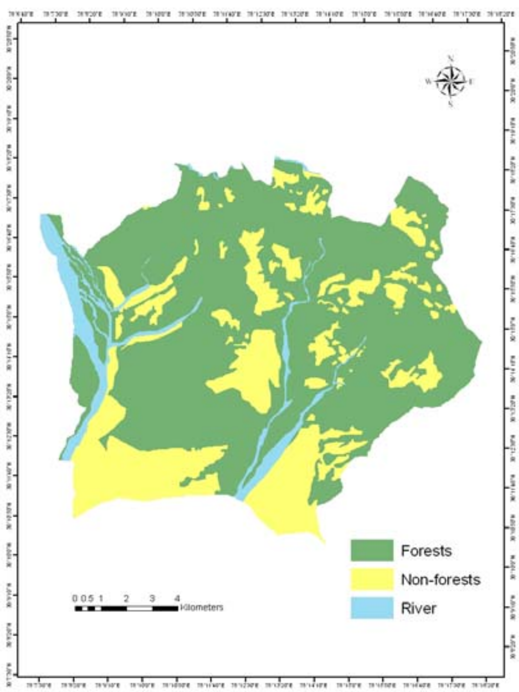


Figure 5.1 Forest and non-forest map

Figure 5.2 Sal forest map

5.2. The Sal forest and dominated Sal forest (SDF) cover subtypes mapping

The area has pure Sal formation in piedmont as well as on hills, it can be said that such forests species composition is more or less having 90% Sal trees. In areas where Sal trees have been removed due to severe attack of Sal heartwood borer (*Hoploceraymbyx spinicornis*) and degradation of these sites, Teak (*Tectona grandis*) plantations have been done by the Forest Department and therefore Sal mixed with Teak forests cover some part of the study area. In some areas, Sal is mixed with natural local forest species like *Terminalia alata, Anogeissus latifolia Haldina cordifolia, Kydia calycina, Lannea coromandelica, Syzygium cumini, Terminalia bellirica, Mallotus philippensis*. Based on species composition, its dominance and location, the Sal forests were classified into four subtypes namely, Pure_Sal (nearly pure formations), Hill_Sal (nearly pure Sal on hills), Sal_Teak (Sal mixed teak) and Sal_Mixed (Sal mixed with other species) after extensive ground truth verification and assessing accuracy with sample plots verification. The map and area of subtypes are given in Figure 5.3 and Table 5.1 respectively. The total SDF covers an area of about 3075.98 ha, out of which Pure_Sal covers maximum area (1723.41 ha) followed by Hill_Sal (887.96 ha).

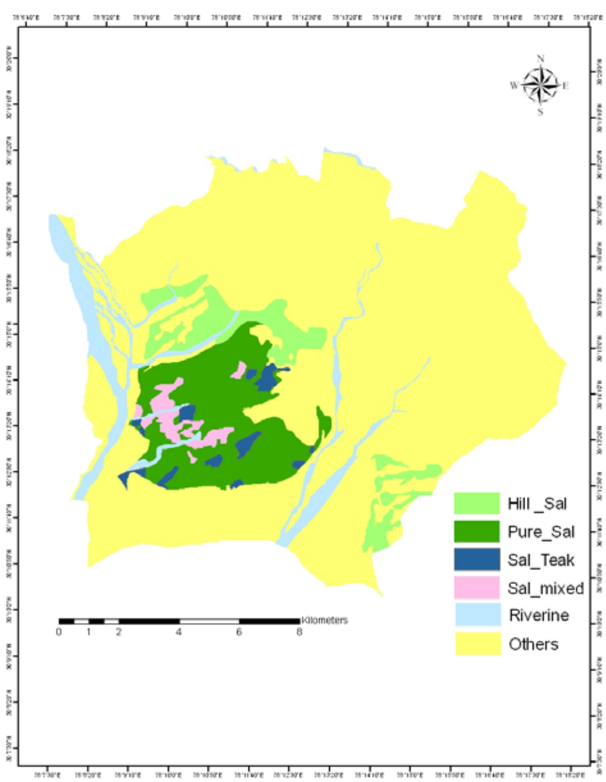


Figure 5.3 Map of Sal and Sal Dominated Forest (SDF) subtypes

Table 5.1 Area of different SDF subtypes

Sl. No.	SDF- subtype	Code	Area (ha)	Area (%)
1	Pure_Sal	PS	1723.41	56
2	Hill_Sal	HS	887.96	29
3	Sal_Teak	ST	218.97	7
4	Sal_Mixed	MS	245.64	8
		Total	3075.98	100

5.3. Forest density mapping

Sal and Sal dominated forest density map was prepared through a model of FCD mapper and visual interpretation after ground truth and from verification of density data taken in sample plots. These forests were classified into 10-40, 40-60, 60-80 and >80 % density classes. The map and area table is at Figure 5.4 and Table 5.2 respectively. The density class 40-60% covers maximum area, followed by very dense forests (>80%).

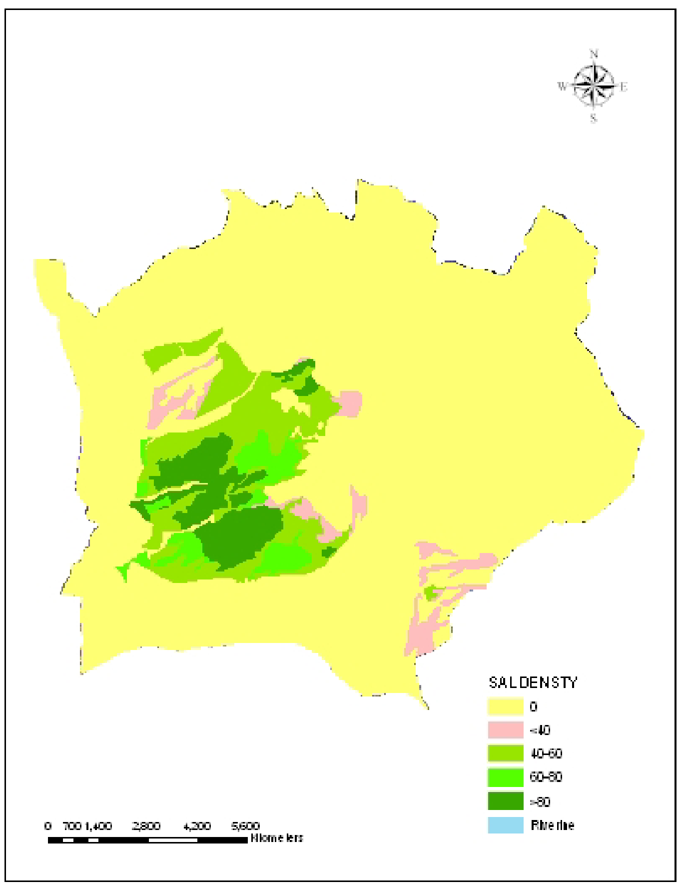


Figure 5.4 Map showing Sal forests density classes

Table 5.2 Area of different density classes

Sl. No.	Density classes (%)	Area (ha)	Area (%)
1	10-40	498.02	16.19
2	40-60	1365.11	44.38
3	60-80	492.94	16.03
4	> 80	719.91	23.4
	Total	3075.98	100

5.4. Homogeneity map

The forest homogeneity map was generated by overlaying forest type and forest density maps (Figure 5.5). The resultant map has 13 homogenous strata. The homogeneity has been described as having same forest density and type of Sal forest in each strata. Slivers with very less area were merged with neighboring classes. The most dominating classes were Pure_Sal (40-60%), followed Pure_Sal (>80%) and Hill_Sal (40-60%). The least representative classes area-wise were Sal_ Mixed (40-60%), followed by Sal_ Mixed (60-80%) and, Hill_Sal (60-80%). The area covered by each stratum is given in Table 5.3.

The sample plots were distributed and laid in all classes considering probability to proportion to size (PPS) except Sal_Mixed (40-60%), being very small area as well as inaccessibility to locate the field site, hence this class was considered for merging into the next class i.e. Sal_Mixed (60-80%) for all purpose of analysis.

From the homogeneity map, it was clear that less dense with open to medium density of forests of Pure_Sal 10-40% and Pure_Sal 40-60% are sharing borders with settlements and agriculture, while dense forests Pure_Sal >80%, Sal_Mixed >80% are in interior of forests, usually at a more distance from settlements and agriculture. It can be explained by the fact that there is more biotic pressure on bordering forests resulting to forest degradation and canopy opening in these forests. High biotic pressure for lopping was also observed in 10-40% density cover classes, being more close as well as surrounded by settlements and agriculture. The photograph of Hill_Sal 10-40% confirms this observation (Figure 5.6). Pure_Sal with 40-60% density cover maximum area (833.68 ha) followed by Pure_Sal with > 80% density (448.1 ha) and Hill_Sal with 40-60% density (445.06). The open forest of Pure_Sal and Hill_Sal occupy 106.86 ha and 391.16 ha respectively (Figure 5.7 and Table 5.3). Local people avoid cutting of Sal trees now because of strict management practices, however, there is a still tremendous pressure for lopping, minor timber and cattle grazing in the area.

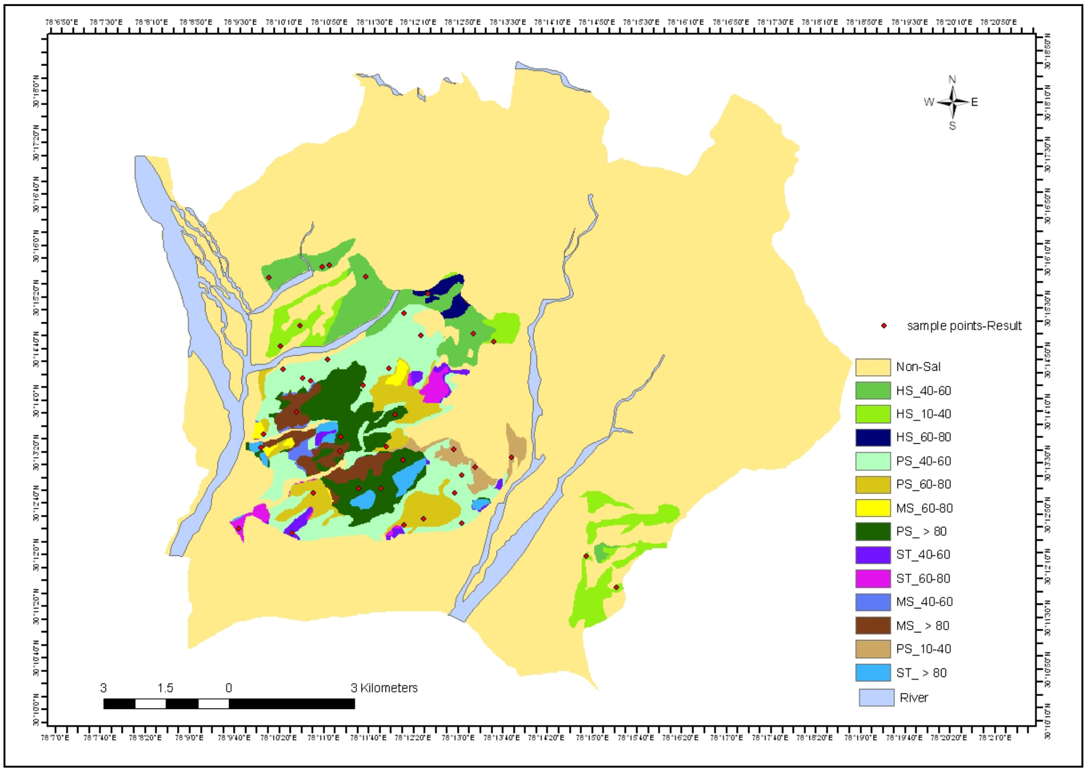


Figure 5.5 Homogeneity map showing homogenous strata.

Figure 5.6 Degraded Sal forests of Hill-Sal_10-40% density class

Table 5.3 Area (ha) of different homogenous strata

Sl. No	Forest strata	Descriptions		Area	Area
		Type	Density %	(ha)	(%)
1	Pure_Sal (10-40)	Pure_Sal	10-40	106.86	3.47
2	Pure_Sal (40-60)	Pure_Sal	40-60	833.68	27.1
3	Pure_Sal (60-80)	Pure_Sal	60-80	334.77	10.88
4	Pure_Sal (>80)	Pure_Sal	>80	448.1	14.57
5	Hill_Sal (10-40)	Hill_Sal	10-40	391.16	12.72
6	Hill_Sal (40-60)	Hill_Sal	40-60	445.06	14.47
7	Hill_Sal (60-80)	Hill_Sal	60-80	51.75	1.68
8	Sal_Teak (40-60)	Sal Teak	40-60	60.14	1.96
9	Sal_Teak (60-80)	Sal_Teak	60-80	70.74	2.3
10	Sal_Teak (>80)	Sal_Teak	>80	88.08	2.86
11	Sal_Mixed (40-60)	Sal_Mixed	40-60	26.23	0.85
12	Sal_Mixed (60-80)	Sal_Mixed	60-80	35.68	1.16
13	Sal_Mixed (>80)	Sal_Mixed	>80	183.73	5.97
			Total area	3075.98	

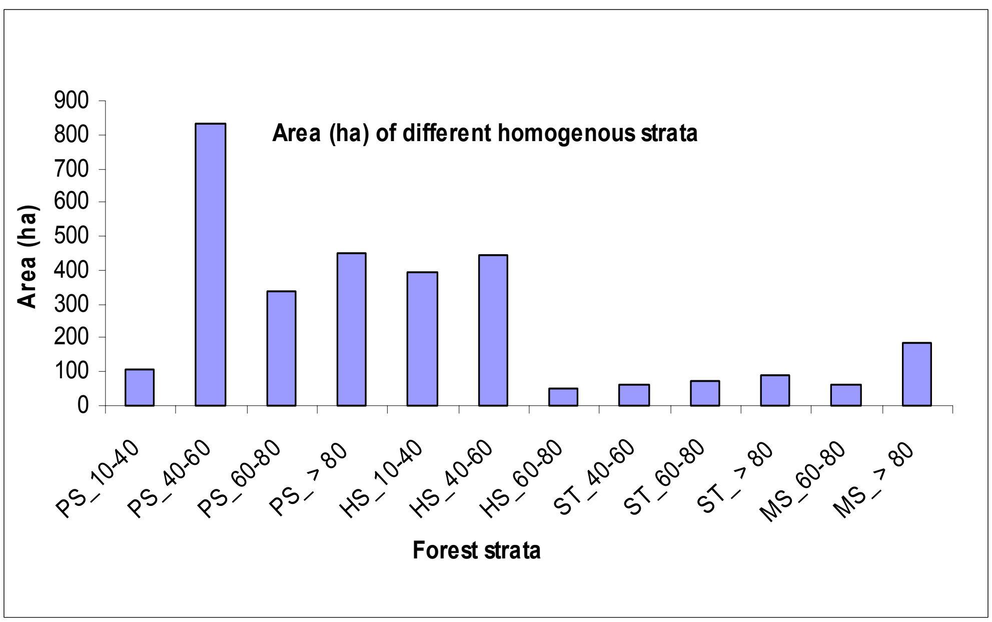


Figure 5.7 Area (ha) in different homogenous strata

5.5. Assessment of variability of biomass/carbon

5.5.1. Biomass

5.5.1.1. Above ground biomass (AGB)

5.5.1.1.1 Biomass of tree layer

As expected the major component of AGB biomass was found in tree layer and contributing almost from 97- 99 % of total above ground biomass. It is also evident that tree layer is most affected by forest degradation and thus causing opening of the canopy density and reduction in biomass. These observations are supported by the comparison of tree layer biomass of Pure_Sal of >80% density (461.33±SE 23.87) and Pure_Sal of 10-40% (138.21±SE 7.94) against the total AGB of Pure_Sal >80% (477.05±SE 22.14) and Pure_Sal of 10-40% (141.92± SE 7.57). The detail is given in Table 5.4 and 5.5. The trend of AGB in tree layer in different strata is shown in Figure 5.8. Based on the data on growing stock and total area of Sal forests in India, Lal and Singh (2003) reported 430.51 t/ha average above ground biomass of tree layer. Similar trends of estimation of Sal forests biomass was also reported by some recent studies made by Negi and Chauhan (2002), Dadhwal et al. (2006) and Srivastava (2009). The above ground biomass of Sal forests reported with density classes are 136.2 t/ha for 0-40 % class, 247.7 t/ha with 40-70% class and 351.5 t/ha with >70% class density (Dadhwal *et* al., 2006). Srivastava (2009) also reported similar results in Barkot Forest Range adjacent to the present study area.

5.5.1.1.2 Biomass in shrubby layer

The biomass of shrubby layer varied from a minimum of 1.76 t/ha in Sal_Teak (60-80%) and 1.78±SE 1.02 t/ha in PS_10-40 to maximum of 5.16±SE 1.78 t/ha in PS_Sal >80 and 4.62±SE 0.64 t/ha in PS_Sal 60-80 (Table 5.4). It has been observed that shrubs species composition in case of higher density classes of Pure_Sal, Hill_Sal and Sal_Mixed belongs to local associate species of Sal forests e.g**.** *Murraya koenigii, Clerodendron viscosum, Adhatoda vasica, Woodfordia fruticosa, Milletia auriculata, Bauhinia vahlii,* while in case of low density classes shrubs species composition has been infested or dominated by exotic weed species e.g. *Lantana camara, Cassia tora, Ageratum conizoides*. The coverage percentage of weed species in some degraded forests was found almost 80-100% especially by *Lantana camara* or in some cases by *Cassia tora* (Figure 3.3). Further the results indicates increasing trend from lower density to higher density in all subtypes except Hill_ Sal which cannot only be explained by forest degradation alone but other factors of location, type of anthropogenic pressure, invasion of weed etc. may also play important role and explanation of these factors are beyond of the scope of this study.

5.5.1.1.3 Biomass in herbaceous layer

The biomass variation in herbaceous layers was found to be 1.93± SE 0.17 t/ha in PS_10-40 followed by 1.49±SE 0.03 t/ha in HS_10-40 and almost nil in case of PS_ >80 Sal_Teak and Sal_Mixed (Table 5.4). It has been observed that usually high accumulation of litter and humus especially in higher density of Pure_Sal and Sal_ Mixed may inhibit growth of herbs while the impact of teak plantations known for its inhibitory role for herbs undergrowth is the possible cause of absence of herb layer in case of Sal_Teak subtypes.

5.5.1.1.4 Biomass in litter-humus layer

The biomass in litter-humus layer was found maximum in MS_>80 (12.09± SE 0.25 t/ha) and PS_>80 (10.56± SE 2.13 t/ha) and found almost nil/negligible in case Hill_Sal, PS_> 10-40 and ST_60-.80, ST_>80 (Table-5.4), indicating positive trend with respect to density classes in Sal forests located plain/gentle undulating slope (Pure_Sal, and Sal_Mixed). It has also been observed that accumulation of large amount of litter and humus as well as less light penetration in dense forests (Pure_Sal and Sal_Mixed) are possible factors of absence/ less amount of herbs, however, this explanation does not hold true in the case of Sal_Teak, The results indicates that the degradation caused reduction of litter and humus and at the same time showed increased trend of herbs where openings were created. The observations of field data also support higher quantity of herbs in degraded forests which was due to invasion of weeds like *Cassia tora*, Eupatorium and grasses. The absence of litter and humus even in higher density of Hill_ Sal may be attributed due to slope factor.

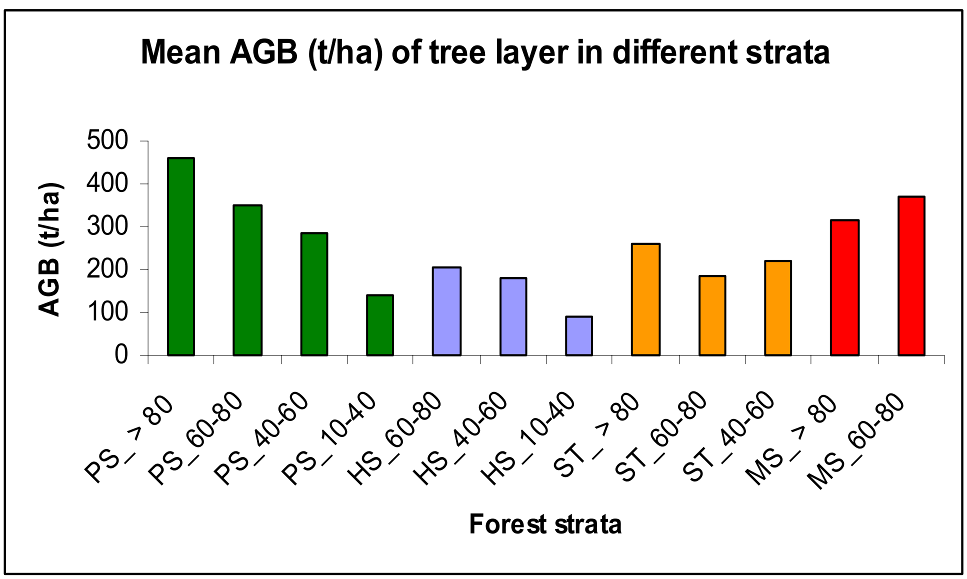


Figure 5.8 Mean AGB density (t/ha) of tree layers in different strata

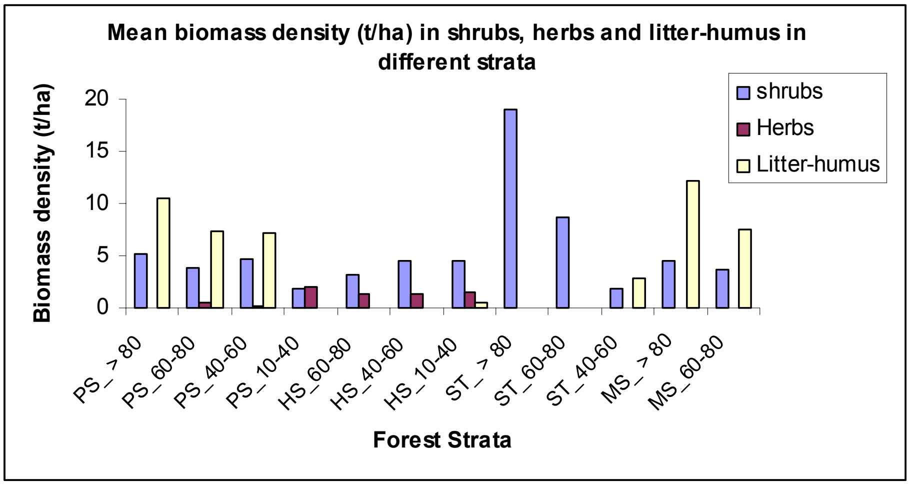


Figure 5.9 Mean AGB density (t/ha) in shrubs, herbs and litter-humus in different strata

5.5.1.1.5 Total Above ground biomass (AGB)

The AGB was assessed in trees, shrubs, herbs, litter and humus layers in each stratum. The maximum mean AGB density (t/ha) was found in PS_ >80 (477.05±SE 22.14), followed by MS_60-80 (379.21) and PS_60-80 (362.00± SE 36.52) and minimum found in HS_10-40 (95.09± SE 26.09), followed by PS_10-40 (141.92± SE 7.57) and HS_40-60 (186.18± SE 38.44) (Table 5.5). The general trend showed the depletion of AGB with decrease of forest density in each SDF type except in Sal_ Mixed type which was represented in the study area only by higher density strata. The decreasing trend of biomass was noted more pronounced in the case of Pure_Sal which is more close to settlements, indicating the depletion of total AGB with forest degradation (Figure 5.10). Similar trend in AGB density was also noted in the tree layer (Figure 5.8). However, biomass variations in shrubs, herbs, litter and humus layer indicates different trends in different strata (Figure 5.9).

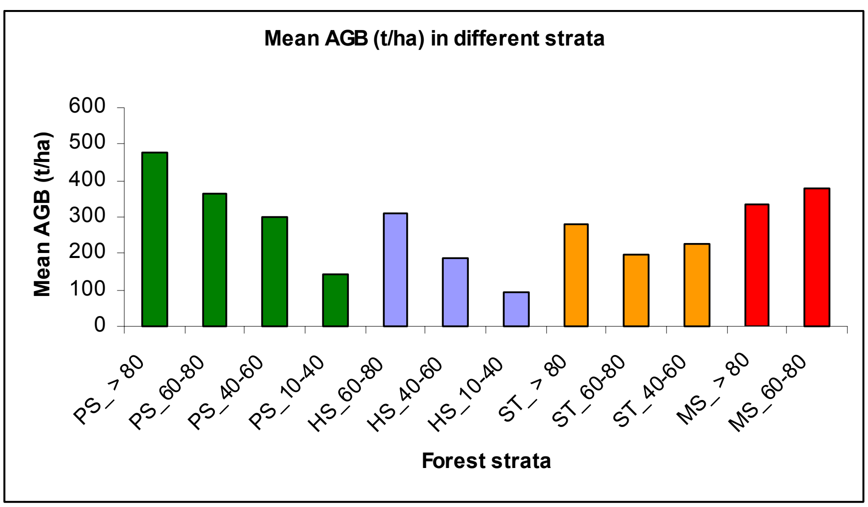


Figure 5.10 Total (mean) AGB density (t/ha) in different strata

Table 5.4 AGB (t/ha) in different layers in each homogenous stratum

Sl.no	Forest strata	BM- tree layer	BM -Shrubs layer	BM- herbs layers	BM-(litter-humus)
1	PS_10-40	138.21±SE 7.94	1.78±SE 1.02	1.93± SE 0.17	0.00
2	PS_40-60	287.22±SE 14.13	4.62±SE 0.64	0.22±SE 0.13	7.10± SE 1.18
3	PS_60-80	350.20±SE 35.94	3.89±SE 1.24	0.51± SE 0.2	7.40± SE 2.01
4	PS_ > 80	461.33±SE 23.87	5.16±SE 1.78	0	10.56± SE 2.13
5	HS_10-40	88.68±SE 27.51	4.44±SE 1.85	1.49±SE 0.03	0.48± SE 0.48
6	HS_40-60	180.38±SE 38.70	4.52±SE 1.20	1.27±SE 0.01	0.00
7	HS_60-80*	204.00	3.19	1.40	0.00
8	ST_40-60*	221.77	1.76	0	2.80
9	ST_60-80*	186.50	8.68	0	0.00
10	ST_ > 80*	261.97	19.04	0	0.00
11	MS_60-80*	367.95	3.69	0	7.57
12	MS_ > 80	315.97± SE 5.66	4.49± SE 1.76	0	12.09± SE 0.25

(*SE= Standard Error. *SE not shown for single plot observation*)

5.5.1.2. Below ground biomass (BGB)

The BGB was assessed by considering the root/shoot ratio for tree layer (Negi, 1984) and therefore the trend of BGB density is almost similar with tree layer of AGB (Figure 5.11). No estimates for shrubs and herbs layer for BGB were made due to non-availability of root/shoot ratio. The maximum BGB recorded 137.11±SE 6.57 t/ha for PS_ > 80 followed by 94.97±SE 0.71 t/ha in MS_>80 and minimum 26.23±SE 8.17 t/ha in HS_10-40 followed by 41.46±SE 2.38 t/ha in PS_10-40 (Table 5.5).

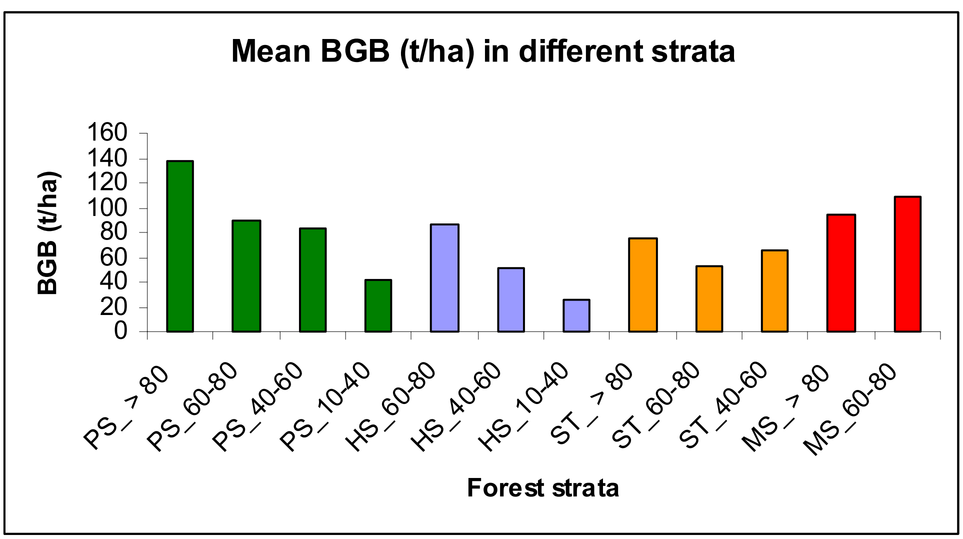


Figure 5.11 Mean BGB density (t/ha) in different strata

Table 5.5 AGB, BGB and total biomass (t/ha) in different strata

Sl.no	Forest strata	AGB	BGB	BM-total
1	PS_10-40	141.92± SE 7.57	41.46± SE 2.38	183.38± SE 9.95
2	PS_40-60	299.17± SE 14.63	82.46± SE 4.92	381.63± SE 18.43
3	PS_60-80	362.00± SE 36.52	89.93± SE 12.62	451.92± SE 38.10
4	PS_ > 80	477.05± SE 22.14	137.11± SE 6.57	614.16± SE 28.63
5	HS_10-40	95.09± SE 26.09	26.23± SE 8.17	121.32± SE 34.26
6	HS_40-60	186.18± SE 38.44	50.63± SE 11.63	236.81± SE 49.73
7	HS_60-80*	308.88	85.67	394.55
8	ST_40-60*	226.33	66.02	292.35
9	ST_60-80*	195.17	52.00	247.17
10	ST_ > 80*	281.00	74.88	355.88
11	MS_60-80*	379.21	108.24	487.45
12	MS_ > 80	332.55± SE 7.67	94.97± SE 0.71	427.52± SE 6.96

(*SE= Standard Error. *SE not shown against single plot observation*)

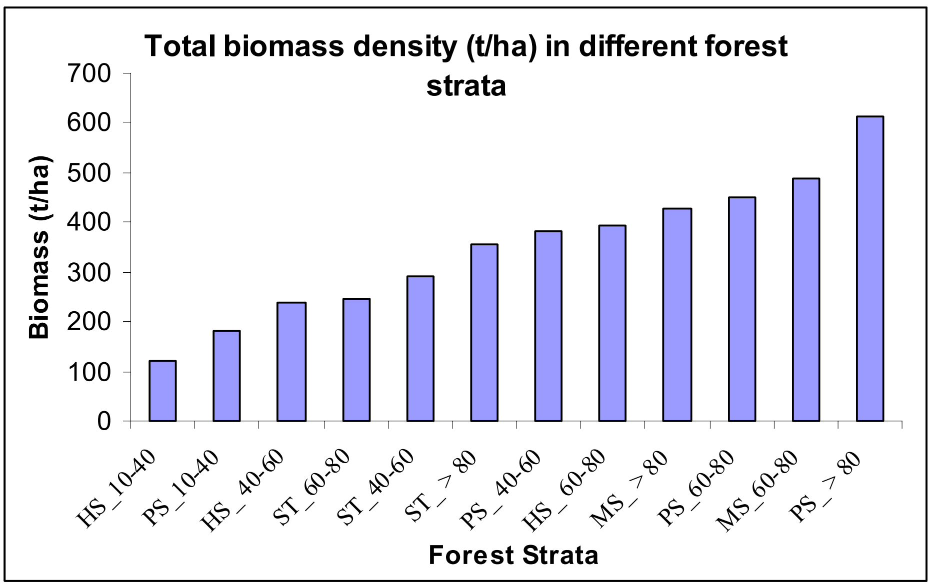


Figure 5.12 Total biomass density (t/ha) in different forest strata.

5.5.1.3. Total biomass

The maximum total biomass (t/ha) was found in PS_>80 (614.16± SE 28.63) followed by PS_ 60-80 (451.92± SE 38.10) and minimum in HS_10-40 (121.32± SE 34.26) and in PS_10-40 (183.38± SE 9.95). These results are also similar to AGB and so also trends in different strata (Table 5.5; Figure 5.12 and 5.13). Though studies are not available on total biomass estimation with respect to density classes/ forest degradation-wise and component-wise in Sal forests, however, available study (Negi and Chauhan, 2002) on average total biomass (AGB+BGB) of tree layer reported 182 -

777 t/ha biomass density in Sal forests of Dehradun region, depending upon stand age and tree density. The results of present study also showed nearly similar range of biomass density (Table 5.5).

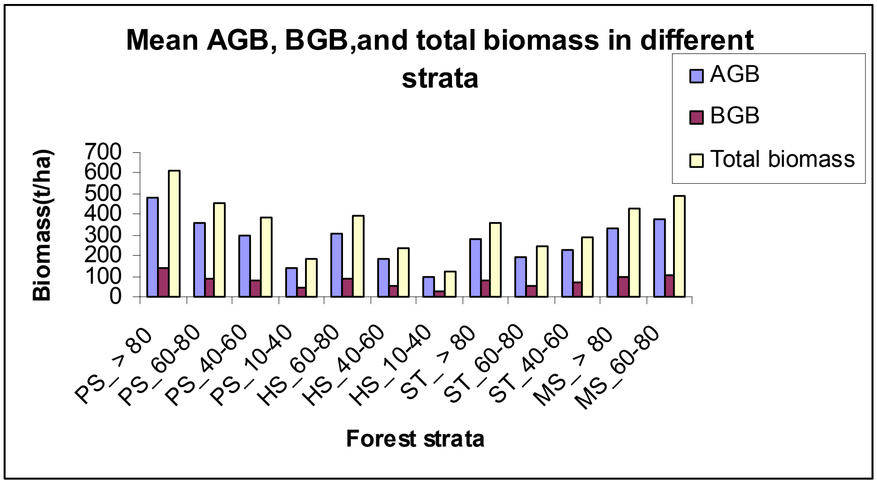


Figure 5.13 Mean AGB, BGB and Total biomass in different strata

5.5.2. Vegetation carbon

5.5.2.1. Above-ground carbon (AGC)

5.5.2.1.1 Carbon in tree layer

The percentage contribution of tree layer in total AGC is highest among all components, and varied from 97% to 99% of the total AGC, while rest of the layers just contributed from 1% to 3%. The details of percentage-wise contributions in different strata are given in Figure 5.14. The analysis did not indicate any pronounced relationship trend with forest density classes/ degradation. The AGC density of tree layer in different forest strata is shown in Figure 5.15.

5.5.2.1.2 Carbon in shrubby layer

The shrubby layer is poor in degraded or disturbed low density Pure_Sal forests, whereas in Hill_Sal the case is reverse. This could be because of comparatively inaccessibility and much dissected terrain supporting minor variations in climate and soil nutrients. The maximum C- density (t/ha) in shrubby layer was observed in ST_>80 (8.95), followed by ST_60-80 (4.08) and PS_>80 (2.43 ± SE 1.00) and minimum was shown in ST_40-60 (0.83), followed by PS_10-40 (0.84 ± SE 0.48), and HS_60-80 (1.50) (Table-5.6). The comparative analysis of percentage of C- density/ha in different density classes of each forest types is shown in Figure 5.16 which indicates increasing trend from lowest densities classes to highest densities classes in all SDF subtypes except Hill_Sal. It is summarized in by the trend graphs shown in Figure 5.17. However, the relative relationship of increase/decrease of C-density in shrubby layer is not only dependent on forest degradation alone but other factors of location, types of anthropogenic pressure, invasion of exotic weed like *Lantana* bushes etc. may play significant role and is a matter of further research.

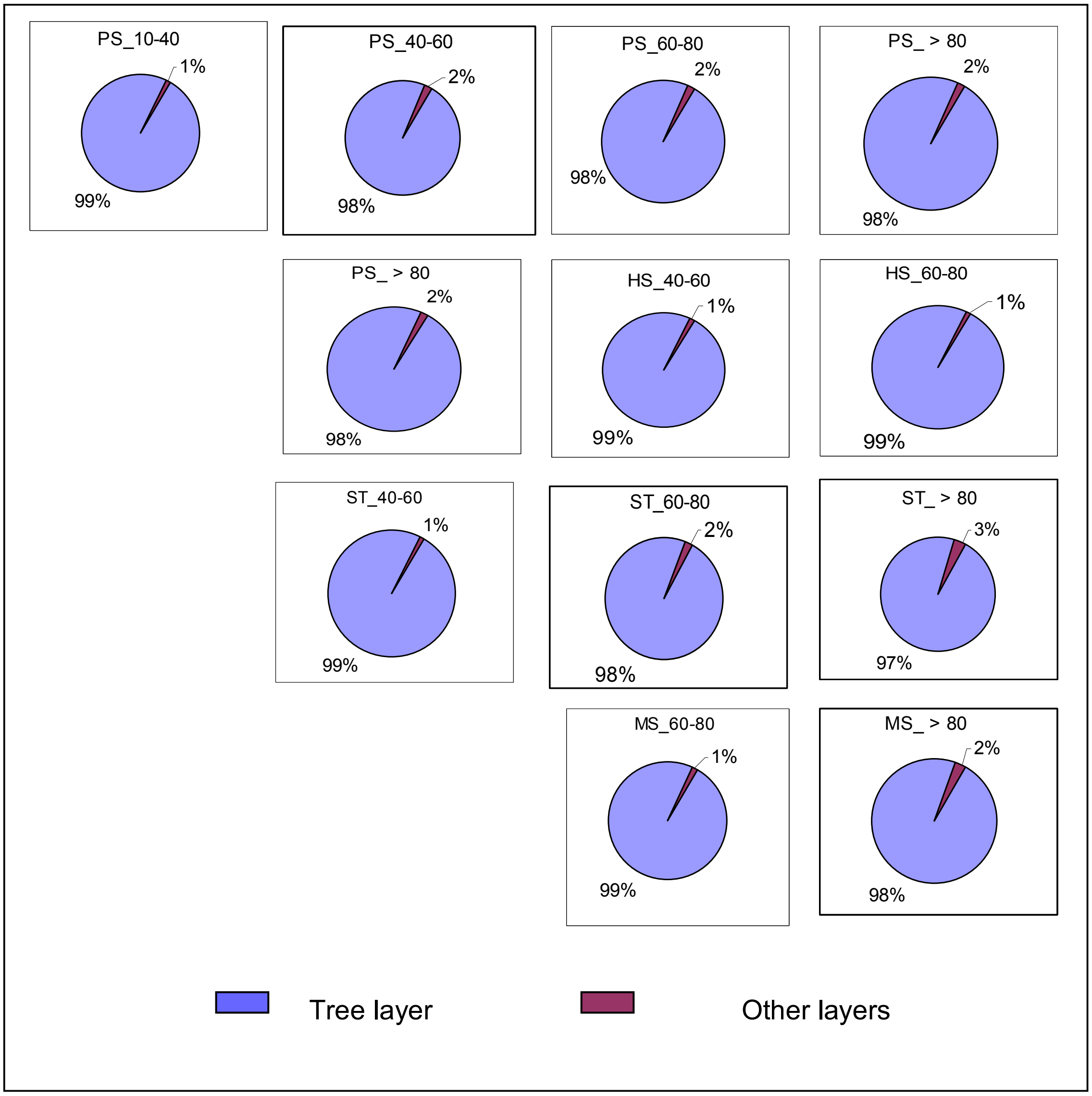


Figure 5.14 Percent contribution of C- tree layer in total AGC

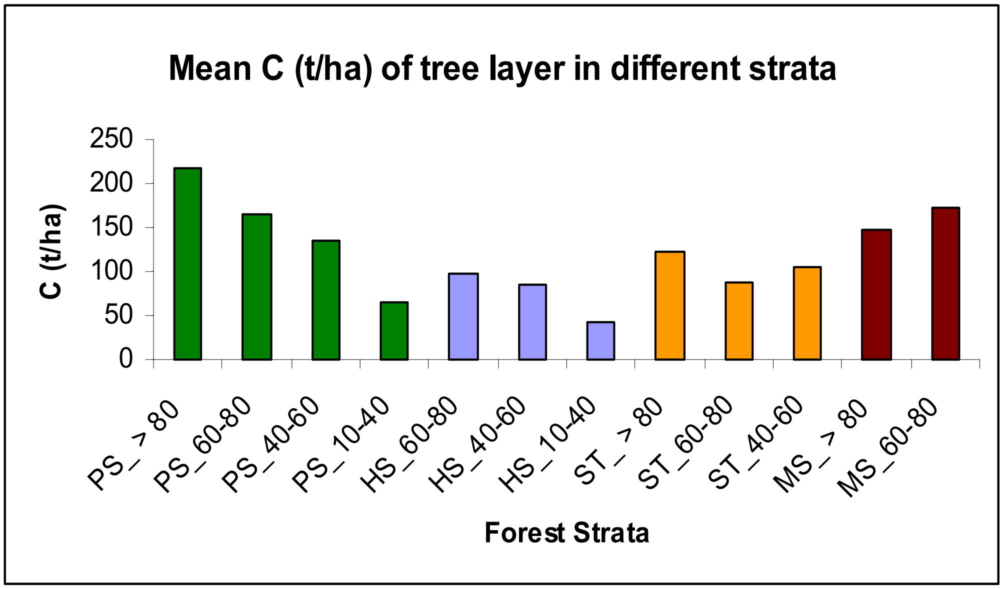


Figure 5.15 Mean C- density (t/ha) of tree layer in different strata class.

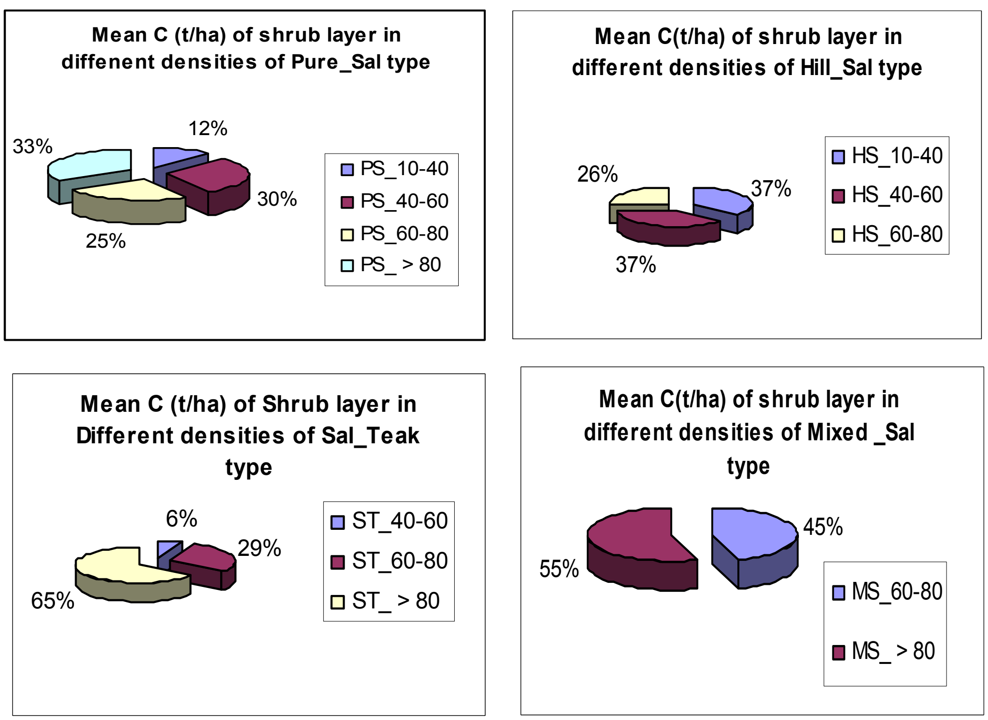


Figure 5.16 Mean %age-wise of shrubs layer in density classes of SDF subtypes

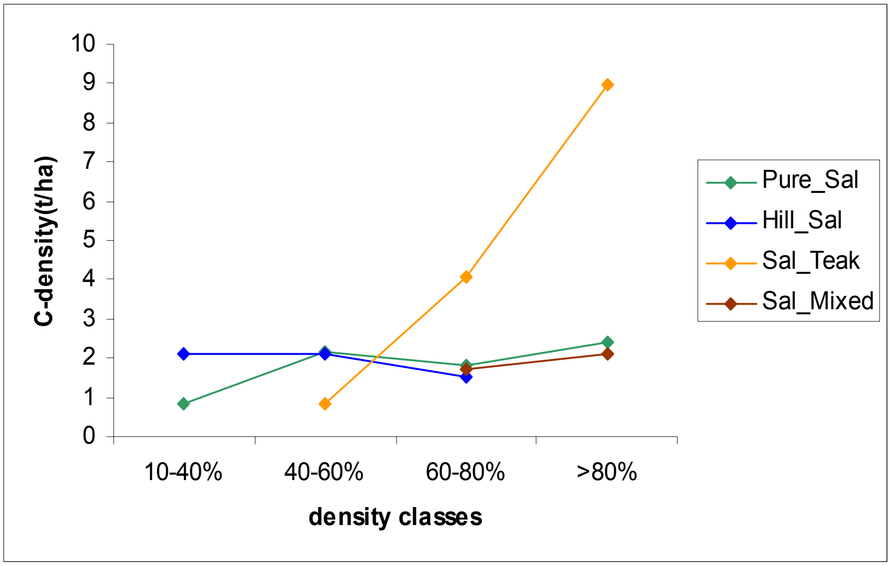
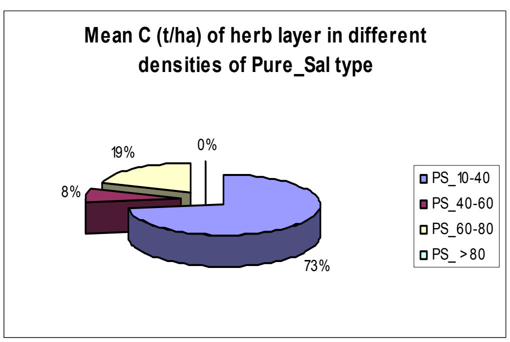


Figure 5.17 Mean C-density (t/ha) of shrubs layer in density classes of SDF subtypes.

5.5.2.1.3 Carbon in herbaceous layer

The maximum C- density (t/ha) in herbaceous layer was recorded in low density class - PS_10-40 (0.91 ± SE 0.08), followed by HS_10-40 (0.70± SE 0.02), and HS_40-60 (0.60± SE 0.00) (Table 5.6). The herbaceous layer was found almost nil in higher density class (PS_> 80) and Sal_Teak and Sal_Mixed subtypes. A comparative analysis of percentage of C-density of herbs among different density classes of respective forests and graph showing trend of C- density are given in Figure 5.18 and 5.19 respectively.



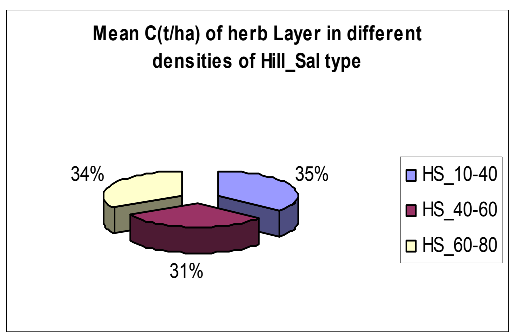


Figure 5.18 Mean %age of herbs layer in density classes of SDF Types

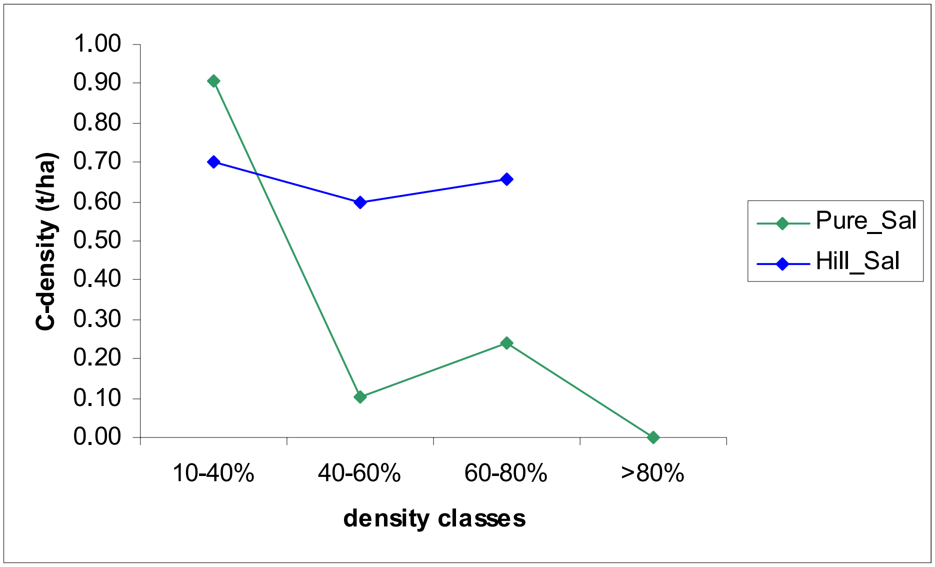
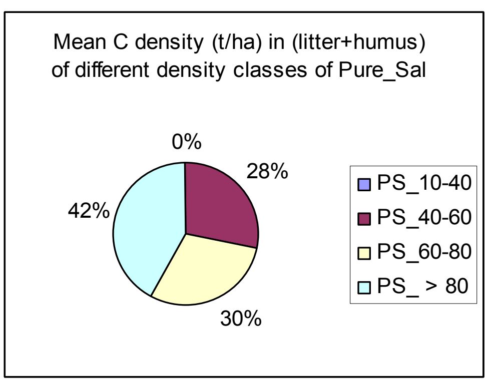


Figure 5.19 Mean C-density (t/ha) herbs layer in density classes of Pure_Sal and Hill_Sal

5.5.2.1.4 Carbon in litter - humus layer

The maximum C-density (t/ha) in litter and humus layer was observed in MS_>80 followed by PS_>80 and found almost nil/negligible in case of Hill_Sal, PS> 10-40 and ST_60-.80, ST_>80 (Table-5.6), indicating positive trend with respect to density classes in Sal forests located plain/gentle undulating slope (Pure_Sal, and Sal_Mixed). A comparative analysis of percentage of C-density of litter and humus among different density classes of respective SDF subtypes and graph showing trend of C-density are given in Figure 5.20 and 5.21 respectively.



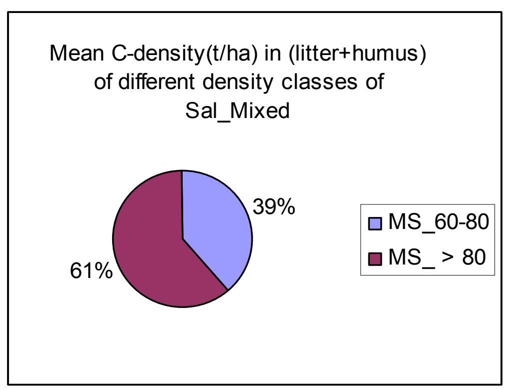


Figure 5.20 Mean %age of (litter+ humus) layer in density classes of Pure_Sal and Sal_Mixed

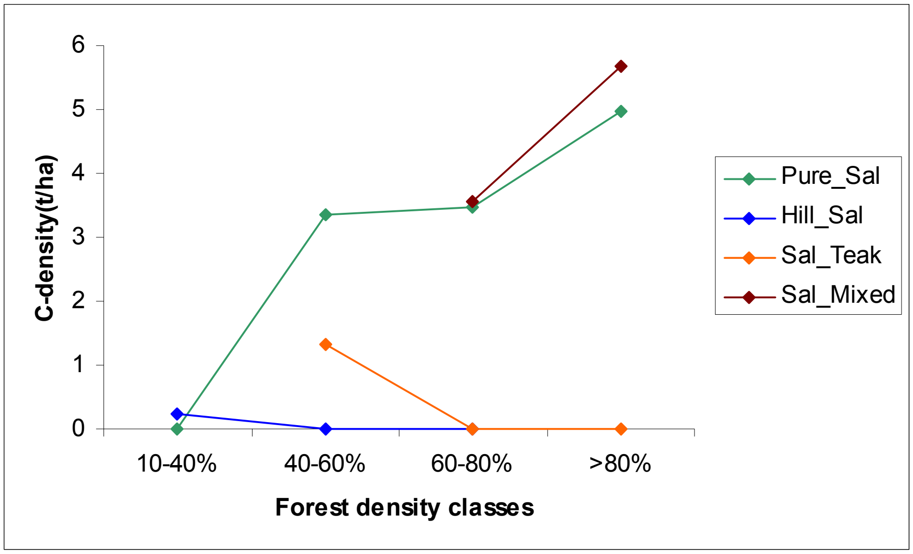


Figure 5.21 Trend of mean C-density (t/ha) in (litter-humus) layer of density classes of SDF types.

The trend of total C- density of (shrubs+ herbs+ litter+ humus) is shown in 5.22 which indicates overall increased trend of C-density with higher density classes except Hill_Sal. Thus, the overall forest degradation depletes AGC, however the impacts on various components of AGC are variable and complex and this phenomenon depends upon location, species composition, type of anthropogenic pressures etc.

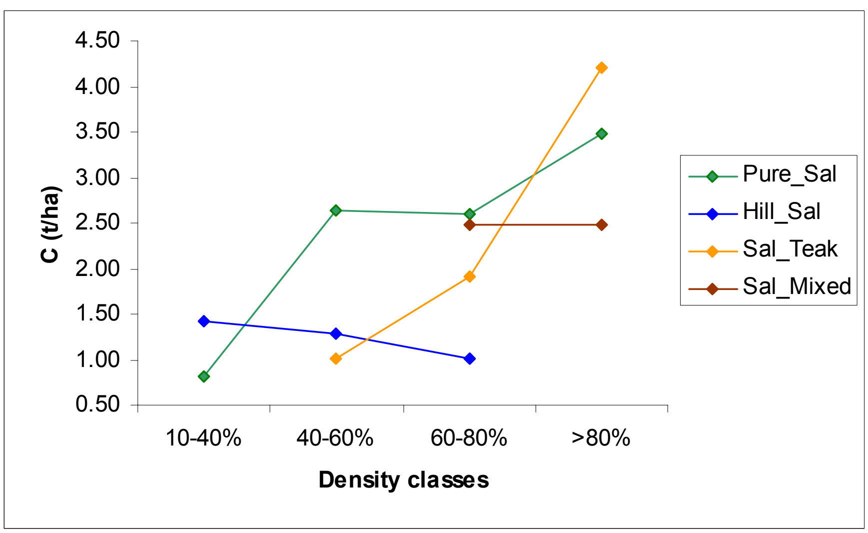


Figure 5.22 Trend of total mean C-density (t/ha) in (shrubs+ herbs+ litter+ humus) in density classes of SDF.

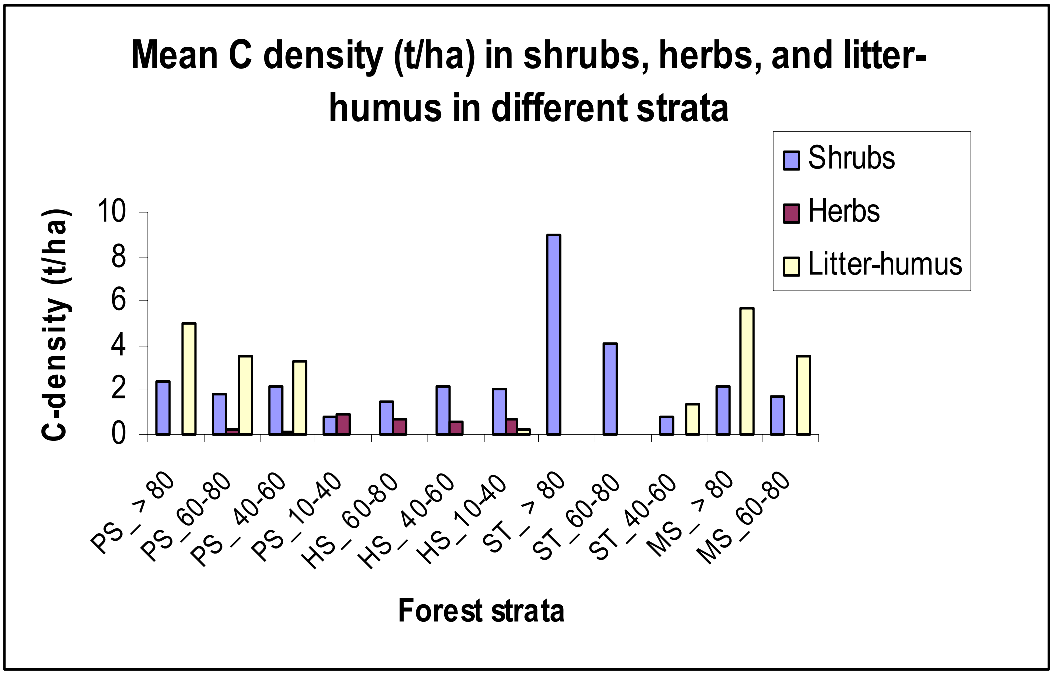


Figure 5.23 Mean C- density (t/ha) of shrubs, herbs, and litter -humus layers in different strata

5.5.2.1.5 Total above ground Carbon

The AGC density was assessed from different components of above ground biomass (trees, shrubs, herbs, litter and humus) in each stratum. The mean AGC density (t/ha) in different strata classes is shown in figure 5.24. The maximum mean AGC density (t/ha) was found in PS_ >80 (226.6 ± SE 10.51), followed by MS_60-80 (180.13) and PS_60-80 (171.95 ± SE 17.35), and minimum was found in HS_10-40 (45.17 ± SE 12 .39), followed by PS_10-40 (67.41 ±SE 3.60) and HS_40-60 (88.44 ±SE 18.257). General trend showed the depletion of AGC with decrease of forest density in each SDF type except in Sal_ Mixed type which is represented in the study area by higher density only. The C- decreasing trend is more pronounced in the case of Pure_Sal which is more close to settlements, indicating the depletion of AGC with forest degradation. The C- density in Sal_Teak forest was found comparatively less than Pure_Sal in the same density class which support that tree species also play significant role in C-sequestration. Similar observations were also reported by Zhou et al. (2008) in the reforestation programme of different species in Guangdong, China. The tree layer component of AGC also shows similar trend (Figure 5.15). The C-variations in shrubs, herbs, litter -humus is given in Figure 5.23, indicating different trends in different strata.

Table 5.6 C-density (t/ha) in different components of above ground biomass

Sl.no	Forest strata	C-tree layer	C- shrub layer	C-herb layer	C-litter - humus layer
1	PS_10-40	64.96 ± SE 3.73	0.84 ± SE 0.48	0.91 ± SE 0.08	0
2	PS_40-60	135.00 ± SE 6.64	2.17 ± SE 0.30	0.10 ±SE 0.06	3.34 ± SE 0.55
3	PS_60-80	164.59 ± SE 16.89	1.83 ± SE 0.58	0.24± SE 0.09	3.48 ± SE 0.94
4	PS_>80	216.82± SE 11.22	2.43 ± SE 1.00	0	4.96 ± SE 1.00
5	HS_10-40	41.68 ± SE 12.93	2.09 ± SE 0.87	0.70± SE 0.02	0.23
6	HS_40-60	84.78 ± SE 18.19	2.13 ± SE 0.56	0.60± SE 0.00	0
7	HS_60-80*	95.88	1.5	0.66	0
8	ST_40-60*	104.23	0.83	0	1.32
9	ST_60-80*	87.65	4.08	0	0
10	ST_>80*	123.12	8.95	0	0
11	MS_60-80*	172.94	1.73	0	3.56
12	MS_>80	148.50± SE 2.66	2.11 ± SE 0.83	0	5.68 ± SE 0.12

*(SE= Standard Error. *SE not shown against single plot observation)*

5.5.2.2. Below ground carbon (BGC)

The BGC was assessed by considering the root/shoot ratio for tree layer and therefore the trend of C density is almost similar with tree layer of AGC (Figure 5.24). Similarly, the results of total vegetation carbon are also in conformity with tree layer and BGC and therefore, it can be concluded that tree layer is most significant in contribution of C-sequestration while rest of the components play limited contribution in C- sequestration. The impact of degradations/ densities are more pronounced in Pure_Sal and Hill_Sal which support that species composition are also important factor in C-sequestration.

5.5.2.3. Total vegetation carbon

The trends of total vegetation C in different forest strata were similar to tree layer, being the major contribution of tree layer in total vegetation C. The vegetation C- density (t/ha) of PS_>80 (291.04±SE 13.57) was found highest among all strata including MS_>80 (202.60±SE 3.31) and ST_>80 (168.67), justifying the fact that Sal forests are better in C-sequestration than Sal_Teak or Sal_ Mixed SDF subtypes in the study area (Figure 5.26 and Table 5.7).

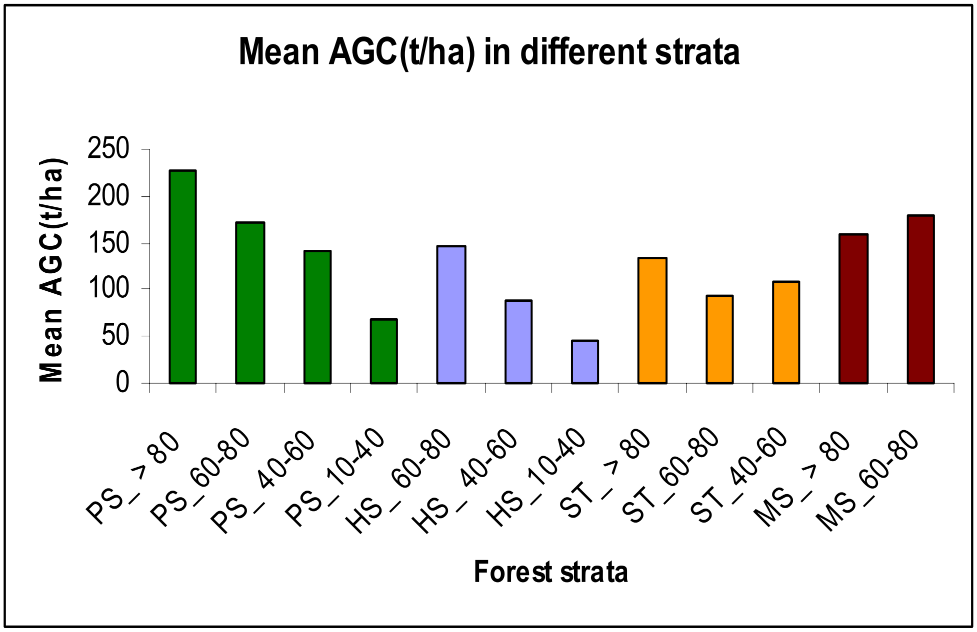


Figure 5.24 Mean (total) AGC density (t/ha) in different forest strata

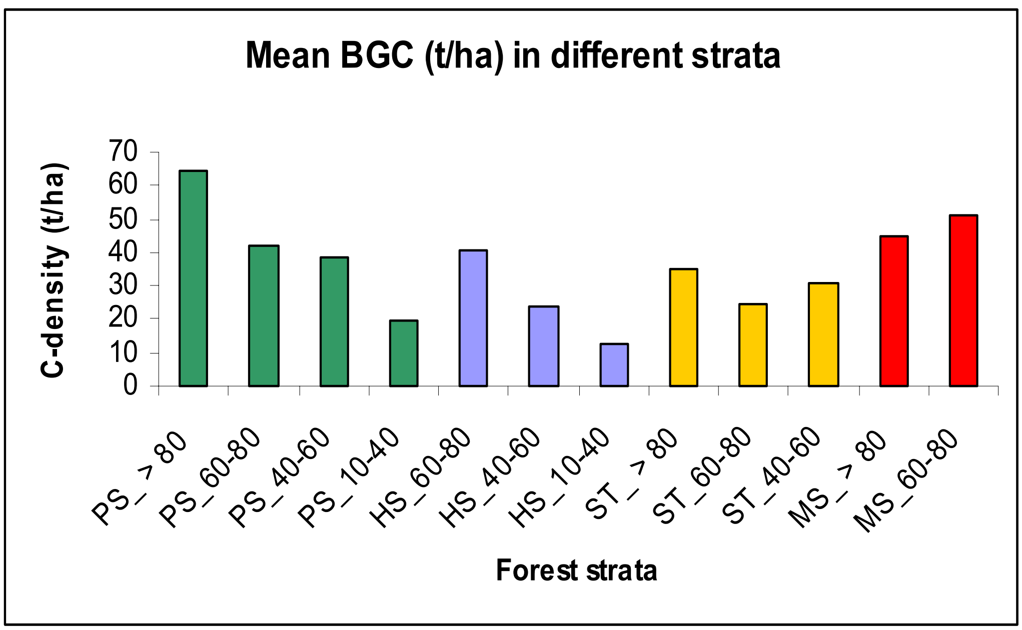


Figure 5.25 Mean (total) BGC density (t/ha) in different forest strata

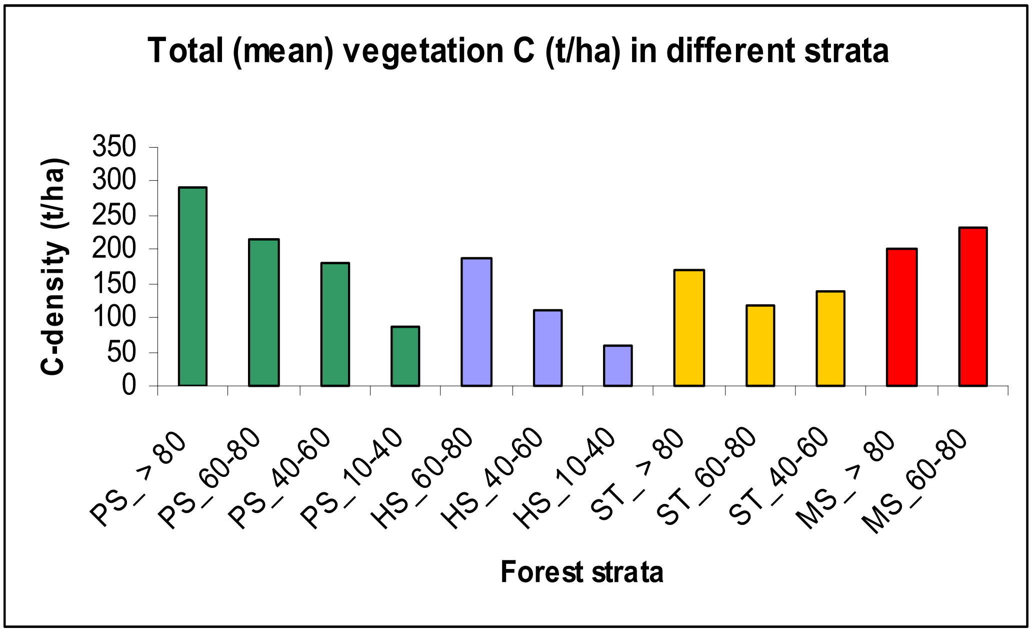


Figure 5.26 Total (mean) vegetation C-density (t/ha) in different strata

Table 5.7 C-Density (t/ha) in tree layer, BGC and Total Vegetation C.

Sl.no	Strata classes	C-tree layer	BGC	C- veg (total)
1	PS_10-40	64.96 ± SE 3.73	19.49± SE 1.12	86.90± SE 4.71
2	PS_40-60	135.00 ± SE 6.64	38.76± SE 2.31	180.86± SE 8.74
3	PS_60-80	164.59 ± SE16.89	42.27± SE 5.93	214.21± SE 18.08
4	PS_>80	216.82± SE 11.22	64.44± SE 3.09	291.04± SE 13.57
5	HS_10-40	41.68 ± SE 12.93	12.33± SE 3.84	57.50± SE 16.23
6	HS_40-60	84.78 ± SE 18.19	23.79± SE 5.34	112.23± SE 23.57
7	HS_60-80*	95.88	40.26	186.98
8	ST_40-60*	104.23	31.03	138.54
9	ST_60-80*	87.65	24.44	117.15
10	ST_>80*	123.12	35.19	168.67
11	MS_60-80*	172.94	50.87	231
12	MS_>80	148.50± SE 2.66	44.64± SE 0.34	202.60± SE 3.31

*(Note: SE = Standard Error, * SE not shown against single plot observation)*

The present results support to the earlier studies on the total vegetation made by Negi and Chauhan (2002) in Sal forests of Doon valley. They reported C-density in total biomass varied from 91.0 - 388.45 t/ha, depending upon stand age and tree density of Sal.

5.5.3. Soil organic carbon (SOC)

SOC density was estimated in 0-30, 30-50, 50-100 cm soil depths in all homogenous strata of vegetation in order to assess the variability of SOC density at different soil depth classes in each stratum as well as comparative study of the trend of the variability of the SOC density in different soil depth with respect to different forest density classes / degradations.

The results were analyzed with respect to percentage C contribution of various soil depth classes in total SOC density in each subtype of Sal forests (Figure 5.29). The variations in percentage contribution of soil depth classes in different density classes was noted in all subtypes of Sal forests which indicates that forest degradation adversely impact SOC density in all soil depth classes. However, the impact of forest degradations on SOC density in Soil depth classes also depend upon other factors such as species composition, physiography etc in overall process of C-Storage in different soil depth classes. Fearnside et al.(1998) and Guo and Gifford (2002) also reported that SOC is a complex phenomenon depending upon number of factors including management practices.

The analysis of SOC density in various soil depths classes indicates the decreasing trend with decrease of forest density classes in each subtype (Table 5.8 and Figure 5.27). In case of Pure_Sal, SOC density (t/ha) from highest density class to lowest density class decreased from 61.16± SE 3.96 t/ha to 28.04± 4.15 in 0-30 cm soil surface layer ; 55.44± SE 5.14 to 22.97± SE 3.54 in 30-50 cm soil depth and 62.45± SE 4.35 to 20.55± SE 4.57 in 50-100 cm soil depth class. While in case of Hill_Sal SOC density (t/ha) from highest to lowest density class decreased from 50.20 to 27.30± SE 2.86 in 0-30 cm soil depth class; 46.46 to 19.92± SE 5.05 in 30-50 cm soil depth and from 53.56 to 21.76± SE 5.25 in 50-100 cm soil depth class. Similarly decreasing trend in each soil depth class was also noted in Sal_Teak. The Sal_Mixed forest has only higher classes of density classes i.e. 60-80% and >80% and the decreasing trend in SOC density was observed only in 50-100 cm soil depth indicating that factors other than forest density also have interactive role in the movement of organic carbon in different soil depth. These results overall confirm that forest degradation adversely affect SOC density in each soil depth, however the quantum of impact may vary in different categories of Sal forests. Dinakaran and Krishnayya (2008) also reported that difference in vegetal cover not only influence the SOC content of the top layer, but also of deep layers.

The total SOC (t/ha) from moderately open forest to high density class varied from 71.56± SE 8.97 in PS_10-40 to 179.05±SE 11.20 in PS_ >80 of Pure_Sal subtype, 68.98 ±11.38 in HS_10-40 to 150.22 in HS_60-80 of Hill-Sal subtype, 71.50 in ST_40-60 to 164.03 in ST_ >80 of Sal_Teak subtype and 157.94 in MS_60-80 to 170.87±14.04 in MS_ >80 of Sal_Mixed subtype. Among all strata, the highest total SOC density was estimated in forest density class of >80% in PS_ >80, followed by MS_ >80 and ST_>80, while lowest was estimated in forest density class of 10-40% in PS_10-40, followed by ST_40-60 and, HS_10-40. Similar trend of variations in different soil depth classes i.e. 0-30, 30-40 and 50-100 cm were also observed among different strata. The total SOC density (0-100 cm) variations indicate an increasing trend with respect to increase in forest density in each subtype of Sal forests and thus confirm the hypothesis that degradation also depletes SOC in natural forests. These results indicate that SOC density decreases with degradation of forests in all strata however; the amount of variation in SOC density also depends on types of forests, level of anthropogenic pressures, terrain etc. The mean SOC density in various soil depth classes in different strata is shown in Figure 5.27 and Table 5.8.

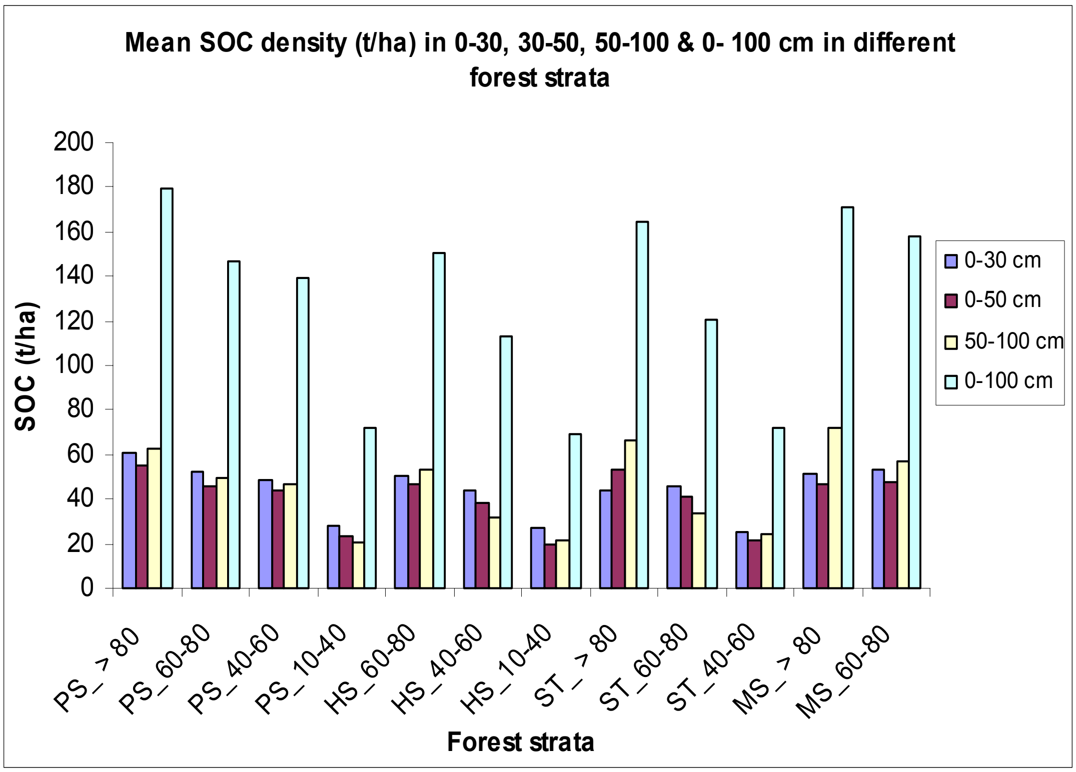


Figure 5.27 Mean SOC density (t/ha) in various soil depth classes in vegetation strata

The results of SOC density in the present study were found comparable with earlier studies carried out in Sal forests of Doon Valley. Negi and Chauhan (2002) reported SOC in Sal forests, varies from 31.0 – 62.9 t/ha in the top 30 cm depth depending upon the tree density and age of the stand tree. They reported highest SOC density (62.9 t/ha) in 30 cm top soil of the Sal forests growing on flat area in Doon Valley.

Table 5.8 SOC density (t/ha) in different Soil depth classes of vegetation strata

Sl. no	Stratum	SOC(0-30 cm)	SOC(30-50 cm)	SOC(50-100 cm)	Total SOC
1	PS_10-40	28.04± SE 4.15	22.97± SE 3.54	20.55± SE 4.57	71.56± SE 8.97
2	PS_40-60	48.45± SE 2.21	43.73± SE 2.14	46.80± SE 3.82	138.98± SE 5.95
3	PS_60-80	51.97± SE 2.48	45.85± SE 2.57	49.23± SE 3.72	147.06± SE 5.12
4	PS_>80	61.16± SE 3.96	55.44± SE 5.14	62.45± SE 4.35	179.05± SE 11.20
5	HS_10-40	27.30± SE 2.86	19.92± SE 5.05	21.76± SE 5.25	68.98± SE 11.38
6	HS_40-60	43.95± SE 3.14	37.87± SE 5.89	31.38± SE 5.05	113.19± SE 12.52
7	HS_60-80*	50.2	46.46	53.56	150.22
8	ST_40-60*	25.64	21.74	24.13	71.5
9	ST_60-80*	46.23	41.1	33.61	120.94
10	ST_>80*	43.50	53.72	66.8	164.03
11	MS_60-80*	53.70	47.58	56.65	157.94
12	MS_>80	51.54± SE 4.86	47.05± SE 5.62	72.28± SE 3.56	170.87± SE 14.04

(*Note: SE = Standard Error, SE not shown against single plot observation*)

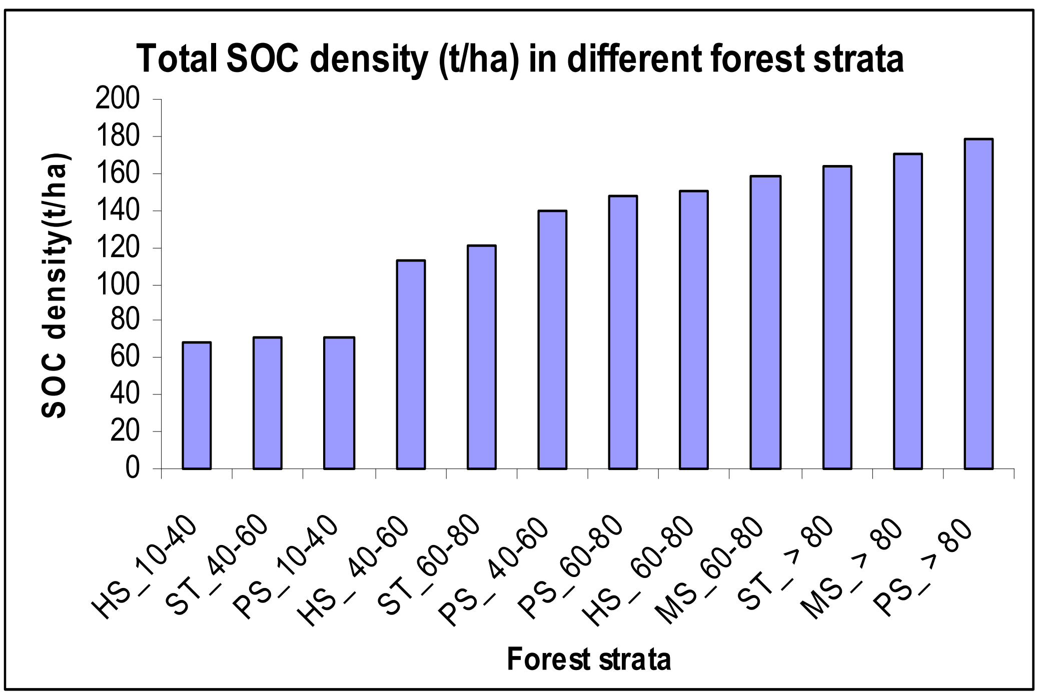


Figure 5.28 Total SOC density (t/ha) in different forest strata

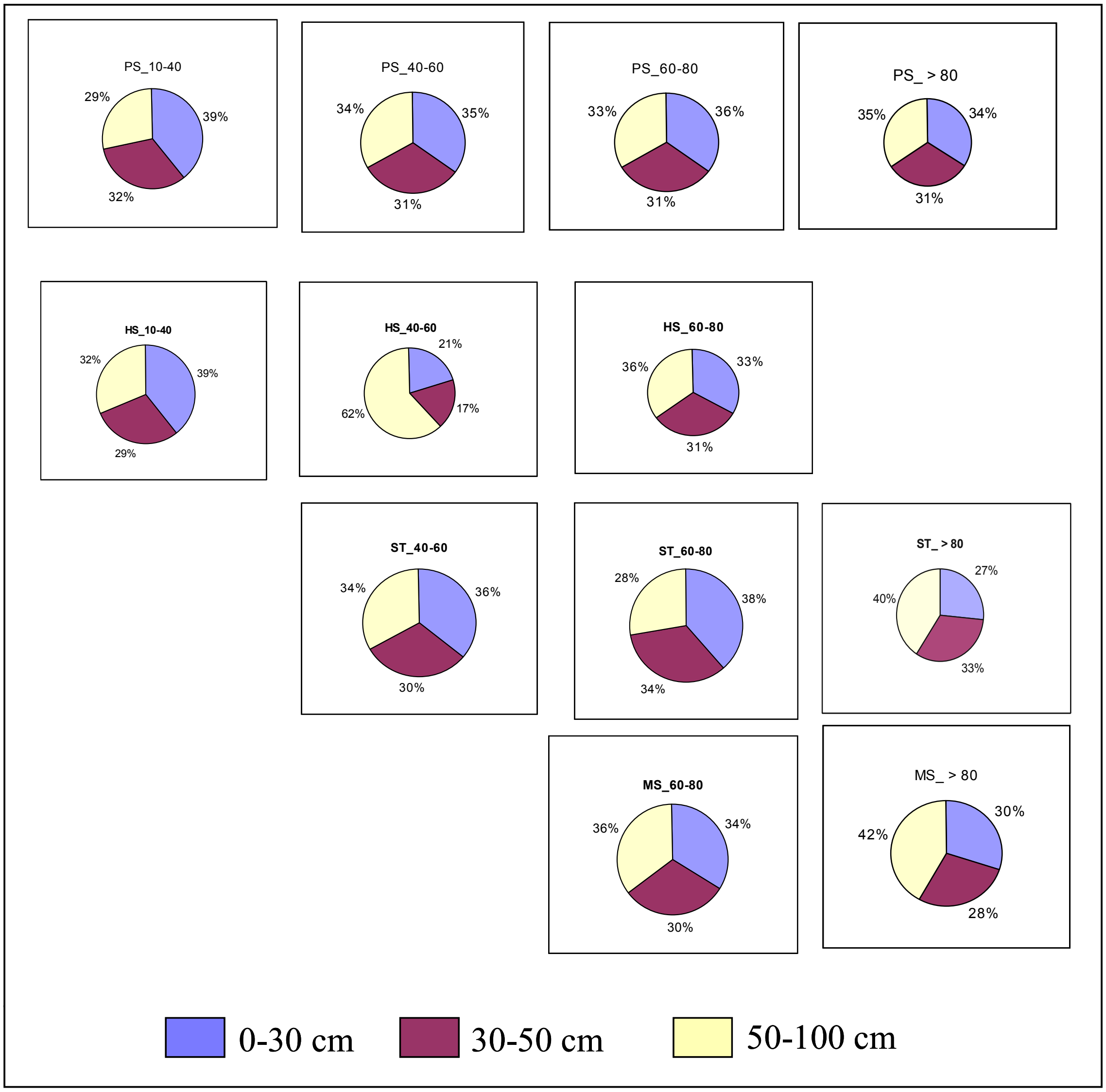


Figure 5.29 Percentage C- contribution in total SOC density (t/ha) in strata

5.6. Spectral modeling of biomass

5.6.1. Establishing correlation between observed biomass and satellite derived parameters

The LISS III satellite data and ground AGB data were used to develop correlation with biomass and spectral properties of vegetation. Different regression models were established between estimated AGB obtained from ground observations and corresponding NDVI values and with different spectral bands. The linear, logarithmic, exponential, and power functions were attempted to obtain best fit correlation coefficients with different DN or reflectance values of red, infrared, NDVI and

$NDVI_{3*3}$ average with biomass of plots at pixel level (23.5×23.5 m). Correlation coefficient of best fit models was used to model biomass in the study area. The best fit correlation was found with $NDVI_{3*3}$ values of linear function having coefficient of determination (R^2) of spectral reflectance equivalent to 0.7026. (Figure 5.30 and Table 5.9). The use of 3*3 window in extraction of NDVI values represent average sizable area on the ground in order to reduce the geometric and GPS errors if any to the best possible extent. The regression equation (y = 110.66x – 8.5882) obtained by plotting values on X-axis against AGB on Y-axis was used to get the predicted above ground biomass. Image thus obtained extrapolated the AGB of Sal forests (SDF).

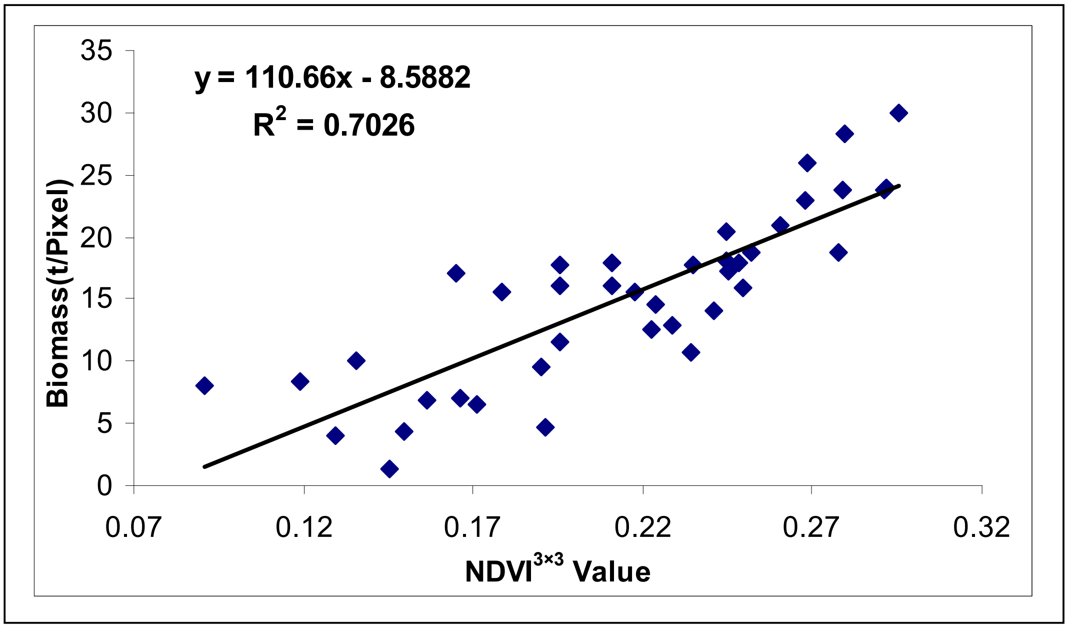


Figure 5.30 Linear regression analysis between $NDVI_{3*3}$ and observed biomass

Table 5.9 Coefficient of determination (R^2) of spectral reflectance of Red, Infrared, NDVI and $NDVI_{3*3}$

Spectral Indices/ bands	linear	Logarithmic	Power	Exponential
Red	0.0854	0.0860	0.0908	0.0900
Infrared	0.4148	0.4240	0.3290	0.3311
NDVI	0.6273	0.5152	0.4636	0.5340
$NDVI_{3*3}$	**0.7026**	0.6295	0.5396	0.5795

5.6.2. Biomass and carbon mapping

Based on the regression equation, y =110.66x-8.5882 (Figure 5.30), the model was run with on the $NDVI_{3x3}$ image of Thano range study area for biomass mapping. Similarly carbon mapping was also done by using the same linear equation and $NDVI_{3*3}$ image along with multiplication factor of 0.47

(Westlake, 1963). From these output images, subsets of Sal forests (SDF) were prepared. These subsets were used for preparing classified maps of biomass and carbon in GIS which are shown in Figure 5.24 and 5.25. The pattern of biomass density and Sal forest density on maps were found more or less similar pattern (Figure 5.31 and 5.4).

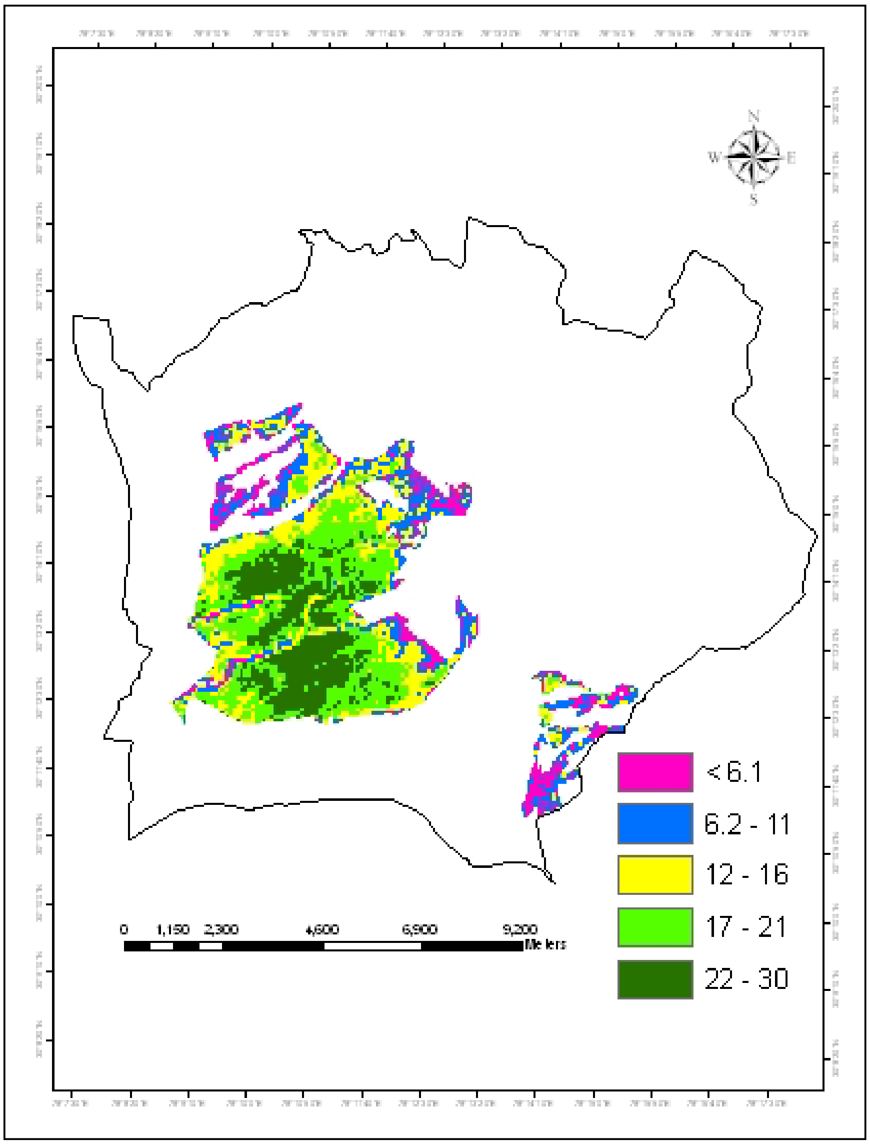


Figure 5.31 Above ground biomass (t/ha) map of Sal forests

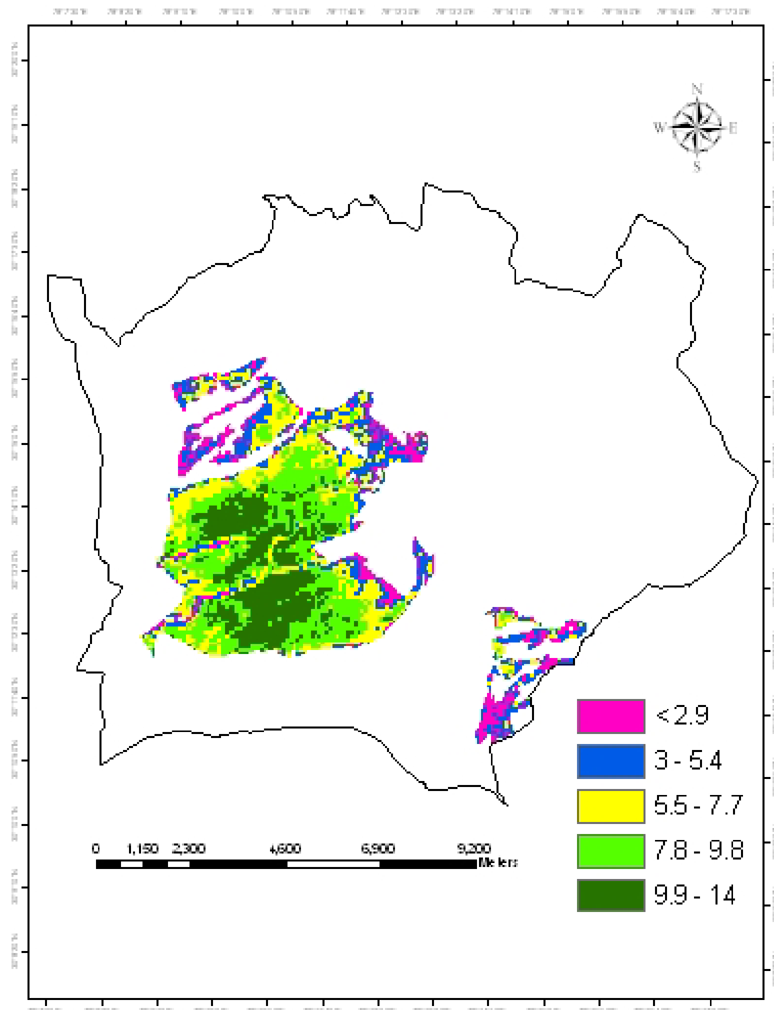


Figure 5.32 Above ground carbon (t/ha) map of Sal forests

5.7. Relationship among AGB, AGC, SOC and spectral properties.

The spectral reflectance and absorption depend upon above ground biomass density especially in red and infrared bands, and vegetation indices such as NDVI and therefore, there is direct relationship between NDVI and biomass. Here, attempts were made to find out correlation between SOC v/s $NDVI_{3*3}$, SOC v/s AGB, AGC v/s $NDVI_{3*3}$, and SOC v/s AGC The regression relationship between:

- SOC and $NDVI_{3*3}$ showed a value of $R^2 = 0.5392$ (Figure 5.33);
- SOC and AGB showed a value of $R^2 = 0.6232$ (Figure 5.34);
- AGC and $NDVI_{3*3}$ showed a value $R^{2=}0.7026$ (Figure 5.35)
- SOC and AGC ; showed a value of $R^2 = 0.6232$ (Figure 5.36)

and based on R^2 values, the results between SOC with NDVI indicates poor relationship but comparatively better with AGB. The results between AGC and NDVI are similar as in case of AGB v/s $NDVI_{3*3}$ having the same value of R^2 (0.7026). Similarly the R^2 value was also found same in case of SOC v/s AGB and SOC v/s AGC (0.6232) because of the same multiplication factor of 0.47 between AGB and AGC. Thus, these results support that $NDVI_{3*3}$ values are not having good correlation with SOC which can be explained that SOC do not impact spectral reflectance directly with respect to red and infrared or NDVI.

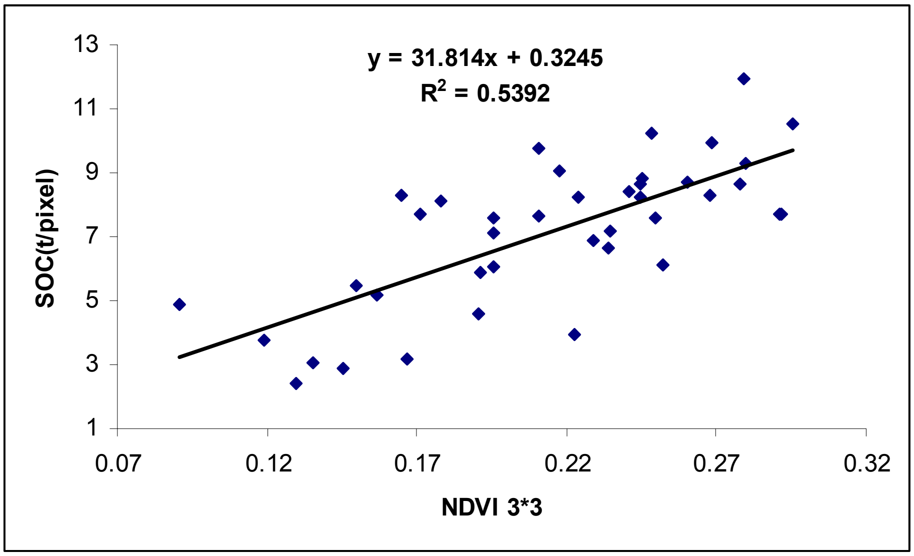


Figure 5.33 Linear regression between NDVI $_{3*3}$ and SOC density (t/pixel)

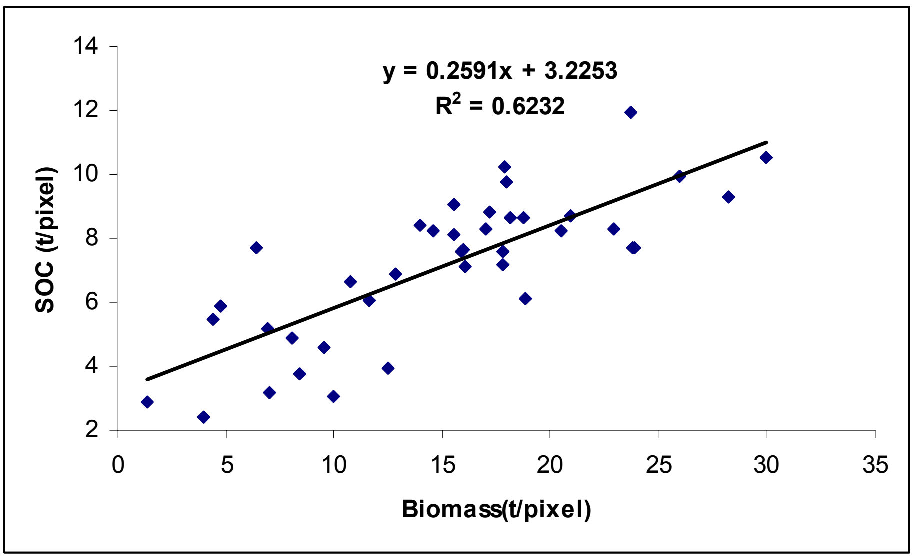


Figure 5.34 Linear regression between biomass (AGB) and SOC density (t/pixel)

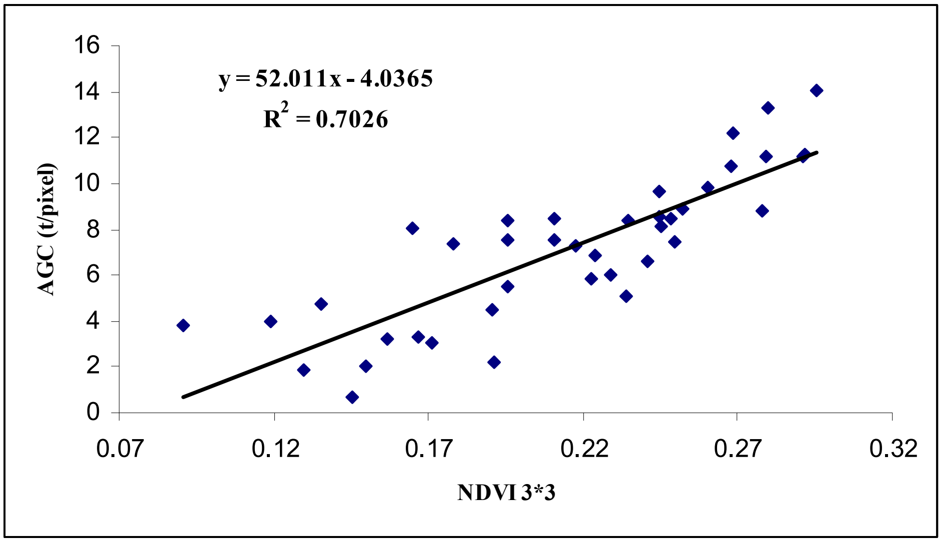


Figure 5.35 Correlation between NDVI $_{3*3}$ and AGC density (t/pixel)

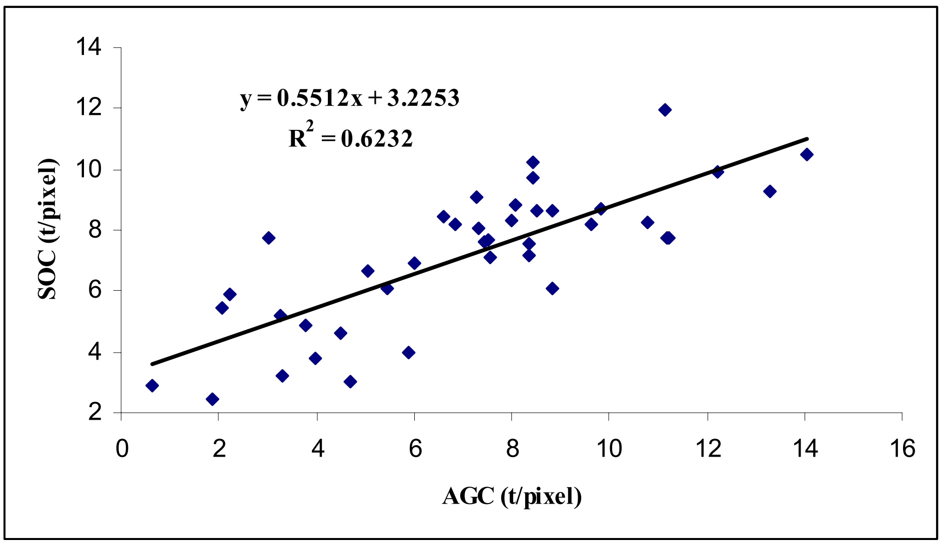


Figure 5.36 Correlation between AGC density and SOC density (t/pixel)

5.8. Assessment of the potential of soil and vegetation C- sequestration.

The potential of C-density (t/ha) was assessed 470.1 ± SE 19.14 for Pure_Sal, 337.2 for Hill_Sal, 332.7 for Sal_Teak and 373.47 for Sal_Mixed. It is based on the assumption that these forests would achieve or have potential to achieve high density (>80%). The mean potential total vegetation carbon, soil organic carbon and total carbon (soil + vegetation) stock of SDF of study area were assessed to the value of 754.31, 519.86 and 1274.17 Gigagram (Gg) respectively. The highest existing carbon stock (266.64 ± SE 10.13Gg) and potential carbon stock (391.91 ±SE 15.96 Gg) was found for PS_40-60 strata class (Table 5.10). The reason of this can be explained by the fact that it covers maximum area (833.68 ha) among all classes. The mean total potential C-stock in vegetation, soil as well as total carbon for different forest strata is shown (Figure 5.37).

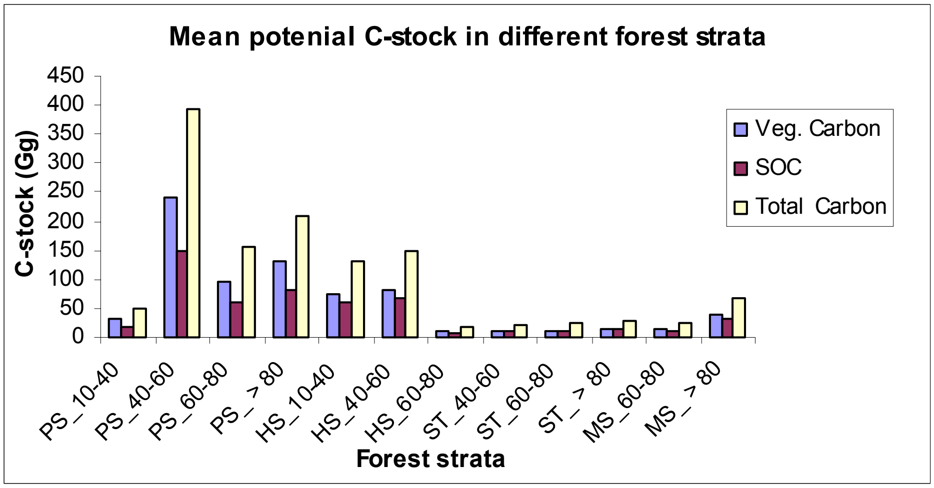


Figure 5.37 Mean potential (total) C- stock in different strata

Table 5.10 Showing C-loss/gap between potential and existing C-stock (Gg) in Sal forests (SDF) of study area.

Sl. no	Strata classes	Potential C-density (t/ha)	Potential C-Stock (Gg)	Existing C-stock (Gg)	Mean C-Loss /gap (Gg)
1	PS_10-40	470.094± SE 19.14	50.23± SE 2.05	16.93± SE 1.30	33.30
2	PS_40-60	470.094± SE 19.14	391.91± SE15.96	266.64± SE 10.13	125.26
3	PS_60-80	470.094± SE 19.14	157.38± SE 6.48	120.94± SE 6.27	36.43
4	PS_ > 80	470.094± SE 19.14	210.65± SE 8.58	210.65± SE 8.58	0
5	HS_10-40	337.200	131.90	49.47± SE 8.12	82.42
6	HS_40-60	337.200	150.07	100.33± SE 14.85	49.75
7	HS_60-80*	337.200	17.45	17.45	0
8	ST_40-60*	332.699	20.01	12.63	7.38
9	ST_60-80*	332.699	23.54	16.84	6.69
10	ST_ > 80*	332.699	29.31	29.31	0
11	MS_60-80*	373.468	23.12	24.08± SE 0.66	-0.96
12	MS_ > 80*	373.468	68.62± SE 1.97	68.62± SE 1.97	0
	Total		**1274.17**	**933.89**	**340.28**

*(Note: SE = standard error, * SE not shown against single plot observation)*

The total existing and potential C-stock of the Sal forests was estimated 933.89 Gg and 1274.17 Gg respectively and its estimated loss/ gap of C-stock was calculated 340.28 Gg. The highest gap in C-stock was found in PS_40-60 (125.26 Gg), followed by HS_10-40 (82.42 Gg), HS_ 40-60 (49.75 Gg) which again explained by combining impact of level of degradation as well as having more covering area than other classes. Similarly, the gap in existing and potential C- density was also estimated and found highest in PS_10-40 (311.63 t/ha), followed by HS_10-40 (210.72 t/ha) and PS_ 40-60 (150.25 t/ha). The existing and potential C- density in different forest strata is shown in Figure 5.39. The impact of gap in C-stock/ C- density was comparatively less pronounced in Sal_Teak forests and negligible for Sal_ mixed (Figure 5.38 and 5.39). It supports that Pure_ Sal is most affected by forest degradation and has better potential for C- sequestration than others subtypes in present study area.

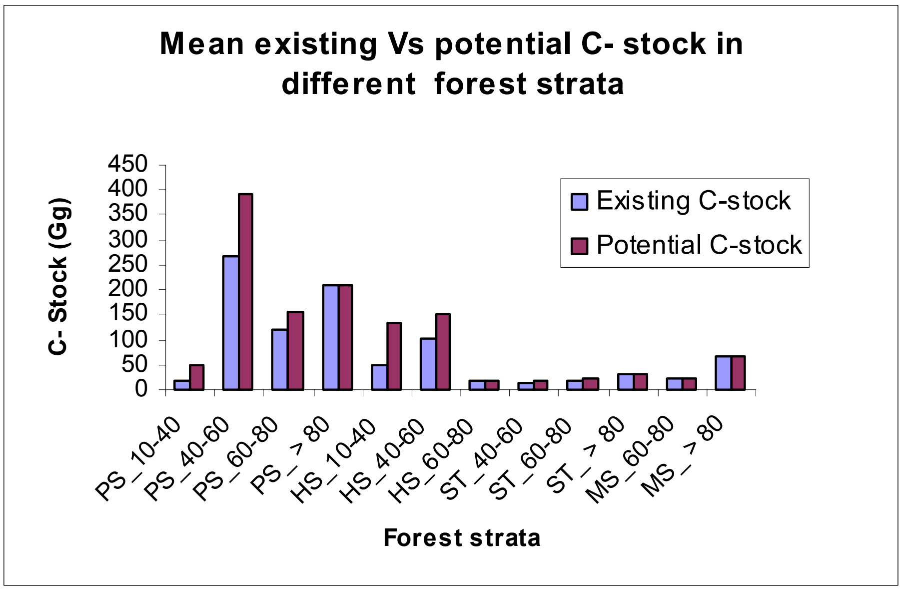


Figure 5.38 Mean total existing Vs potential C-stock (Gg) in different strata

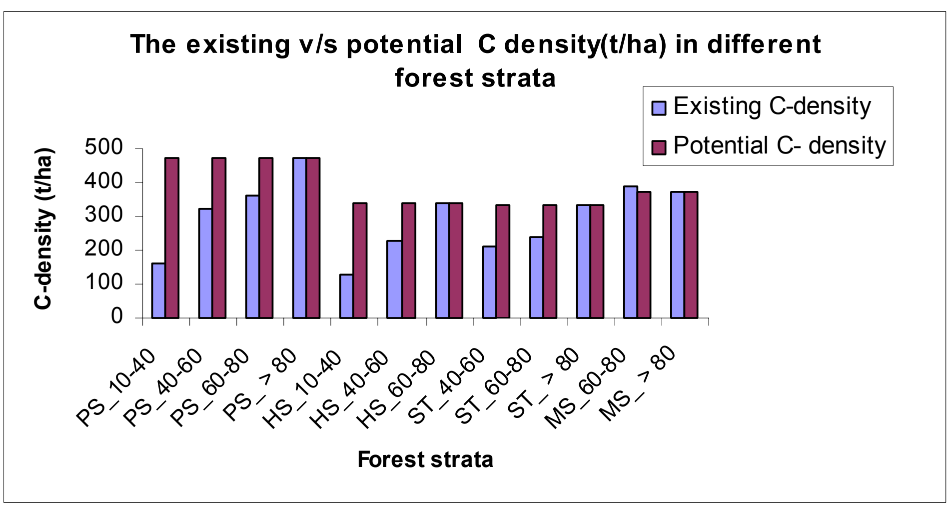


Figure 5.39 The existing v/s potential C density (t/ha) in different forest strata

The comparative assessment of loss/gap in total vegetation and Soil C was analyzed with respect to extrapolated value of Potential C. The analysis indicates more pronounced impact in vegetation C than SOC, however, similar trend of C- loss/gap are recorded in both cases The highest C-loss/gap was recorded in Vegetation C (91.85 Gg) in PS_40-60 among all strata classes. Similarly, the highest C-loss/gap in SOC (33.41Gg) was also found in PS_40-60 strata class (Table 5.10 and Figure 5.40). It can be explained that that PS_40-60 subtypes covers more area than other forest strata.

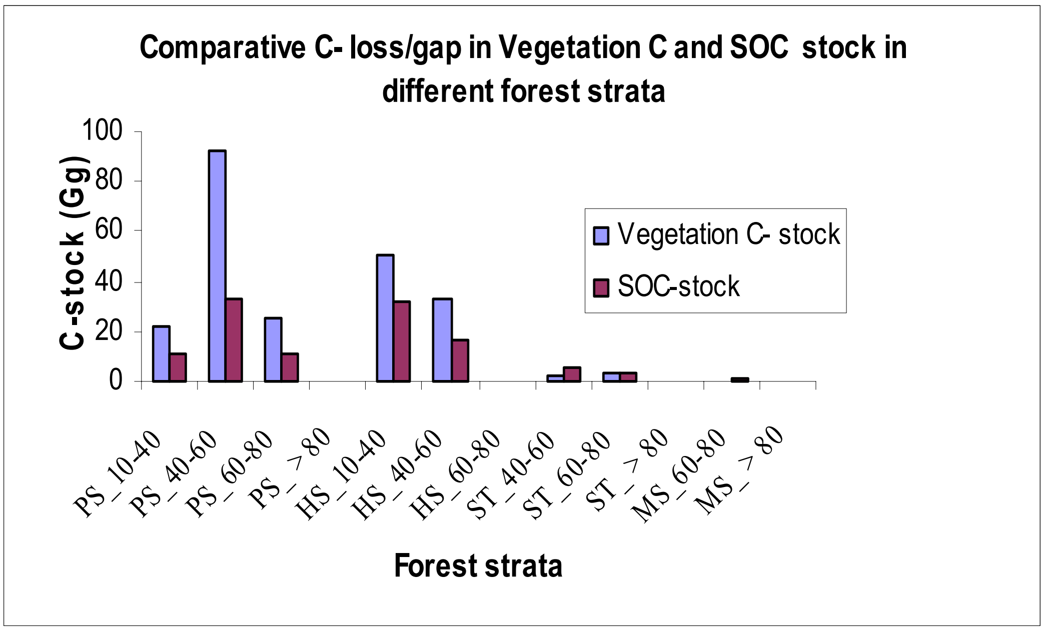


Figure 5.40 Comparative C-loss/gap (Gg) in total vegetation & soil C with respect to extrapolation of potential carbon in Sal forest of study area

5.9. Validation of the results

The results of above ground biomass mapping were prepared from the model based on the linear equation of the relation of spectral values of NDVI $_{3*3}$ and ground data of 40 sample points laid in different strata classes. For validation of these results, additional 15 sample plots were laid in different forest strata. The validation sample points were overlaid on the above ground biomass model to extract predicted values of the model against these observed values of the validation sample plots. The linear regression analysis was carried out between predicted values v/s observed values of the validation points (Figure 5.41). These validation results gave the value of $R^2 = 0.7536$ indicating good prediction with the model developed.

In addition to this, Coefficient of efficiency (CE) and root mean square error (RMSE) were also used to validate the results and assessing the performance of above ground biomass model. The coefficient of efficiency also known as model efficiency compares the variance of predicted from the observed values to the variance of the observed values from the mean of the observations. A value of 1 denotes a perfect match of predicted and measured values. The RMSE provides a term for the total difference between the predicted and the observed values. The lower limit is 0, which indicates no difference between measured and simulated values (Kersebaum et.al 2007).

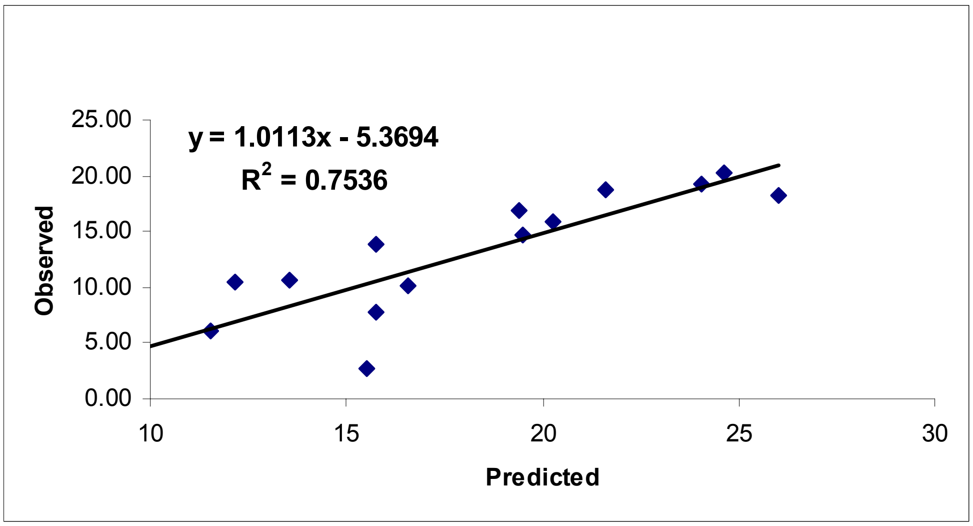


Figure 5.41 Predicted v/s observed of validation sample plots

The coefficient of efficiency (CE) value was estimated 0.43 and the RMSE value was found 1.52 which also indicates good prediction with the model developed. Since the aboveground biomass carbon is derived from aboveground biomass simply by the multiplication factor of 0.47 and therefore, the results of validation of carbon model were also similar to aboveground biomass model.

6. Conclusion and recommendations

6.1. Conclusion

Forest degradation has been considered critical in carbon sequestration process both in soil and vegetation of forest ecosystem. It is important to understand the relationship of variations in vegetation and soil organic carbon with respect to forest degradation and assess the potential of carbon stock in the Sal forests of study area. The study has concluded the following:

What is the impact of forest degradation due to anthropogenic activities on soil and vegetation?

The overall decrease in vegetation carbon as well as in soil organic carbon density with respect to forest degradation has been found. The decreasing trend of aboveground carbon was noted more pronounced in the case of Pure_Sal due to anthropogenic activities located close to settlements, indicating the depletion of total aboveground biomass and carbon with forest degradation. The maximum aboveground carbon density was found in Pure_Sal with highest density class (>80%) located interior in the forests with least anthropogenic pressure and minimum in Hill_Sal and Pure_Sal with lowest density class (10-40%) facing maximum forest degradation. As expected, the tree layer of total aboveground carbon has the major contribution among all components, varies from 97% to 99% of the total aboveground carbon. The carbon density in tree layer showed decreasing trend with decrease of forest density classes similar to total aboveground carbon and tree layer was most adversely affected by forest degradation. However, the carbon density in shrubs, herbs, and litter-humus layer showed variable trends with different forest strata exposed to various level of forest degradation except in litter-humus in Pure_Sal and Sal_Mixed forests. Belowground biomass carbon was estimated only for tree layer based on root/ shoot ratio and therefore the result were also similar to tree layer. Thus, It has been concluded that overall forest degradation depletes vegetation carbon, however, the trend in various components of aboveground biomass noted variable and complex, indicating complex interaction of forest degradation with other factors such as terrain, species composition, weed infestation, types of anthropogenic pressures etc.

How is SOC changing in surface and subsurface layers in different forest density classes of Sal forests due to anthropogenic pressures?

The decreasing trends of soil organic carbon density in each soil depth classes was observed with respect to decrease in forest density in each category of Sal forests and thus confirm the hypothesis that degradation also depletes SOC density in natural forests. The adverse impact of forest degradation also found even in subsurface soil layer. Among all strata, the maximum total SOC density was found in Pure_Sal with >80% density class with least forest degradation, while the minimum in Pure_Sal with 10-40% density class with highest forest degradation. Thus, overall SOC density depletes with degradation of Sal forests in all forest strata however, the amount in variation depends on complex interaction of forest degradation with other factors such as species composition, terrain and types of anthropogenic pressures, weed infestation, soil erosion etc.

What is the total potential of C sequestration in terms of vegetation and SOC in Sal forests of study area?

The highest potential carbon density was assessed for Pure_Sal, followed by Sal_Mixed, Hill_Sal and Sal_Teak, indicating that Pure_Sal forests are better in carbon sequestration in the present study area. The total potential of vegetation carbon, soil organic carbon and total carbon stock was estimated to the value of 754.31, 519.86 and 1274.17 Gigagram (Gg) respectively. The highest existing and potential carbon stock was found in Pure_Sal with 40-60% density class which also covers the maximum area among all forest strata classes. The highest gap/loss in C stock was also found in Pure_Sal with 40-60 % density, followed by Hill_Sal with 10-40% density while gap/loss in existing and potential carbon density was assessed highest in Pure_Sal with 10-40% density, followed by Hill_Sal with 10-40% density class.

What is the relationship among biomass C, SOC and forest density classes and /or degradation?

The regression correlation between aboveground vegetation carbon and Soil organic carbon of corresponding forest density classes and /or degradation shown 0.6232 value of R^2 which was comparatively recorded better than the relationship between soil organic carbon and NDVI which supports that spectral reflectance in optical region of EMR is not directly related with soil organic carbon.

What is the relationship between above ground biomass related C density and spectral reflectance?

The best fit regression correlation of estimated aboveground biomass carbon was found with NDVI $_{3*3}$ (window average) values of linear function. The best fit correlation equation was used to for modelling biomass/carbon mapping. The results of aboveground biomass and carbon mapping was validated which indicates good prediction with the model developed.

6.2. Recommendations of the study

It may be concluded from the present study that Pure Sal forest is better in C-sequestration and therefore, may not be considered for the replacement from Teak plantation as has been observed in the study area**.** It is proposed that future research may also consider the analysis of impact of various types of anthropogenic pressures, with respect to forest degradations and carbon sequestration to understand complex process of depletion of carbon in soil and vegetation in different forest strata. Future study should consider more high resolution data for further better density class stratification. The present data can be used as baseline information for further temporal studies to ascertain the status of carbon sequestration in Sal forests and in planning of forest management plan to address the problem of forest degradation to enrich the carbon sequestration and long term carbon stock as mitigation measures of global warming.

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8. Appendices

8.1. Appendix –A: Proforma for field data collection of the sample plot.

SAMPLE SITE:

Area/Location (any landmark):

Sample Site-/Plot No.: Date: ……/……./ 2009

G.P.S. Reading : Latitude……º…...'……"Longitude ……º……..'…..…Altitude: …..mt

Slope (°):

Aspect : N/E/S/W/NE/SE/SW/NW Topography -General observations

A. VEGETATION SAMPLING

1: FOREST AND SOIL- GENERAL:

Forest Type: …………

Storey Number and Description – No. of storey….:

Top canopy species (Leaves/Without leaves):

First storey species (Leaves/Without leaves):

Second storey species(Leaves/Without leaves):

Regeneration – only tree species (in general very good, good and poor):

Evidence of disturbance -(Lopping/ Cutting/Fire/ Grazing etc)

Grass Cover (%): Ground Cover (overall % including grasses):

Stoniness (pebbles/boulders %): Rock Out-crop (%):

3: QUANTITATIVE MEASUREMENTS

Crown Density (%) (make small hole in leaf/paper and count sky or crown cover hits and steps, count which is ever is less in count):

North- south diameter: Steps: Hits: (Canopy/Sky)

East- west diameter: Steps: Hits: (Canopy/Sky)

1. Field data for Trees in sample plot (12.62 mt in radius (0.05 ha)).

Sl. No.	Name of the species	Girth of trees (cm)	Height of trees(mt)
1			
2			
3			
. n			

2. Field data for Shrubs/Tree sapling in sample plot (2.52 m radius(0.02 ha))

The measurement of girth to be taken at 30 cm above base (the representative stem of all shrub species either entire stem or pieces of 15 cm long from base, middle and top of the tiller to be collected) Girth class e.g.: Thick ≥15 cm, Medium 7-<15 cm and Thin <7 cm, can be considered with species and site-to-site.

Name of species	No. of bushes	Number of tillers in 3 bushes		Girth/Dia. (cm)	Height (mt)	Fresh Weight (gm)
		Bush No.	1 2 3	1 2 3	1 2 3	1 2 3
		Thick				
		Medium				
		Thin				
		Thick				
		Medium				
		Thin				
		Thick				
		Medium				
		Thin				

4. Field data for Herbs in sample plot (0.05 m radius(ha))

i. Fresh weight of herbs harvested in sample plot : …………………gm

ii. Oven dry weight of herbs of sample plot in lab: ……………….. gm

5. Field data for Litter and Humus in sample plot (0.05 radius(ha)).

i. Fresh Litter weight …… gm. Oven dry weight in lab ….. gm

ii. Fresh Humus weight …. gm Oven dry weight in lab .….. gm

6. Additional information:

i. level of biotic interference. Very high/ high/ medium/ low/ nil.

ii. Kind of biotic interference. Grazing/firewood/ lopping/ timber/ any other

iii. Approximate distance of nearby habitation/village ……..

iv. Forest working management system

v. Plantation if any

vi. Incidence of forest fire … high/ medium/ low/ very low.

B. SOIL SAMPLING

Sl. No.	Plot No	Depth range profile-wise		Soil sample collected profile-wise		Clod sample collected for profile-wise		Color of soil profile wise		% of coarse fragment profile-wise	
		No. soil profile	Depth range	No. soil profile	Soil sample	No. soil profile	Clod	No. soil profile	Color	No. soil profile	%
1.		1.									
2.		2									
3.		3									
4.		4									

8.2. Appendix – B: Volume equations of the tree species present in the study area

(Source: FSI, 1996. Volume equations for forests of India, Nepal and Bhutan, Forest Survey of India publication, Dehradun, India.)

Sl. No	Botanical name	Local name	Volumetric/biomass equation
1	*Adina cordifolia*	Haldu	$V= 0.378691+0.200954*D^2H$
2	*Aegle marmelos*	Bel	$V=0.000342+0.0922D+2.28178D^2H$
3	*Anogeissus latifolia*	Bakli	$\sqrt{V}=0.46976+5.99849D-2.60729\sqrt{D}$
4	*Bauhinia variegata*	Kachnar	$V= -0.04262+6.09491D^2$
5	*Casearia elliptica*	Chilla	$V=0.14031+2.06478D+11.25750D^2$
6	*Cassia fistula*	Amaltas	$V=0.066+0.287D^2 H$
7	*Cordia obliqua*	lissora	$V=0.00855+0.4432*D^2+0.28813*D^2H$
8	*Ehretia laevis*	Chamror	$V= -0.03844+0.946490D-5.40987D^2+33.17338D^3$
9	*Ficus religiosa*	Pipal	$\sqrt{D}=03629+3.95389D-0.84421\sqrt{D}$
10	*Garua pinnata*	Kharpat	$V= -0.014212+0.390288D^2H$
11	*Holoptelea integrifolia*	Kanju	$V=0.00342-0.0922D+2.28178D^2+9.46641D^3$
12	*Kydia calcycina*	poola	$V=0.000342- 0.0922D+2.28178D^2+9.46641D^3$
13	*Lagerstroemia parviflora*	Dhauri	$V=0.1649/D^2+2.42518/D-8.60085+28.48599D$
14	*Lannea coromandilica*	Jhingan	$V=0.19381-0.83928\sqrt{D} +10.32053 D^2$
15	*Mallotus philippensis*	Rohini	$V=0.14749-2.87503*D+19.61977*D^2-19.1163*D^3$
16	*Miliusa velutina*	Domsal	$V=0.00855+0.4432*D^2+0.28813*D^2H$
17	*Shorea robusta***	Sal	$\log y = (- 1.78825 + 1.04848 \log x)$
18	*Syzygium cumini*	Jamun	$V/D^2= 0.09809/D^2-1.94468/D+13.36728-6.33263 D$
19	*Tectona grandis*	Teak	$V=0.08847-1.46936D+11.98979D^2+1.970560D^3$

** Total above ground biomass equation developed by Negi (1984) for Sal trees of Doon Valley.

Abbreviations

D= Diameter of tree at breast height (meter).

H= Height of tree (meter)

V= Volume of tree bole

Y= total Above ground biomass of Sal tree (Kg)

X= D^2 H (diameter in centimeter and height in meter)

8.3. Appendix – C: Specific gravity of the species encountered in the study area

(Source: Indian woods, their identification, properties and uses. Vol: I-VI, (FRI publication, Dehradun)

Sl. no	Botanical name	Local name	Specific gravity
1	*Adina cordifolia*	Haldu	0.583
2	*Aegle marmelos*	Bel	0.754
3	*Anogeissus latifolia*	Bakli	0.757
4	*Bauhinia variegata*	Kachnar	0.571
5	*Casearia elliptica*	Chilla	0.70
6	*Cassia fistula*	Amaltas	0.746
7	*Cordia obliqua*	lissora	0.615
8	*Ehretia laevis*	Chamror	0.571
9	*Ficus religiosa*	Pipal	0.385
10	*Garua pinnata*	Kharpat	0.511
11	*Holoptelea integrifolia*	Kanju	0.498
12	*Kydia calcycina*	poola	0.347
13	*Lagerstroemia parviflora*	Dhauri	0.62
14	*Lannea coromandilica*	Jhingan	0.497
15	*Mallotus philippensis*	Rohini	0.571
16	*Miliusa velutina*	Domsal	0.615
17	*Shorea robusta*	Sal	0.728
18	*Syzygium cumini*	Jamun	0.647
19	*Tectona grandis*	Teak	0.57