It is now a well known fact that climate change will affect the forest conditions viz. area, health, vitality and biodiversity, threatening the survival of species and forest communities in some areas while allowing the increases in growth rates in others. Temperature, availability of water and changes in seasonality may all become limiting factors, depending on geographic area, climatic conditions, species diversity and human activities (FAO, 2012). Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability including alteration of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, morbidity and mortality, and consequences for mental health and human well-being (IPCC, 2014).

A close interaction exists between carbon storage and sequestration by forests and changing temperatures and precipitation. Increasing temperatures, longer dry seasons and increasing CO₂ concentrations in the atmosphere in the long term, are expected to reduce the capacity of forests to store and sequester carbon, possibly converting forests from carbon sinks to the carbon sources (Nepstad et al., 2008; Ollinger et al., 2008; Saigusa et al., 2008 and Clark et al., 2003). Hence, estimating the role of forest and tree plantations in carbon sequestration becomes crucial.

In the present study, efforts were made to assess the carbon sequestration potential of five different tree plantations in the University Campus of Kurukshetra University. The tree plantations selected for study were (1) mixed plantation of Acacia nilotica + Dalbergia sissoo, (2) pure plantations of Syzygium cumini and (3) Tectona grandis (all native species) and pure plantations of (4) Populus deltoides and (5) Eucalyptus tereticornis (exotic species). The trees were planted under social forestry schemes of Forest Department of Haryana. All the plantations were of uniform i.e. 10 years. However, the tree density of these plantations varied (A. nilotica+D. sissoo: 765 trees/ha, S. cumini: 1125 tree/ha, T. grandis: 400 tree/ha, E. tereticornis: 1350 tree/ha, and P. deltoides: 700 trees/ha).

The plantations were assessed for their herbaceous diversity, seasonal variations in physico-chemical properties of soil up to one meter depth, soil carbon stocks, soil respiration rates and soil microbial biomass carbon. The tree biomass and net primary productivity, vegetation carbon stocks and carbon flux, CO₂ assimilation rates by tree
biomass, monthly variations in litter fall were also determined for the selected plantations. The vegetation and soil carbon stocks were summed up for estimating the total carbon stocks of each plantation. The sum of carbon stocks of all the plantations was represented as the carbon stocks of the study area. The study was carried out over a period of three years from 2009 to 2012 and seasonal variations (winter, spring and rainy) were recorded for soil parameters. Soil parameters were studied across one meter depth divided into five depths (0-15cm, 15-30cm, 30-45cm, 45-60cm and 60-100cm).

Out of the five plantations selected for the study, higher herbaceous diversity was found in S. cumini followed by A. nilotica+D. sissoo and T. grandis. The least number of herbs were observed in P. deltoides plantation. The value of Simpson Index and Shannon Weiner Index was highest in S. cumini plantation. The lowest value of Simpson Index for herbaceous community was in T. grandis and A. nilotica+D. sissoo while that of Shannon-Weiner Index was in P. deltoides. The herb communities of A. nilotica+D. sissoo-S. cumini and S. cumini-T.grandis were found be most similar with each other on the basis of Index of Similarity and the least similar pair was A. nilotica+D. sissoo-E. tereticornis. Generally, the plantations of exotic species such as E. tereticornis and P. deltoides have very sparse understorey vegetation that may be due to the allelopathic interference of these trees besides the competition (Kohli, 1998; Singh et al., 2001).

In terms of soil properties, generally highest soil moisture content was observed in the plantation of A. nilotica+D. sissoo in all seasons and across all depths whereas soil of T. grandis had least moisture content. All the plantations accounted for higher moisture content in rainy season followed by winter and spring across all depths. Increasing trends in winter and spring and decreasing trends in rainy season down the depth were observed in the soil moisture. The soil of study sites was found to be moderately acidic (5.6-6.0) to moderately alkaline (7.9-8.5). The least or moderately acidic values of pH were observed in A. nilotica+D. sissoo plantation and higher or moderately alkaline values were observed in E. tereticornis plantation. Soil pH, in general, increased down the depth in all the seasons and plantations. Also, the bulk density of soil increased down the depth in all plantations. The highest values of soil bulk density were observed in T. grandis plantation followed by E. tereticornis and P. deltoides. The plantation of A. nilotica+D. sissoo accounted for least soil bulk density.
The highest percentage of total soil carbon was observed in *A. nilotica*+*D. sissoo* plantation followed by *S. cumini* and *P. deltoides* plantation. *T. grandis* plantation accounted for lowest percentage of soil total carbon in upper soil profiles while *E. tereticornis* plantation accounted for lowest soil total carbon in deeper soil profiles. In general, the percent total soil carbon content decreased down the depth and increased from the initiation to the end of study. The upper soil profiles (0-30cm) of all plantations showed a decrease in the soil total carbon content in different seasons as compared to the respective previous sampling season [0-15cm: *A. nilotica*+*D. sissoo* (rainy seasons); *S. cumini* plantation (winter, 2011); 0-30cm: *E. tereticornis* (spring, 2011); *T. grandis* (spring 2012) and *P. deltoides* (spring seasons)].

The general trend of soil organic carbon was same as that of total soil carbon with a decline down the depths and an increase over the study period. The percentage of soil organic carbon was higher in soil of mixed plantation of *A. nilotica*+*D. sissoo* followed by *S. cumini* and *P. deltoides*. *T. grandis* plantation accounted for lowest percentage of soil organic carbon in surface soil while in deeper layers the lowest soil organic carbon content was observed in *E. tereticornis* plantation. A little lowering in percentage of soil organic carbon content was observed in surface soils of all plantation in some seasons as compared to respective previous sampling seasons [0-15cm: *A. nilotica*+*D. sissoo* (rainy seasons); 15-30cm: *E. tereticornis* and *P. deltoides* (spring seasons), *T. grandis* (spring, 2012) and *S. cumini* (winter, 2011)]. The carbon held in the upper profile is often the most chemically decomposable and directly exposed to natural and anthropogenic disturbances. Changes in forest type, productivity, decay rates and disturbances can effectively modify the carbon contents of forest soils. Different forest management activities, such as rotation length; harvest practices; site preparation activities and fertilization can interfere more or less strongly with soil organic carbon (Harmon and Marks, 2002; Liski et al., 2001; Johnson and Curtis, 2001). Inorganic carbon content of soil generally increased with increasing depth in all the plantations. Significant differences were generally observed in the total carbon and organic carbon content of soil between different depths, between different seasons and between different species.

The soil total and organic carbon stocks based on percentage of total and organic carbon content in the soil, soil bulk density and soil depths were highest in *A. nilotica*+*D. sissoo* plantation followed by *S. cumini* and *P. deltoides* over the study
period. The incremental changes in total carbon stocks of soil over the entire study period were highest in *S. cumini* plantation followed by *A. nilotica+D. sissoo* and *T. grandis*. However, the incremental changes in the soil organic carbon during the study period were observed to be highest in *A. nilotica+D. sissoo* followed by *S. cumini*, and *T. grandis*. The *E. tereticornis* plantation accounted for least incremental changes in both total carbon stocks and organic carbon stocks of soil. Increased SOC has positive impacts on soil physical properties, including increased stable aggregates, decreased risk of run-off, erosion or surface capping, increased rate of water infiltration and increased water retention (Angers and Carter, 1996; Snyder and Vazquez, 2005; Johnston *et al.*, 2009). The stocks of inorganic soil carbon showed an increase over the study period in *A. nilotica+D. sissoo, E. tereticornis, S. cumini* and *P. deltoides* plantation. However, the plantations of *T. grandis* accounted for a decrease in inorganic soil carbon stocks.

Soil aggregates play central roles in most ecosystems, both as storage complexes of organic matter and mediators of belowground carbon transport (Verchot *et al.*, 2011). Micro-aggregates are primarily held together by microbial polysaccharides and humic matter and have slower turnover rates than macro-aggregates (Liao *et al.*, 2006; McCarthy *et al.*, 2008; Tisdall and Oades, 1982). Hence, micro-aggregates significantly contribute to long term storage of carbon. Fractionation of whole soil in to aggregates of different size classes depicted that major portion of whole soil was occupied by the micro-aggregates of size 250-53µm followed by silt and clay associated fraction of size <53µm. The least contribution to the whole soil was from macro-aggregates (2mm-250µm). These trends were found to be similar across all depths and all plantation species. Although the percentage of organic carbon was observed to be highest in macro-aggregates, the carbon storage (mg/g) based on weight fraction and bulk density values was highest in micro-aggregates among all plantations and soil depths.

The soil respiration in terms of CO$_2$ efflux was highest in rainy season in all plantations. Among different plantations, the higher respiration rates were observed in *P. deltoides* plantation followed by *T. grandis, S. cumini* and *E. tereticornis*. The least values of soil respiration were observed in *A. nilotica+D. sissoo* coinciding with its highest soil carbon content. Seasonal variation in soil respiration occurs because the respiratory activities of roots and soil microorganisms vary during the year. These variations among the tree plantations were found to be significant between different
species and between different months. Various factors like soil temperature, moisture, site productivity, soil physico-chemical properties and soil microbial communities greatly influence the rates of soil respiration in the form of CO$_2$ loss. The rates of CO$_2$ evolutions from the soil surface in the present study were found to be positively correlated with soil moisture, soil temperature, rainfall and atmospheric temperature. The soil respiration rates were significantly correlated with soil moisture and rainfall in all the plantations. However, significant correlation between soil respiration rate and soil temperature were observed only in *A. nilotica+D. sisoo* and *E. tereticornis*. The correlations were also significant between soil respiration rates and rainfall for *S. cumini, T. grandis, P. deltoides, and E. tereticornis* plantations. The significant correlation between soil respiration rates and mean monthly atmospheric temperature were observed for the plantations of *A. nilotica+D. sisoo* and *P. deltoides*.

The microbial biomass has an essential role in the cycling of nutrients and in the mineralization of organic C. Several studies of soil fertility include measurements of the microbial biomass in soil (Franzluebbers *et al.*, 1995; Jordan *et al.*, 1995; Yoshikawa and Inubushi, 1995). At the initiation of assessment of SMBC, the plantation of *T. grandis* accounted for higher SMBC followed by *A.nilotica+D. sissoo* and *S. cumini* whereas lowest SMBC was in *E. tereticornis*. The total soil microbial biomass carbon up to 30cm of soil depth as assessed for the tree plantations at the end of study period was higher in *S.cumini* followed by *T. grandis* and *E. tereticornis* whereas, the mixed plantation of *A.nilotica+D. sissoo* accounted for least soil microbial biomass carbon. In general, the SMBC decreased with increasing depth in all the plantations. The SMBC was higher in rainy season as compared to winter and summer, coinciding with the higher soil respiration rates. The lower soil respiration rates in case of *A. nilotica+D. sisoo* can also be attributed to the lower soil microbial biomass carbon. The differences in the soil microbial biomass carbon were found to be significant between species and between different depths.

Biomass and volume equations were applied to estimate the biomass of different components of all tree plantations. The highest total biomass (AGB+BGB) was of *T. grandis* plantation followed by *P. deltoides, E. tereticornis* and *A. nilotica+D. sissoo*. The lowest biomass was of *S. cumini*. However, the highest Net Primary Productivity was observed in *Eucalytpus* plantation indicating its fast growing characteristics followed by *P. deltoides* and *S. cumini*. The mixed plantation of *A. nilotica+D. sissoo*
accounted for least Net Primary Productivity over a period of one year. The biomass accumulation ratio was highest in *T. grandis* and lowest in *S. cumini* plantation. The biomass of the different tree components was significantly correlated with the basal area of the trees of all the studied tree plantations.

The carbon pools on the basis of biomass were also found to be highest in *T. grandis* and lowest in *S. cumini* plantation. The carbon fluxes as corresponding to NPP were higher in case of *Eucalyptus* and lowest in *A. nilotica+D. sissoo* plantation. However, the mean carbon pools per tree were found to be highest in *T. grandis* plantation followed by *P. deltoides* plantation representing their higher carbon sequestration potential over other species. These were followed by mixed plantation of *A. nilotica+D. sissoo*, and pure plantations of *E. tereticornis* and *S. cumini*. Based on amount of vegetation carbon pools, the *T. grandis* plantation also accounted for highest CO$_2$ assimilation in its biomass followed by *P. deltoides* and *E. tereticornis*. Among all plantation sites, the least amount of CO$_2$ was assimilated by *S. cumini*.

A large proportion of the above ground net primary productivity of the trees is added to the soil surface in the form of litter fall. Litter-fall in present field study and carbon content in the litter as a fraction of its biomass was observed to be highest in *T. grandis* plantation followed by *E. tereticornis* and *S. cumini*. The mixed plantation of *A. nilotica+D. sissoo* accounted for lowest litter-fall during the period of one year. In general, most of the litter-fall was concentrated in the dry winter and summer season in all the plantations. Leaf litter accounted for a major part of the total litter fall while minor contribution was observed to be from twig litter. The differences in the amount of litter fall were significant between different species and different months.

Total carbon stocks of the plantation as a sum of vegetation and soil carbon stocks were found to be highest in the *T. grandis* plantation. This was followed by *P. deltoides* and *A. nilotica+D. sissoo*. The least stocks were of *S. cumini* plantation. The soil carbon stocks contributed 41-79% to the total carbon stocks of respective plantation being maximum in *S. cumini* and minimum in *T. grandis* plantation. The contribution from vegetation carbon stocks to the total carbon stocks of plantations varied from 21-59% being highest in *T. grandis* and lowest in *S. cumini*. Out of the total carbon stocks summed up for all studied plantations in the University Campus, the highest carbon was sequestered by *T. grandis* plantation (25%). This was followed by *P. deltoides* (22%).
A. nilotica + D. sissoo (20%) and E. tereticornis (17%). The least values were observed for S. cumini plantation (16%). The highest contribution to the total soil organic carbon stocks over these five plantations was from A. nilotica + D. sissoo (26%) and to the vegetation carbon stocks were from T. grandis (34%). The low soil carbon pools of T. grandis, P. deltoides irrespective of their higher vegetation carbon pools can be attributed to the high soil respiration rates as compared to other species resulting in the loss of soil carbon. Also, large scale human interference such as fires, throwing of construction material on the soil surface, tillage of the field etc may have negative impact on the soil carbon pool. These activities may hinder with the natural decomposition process of the fallen litter as well as the recovery of soil carbon. The low soil carbon pools of fast growing exotic species like E. tereticornis may also be due to its negative impacts on physico-chemical properties of soil, water usage, understorey ground cover along with its allelopathic effects.

There are many benefits attributed to planting a mixed plantation which include more efficient nutrient use, conservation of site quality and biodiversity, enhanced yields over time, reduced risk of catastrophic damage from pests and disease outbreaks. Mixed-species can use nutrients more efficiently because of differences among species in rooting patterns occupying different soil strata for complete utilization of soil and water resources (Lamb and Lawrence, 1993), mycorrhizal associations (Perry et al., 1992), growth rate and form (Menalled et al., 1998), nutrient demands (Kelty, 1992) and soil mineralization rates (Matthews, 1989), and can be more productive than monocultures due to reduced competition and integral use of the site. Although, the plantations of T. grandis and P. deltoides, in the present study were observed to be much more efficient in storing carbon in their biomass, their efficiency of sequestering carbon in the soil was comparatively lower than that of mixed plantation of A. nilotica + D. sissoo due to higher soil respiration rates. The mixed plantation, along with its highest soil carbon pool also had a considerable amount of vegetation carbon stocks (Table 5.1). From these results, it can be inferred that the mixed plantation should be preferred over the monocultures.

In the present scenario, exotic species are preferred over native species because of their short-term visible economic gains, higher growth rates and productivity per unit area, resource demand and least post plantation care rather than ecological aspects, environmental suitability and sustainability (Sangha and Jalota, 2005; Kohli, 1998).
The potential disadvantages associated with exotic species are the problems of adaptability and susceptibility of the species to diseases, negative impacts on the environment resulting in undesirable changes in the physical, chemical and biological conditions of the soil and undesirable invasion or colonization of arable lands, pastures and native vegetation as well as displacement of the local flora (Senbeta et al., 2002). The results of the present study explained the benefits of native species over exotic species (viz E. tereticornis and P. deltoides) in terms of conserving more herbaceous diversity, higher vegetation and soil carbon pools as in case of T. grandis, and in terms of higher herbaceous vegetation and soil carbon pools as in A.nilotica+D. sissoo and S. cumini.

The results of the present study demonstrated that tree plantations with such large storage houses of carbon in their vegetation and soil can play a significant role in mitigating the dire consequences of climate change by decreasing or stabilizing the concentrations of atmospheric carbon dioxide. Tree plantations can maintain the health of soil that can provide a wide range of ecosystem goods and service and hence play a crucial role in sustaining biological productivity of the land. Less interference with natural growing system and avoidance of anthropogenic disturbances and adoption of best management practices can further increase the carbon sequestration potential of the tree plantations. Management systems that maintain a continuous canopy cover and mimic regular natural forest disturbance are likely to achieve the best combination of high wood yield and C storage (Thornley and Cannell, 2000).

There are many relatively recent developments in society that shape how the public views forest management, e.g., environmental movements and organizations, global-access to information etc. (Hughes, 1994; Hartley, 2002). Social forestry schemes in this regard play a crucial role for the betterment of existing forest, creating new areas with tree cover with significant ecological and environmental benefits. Through the social forestry scheme, the government has involved community participation, as part of a drive towards afforestation, and rehabilitating the degraded forest and common lands. Public opinions appreciably influence how forests are managed in some situations such as timber concessions on public lands, increased forest legislation in many states and nations, green-certification, and consumer preferences. Failure to consider public opinion thus can prove to be costly for foresters. For the better management of plantations the proactive managers should be rewarded over time for
including biodiversity considerations in plantation management practices, and for risking possible fiber reductions in order to experiment and evaluate potentially beneficial innovations in plantation management. In this way, along with the natural forests, the tree plantations through afforestation and reforestation programmes comprising social forestry schemes can prove to be a successful pathway in carbon sequestration and climate change mitigation.

Furthermore, sustainable harvesting of timber and other forest products should be ensured through the strict implementation of community forest operational plans. Control of forest fire is essential not only to protect aboveground biomass but also to protect and increase SOC pools. Land encroachment for new settlement and agricultural land should be stopped through the strict enforcement of laws and recurrent joint monitoring and supervision of local communities and government authorities. Access to biogas technologies by local communities as an alternative of fuel wood will also significantly reduce the stress on forests. Nurseries to grow fast growing native species, predominantly pioneer species, should be given priority for the biodiversity conservation. For forests and plantations, to fully achieve their potential to address climate change, their governance must be improved as forestry projects can provide low cost mitigation strategies for climate change as well as adequate standards of living by improved food security, reduced poverty and increased sources of income (Arora et al., 2012).
Table 5.1 Response of different tree plantations with respect to various parameters studied.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Incremental Changes in STC Stocks (Mg/ha)</th>
<th>Incremental Changes in SOC Stocks (Mg/ha)</th>
<th>Incremental Changes in SIC Stocks (Mg/ha)</th>
<th>Soil Respiration (Mg/ha/yr)</th>
<th>SMBC (mg/g)</th>
<th>Biomass (Mg/ha)*</th>
<th>NPP (Mg/ha /yr)*</th>
<th>Litter Fall (Mg/ha /yr)</th>
<th>Biomass Accumulation Ratio</th>
<th>Carbon Pools (Mg/ha)*</th>
<th>Carbon Flux (Mg/ha /yr)*</th>
<th>CO₂ Assimilation rates (Mg/ha/yr)*</th>
<th>Total Carbon Stocks (Mg/ha)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.nilotica+</td>
<td>Intermediate (23.94)</td>
<td>High (23.43)</td>
<td>Low (0.51)</td>
<td>Low (9.99)</td>
<td>Low (0.72)</td>
<td>Low (91.33)</td>
<td>Low (4.86)</td>
<td>Low (4.02)</td>
<td>Intermediate (18.79)</td>
<td>Low (43.22)</td>
<td>Low (2.32)</td>
<td>Low (8.53)</td>
<td>Intermediate (154.93)</td>
</tr>
<tr>
<td>D.sissoo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. cumini</td>
<td>High (31.05)</td>
<td>High (22.26)</td>
<td>High (8.79)</td>
<td>Intermediate (12.46)</td>
<td>High (1.49)</td>
<td>Low (53.84)</td>
<td>Intermediate (7.20)</td>
<td>Intermediate (8.10)</td>
<td>Low (7.48)</td>
<td>Low (25.58)</td>
<td>Intermediate (3.42)</td>
<td>Intermediate (12.53)</td>
<td>Low (98.94)</td>
</tr>
<tr>
<td>T. grandis</td>
<td>Low (17.09)</td>
<td>Intermediate (17.29)</td>
<td>Low (-0.20)</td>
<td>Intermediate (12.88)</td>
<td>Intermediate (0.95)</td>
<td>High (232.31)</td>
<td>Intermediate (6.05)</td>
<td>High (13.94)</td>
<td>High (38.37)</td>
<td>High (110.35)</td>
<td>Intermediate (2.83)</td>
<td>Intermediate (10.55)</td>
<td>High (171.49)</td>
</tr>
<tr>
<td>P.deltoides</td>
<td>Low (16.03)</td>
<td>Low (14.66)</td>
<td>Intermediate (1.37)</td>
<td>High (13.02)</td>
<td>Low (0.76)</td>
<td>Intermediate (186.21)</td>
<td>High (9.74)</td>
<td>Intermediate (7.29)</td>
<td>Intermediate (88.35)</td>
<td>High (4.63)</td>
<td>High (16.97)</td>
<td>Intermediate (153.52)</td>
<td></td>
</tr>
<tr>
<td>E .tereticornis</td>
<td>Low (14.15)</td>
<td>Low (13.51)</td>
<td>Low (0.64)</td>
<td>Low (10.16)</td>
<td>Low (0.77)</td>
<td>Low (98.50)</td>
<td>High (11.83)</td>
<td>High (10.84)</td>
<td>Low (8.33)</td>
<td>Intermediate (51.94)</td>
<td>High (5.62)</td>
<td>High (20.60)</td>
<td>Intermediate (128.42)</td>
</tr>
</tbody>
</table>

*total for above ground and below ground tree components, **total for soil and biomass carbon stocks