Above-ground tree outside forest (TOF) phytomass and carbon estimation in the semi-arid region of southern Haryana: A synthesis approach of remote sensing and field data

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Trees outside forest (TOF) play an important role in global carbon cycling, since they are large pools of carbon as well as potential carbon sinks and sources to the atmosphere. In view of the importance of biomass estimates in the global carbon (C) cycle, the present study demonstrates the potential of the standwise tree outside forest inventory data and finer spatial resolution of IRS-P6 LISS-IV satellite data to classify TOF, to estimate above-ground TOF phytomass and the carbon content of TOF in a semi-arid region of the southern Haryana, India. The study reports that above-ground TOF phytomass varied from 1.26 tons/ha in the scattered trees in the rural/urban area to 91.5 tons/ha in the dense linear TOF along the canal. The total above-ground TOF phytomass and carbon content was calculated as 367.04 and 174.34 tons/ha, respectively in the study area. The study results conclude that the classification of TOF and estimation of phytomass and carbon content in TOF can be successfully achieved through the combined approach of Remote Sensing and GIS based spatial technique with the supplement of field data. The present approach will help to find out the potential carbon sequestration zone in the semi-arid region of southern Haryana, India.

1. Introduction

The world's tree resources have a substantial role in the global carbon cycle. Although tree resources are mainly associated with the forest area, generally there is an extensive tree wealth exists outside continuous forested areas in every country. In general, trees outside forests (TOF) mean the trees available on agricultural land, along road, railways, canals, ponds, orchards, parks, gardens and homestead. In India, TOF is defined as all those trees, which have attained 10 cm or more diameters at breast height, available on land, which is not notified as forests (FSI 2011). However, FAO defines TOF as trees available on lands which is not defined as 'forests' or 'other wooded land' (Kumar 2006; FAO 2005). They make a critical contribution to sustainable agriculture, food security and rural household economies; they supply many products and services similar to forests; and they protect crops and the soil against water and wind erosion, thus combating drought and desertification and protecting water resources. Also, they embrace many ecological functions like conservation of

Keywords. Trees outside forest (TOF); phytomass; TOF mapping; LISS-IV; carbon sequestration.

biodiversity and carbon sequestration (Schroeder 1994; Rawat *et al.* 2004; FAO 2005). Tree's phytomass, the dry weight of a tree, is an information required for economic and environmental activities such as the development of policies for the use of timber resources, forest management, nutrient cycling, and CO_2 sink (since trees act as a reservoir for most carbon on the earth biota and soils), among other (Brown *et al.* 1989; Silva *et al.* 1993; Foody *et al.* 1996). Vegetation or plantation provides one of the natural ways of cleansing the atmosphere by absorption of gaseous and some particulate matter through leaves (Varshney 1985). Trees are good indicators of air pollution, and some of them do well under certain pollution to some degree and still there are others known to fix air pollutants also, but practically all of them provide innumerable environmental benefits. Plantation tree species are able to improve carbon sinks by absorbing CO_2 emissions and mitigate by drawing CO_2 from air into biomass, being only practical way of mitigating the gas from the atmosphere. Apart from that, plantations with pollution trap species along the linear features (such as roadside, canal side) and in the form of green-belts and agroforestry in urban periphery is one of the potential alternatives to mitigate air pollution as plants produce oxygen, serve as a sink for pollutants, and also check the flow of dust and fly-ash to the areas of human settlements and bring down noise pollution level (Rawat *et al.* 1998). Agrawal and Tiwari (1997) have studied the tolerance of species for the abatement of air pollution. The study found that *Albizzia lebbek, Ficus gibbosa syn. Ficus tinctoria, Terminalia arjuna*, and *Madhuca latifolia* are found to be good for the abatement of air pollution.

Thus, the reliable information on TOF presence, spatial distribution, type, quality, and temporal changes is needed, particularly in the larger areas where forest cover is very less such as provinces, countries or regions (FAO 2005). The need for reporting carbon stocks and stock changes for the Kyoto Protocol have placed additional demands for accurate surveying methods that are verifiable, specific in time and space, and that cover large areas at acceptable cost. Remote sensing has opened an effective way to estimate forest biomass and carbon. According to the IPCC GPG (Intergovernmental Panel on Climate Change, Good Practice Guidance 2004), remote sensing methods are especially suitable for quantification of aboveground vegetation biomass stocks and associated changes. Patenaude *et al.* (2005) have reviewed the applicability of different optical and microwave remote sensing techniques in the forest carbon estimation in relation to the 'Kyoto Protocol'. In recent years, impetus has been given to the road side, wasteland and farm forestry plantations. This points out to the fact that substantial tree wealth (TOF) exists in the country, which includes small wood lots (less than 1 ha in extent), block plantations, linear plantation along roads, canals, etc., and scattered trees on homesteads, farmlands and urban areas. Considering its intrinsic and tangible contribution to the national bio-resource stock, it is essential to account this valuable resource on a periodic basis. The status of TOF would also indicate the success of afforestation projects such as social forestry and wasteland development. As information on TOF is mostly absent from official statistics, policy initiatives for its management is also hurdled with time consuming methods of age-old inventorying. Although, there are a number of studies which mainly concentrate on the mapping and quantifying the deforestation, biomass, phytomass and carbon content estimation in forest area, very few are concerned about the fate of land formerly under forest and the tree wealth outside the forest area or on farmlands. Similarly, little is known about changes in tree cover in fields and urban systems (FAO 1999). For many developing countries where carbon database is either not available or incomplete, remote sensing coupled with ground-based observations can be used not only to generate and disseminate the carbon information but also pinpointing the potential locations for generating carbon credit pools (Kale *et al.* 2002).

There are a number of studies carried out on TOF resources from the last decades worldwide. De Gier *et al.* (2001) modeled the above-ground woody biomass assessment (fresh weight, volume, dry weight) of TOF using field data collected in three central American countries (30–45 trees per study site). Koukal and Schneider (2003) developed automatic algorithms in order to classify TOF on satellite imagery. The procedure shows acceptable results for classifying TOF combining Landsat ETM+ image (30 m) and IRS panchromatic images (5.8 m). They also tested the algorithm for an IKONOS panchromatic (1 m), covering a relative small area in the pacific region of Costa Rica. In India, Forest Survey of India (FSI) has been engaged in assessing the TOF wealth of the country since 1991. From 1991 onwards, the organization has been trying to improve the methodology of TOF assessment which has so far been based on field inventory methods, by incorporating satellite data of IRS LISS III, PAN and fused image from these two for editing and refinement of classified images (Rawat *et al.* 2004). At the national level, an attempt is being made in the National Carbon Project (NCP) to estimate the total phytomass and carbon density for plants/trees inside and out-side the forest through a project taken up by the Indian Space Research Organization (ISRO), Government of India under its ISRO-Geosphere and Biosphere Programme in XI FYP. Inventories of non-forest areas were also designed to generate information at the state level. In Kerala state, the Kerala Forest Research Institute carried out a systematic survey using small villages as sampling units in 1987–1988. This study estimated that the home gardens of Kerala had a total of 440 million trees – equivalent to an estimated growing stock of 134.13 million cubic meters, of which 8.15 million cubic meters meet the substantial portion of the total fuelwood requirements in the state. A systematic study of TOF in the state of (undivided) Madhya Pradesh was conducted by Indian Institute of Forest Management, Bhopal. This study relied on secondary as well as a primary source of data collected from eight districts and discussed the spatial distribution of TOF in these areas and its importance to the livelihoods of the local people.

The less forested semi-arid region of India, such as Haryana, Punjab, Maharashtra, Rajasthan, and central India, nearly the entire total fuelwood requirement are met from non-forest resources (Prasad *et al.* 2000). The significance of TOF in such areas plays a crucial role to relieve the pressure on forest resources, conserve farmland, and increase agricultural productivity, increase food supplies, etc. (FAO 2006). The large part of Haryana comes into the semi-arid region, which had only 3.53% forest lands (FSI 2011), and mainly covers with TOF. Besides, there is no well framed management policies exist in Haryana as far as the state or district level for the sustainable management of TOF is concerned. The quantity and distribution of TOFs are also unknown to liaison and policy makers in the state. It becomes more crucial that TOF assessment must be carried out in this region for the conservation and management of environmental resources. The present study aims to consider all these factors into account and target to assess the TOF resource in this semi-arid region. In order to bridge the gap of current research that exists, the study aims to meet two distinct objectives, first to present a standardized procedure for extracting the TOF information from the satellite image of IRS-P6 LISS-IV sensor and second is to estimate the above-ground TOF phytomass and carbon content in the semi-arid region of southern Haryana supplemented by extensive field data to remote sensing data of IRS-P6 LISS-IV sensor.

2. Materials and methods

2.1 *Study area*

The study area selected to estimate above-ground TOF phytomass and carbon content is a part of Mahendergarh district and located in the southern part of Haryana in India (figure 1). The area lies between 27°47′–28°26′N latitude and 75°56′–76°51′E longitude. The study carried out analysis for approximately two-third area of the total area of Mahendergarh district which is about 1228.12 km^2. Topographically this region is mostly plain and interspersed with isolated parallel hillocks of Aravali range with an altitudinal range of 67–529 m. The climate of the area is hot-tropical to sub-tropical and is characterized by high temperature and moisture deficiency for most of the year. The average annual rainfall is about 310 mm with a wide range of variation from 240–650 mm. The area is considered deficient in forest resources. However, it is mostly covered with strip forests having a small area under block forests. Strip forests are mainly situated along the railway lines, roads and canals. The area contains all the intended variations of TOF which were prerequisites for the research work, *viz.*, single tree, linear tree (plantation along the road and field bunds), the cluster tree, etc. Total area under various categories of strip forests in the district is 2394.26 ha. The area is dominated with the species like *Acacia nilotica, Acacia senegal, Capparis deciduas, Acacia nilotica, Azadirachta indica* and *Prosopis cineraria.*

2.2 *Data used and preparation*

The study utilized remote sensing data, ancillary data and extensive field data, the multi-spectral high spatial resolution data of IRS-P6 LISS-IV sensor has been procured from the National Remote Sensing Agency (NRSA), Hyderabad in a digital form. The IRS-LISS-IV sensor uses a CCD-linear push broom scanning system and provides data in three spectral bands: green, red and near-infrared with a resolution of 5.8 m. The data is procured for the month of October since during this month deciduous tree, which constitutes the larger part of TOF in the study area bear adequate foliage. It helps to identify and distinguish vegetation from other land cover features on the satellite image. The reason to select the LISS-IV data is mainly due to its high spatial resolution characteristics, which generally portrays more natural representations of objects that assist to map TOF from this data. It can also be used to demarcate small patches of TOF along the agricultural plots easily with the supplement of logical rule and interpretation keys. The present study carried out the analysis of the available single scene of IRS-P6 LISS-IV for the Mahendargarh district mainly due to limited satellite swath and to avoid the merging of different temporal datasets. Pre-processing and geo-referencing of procured satellite data was

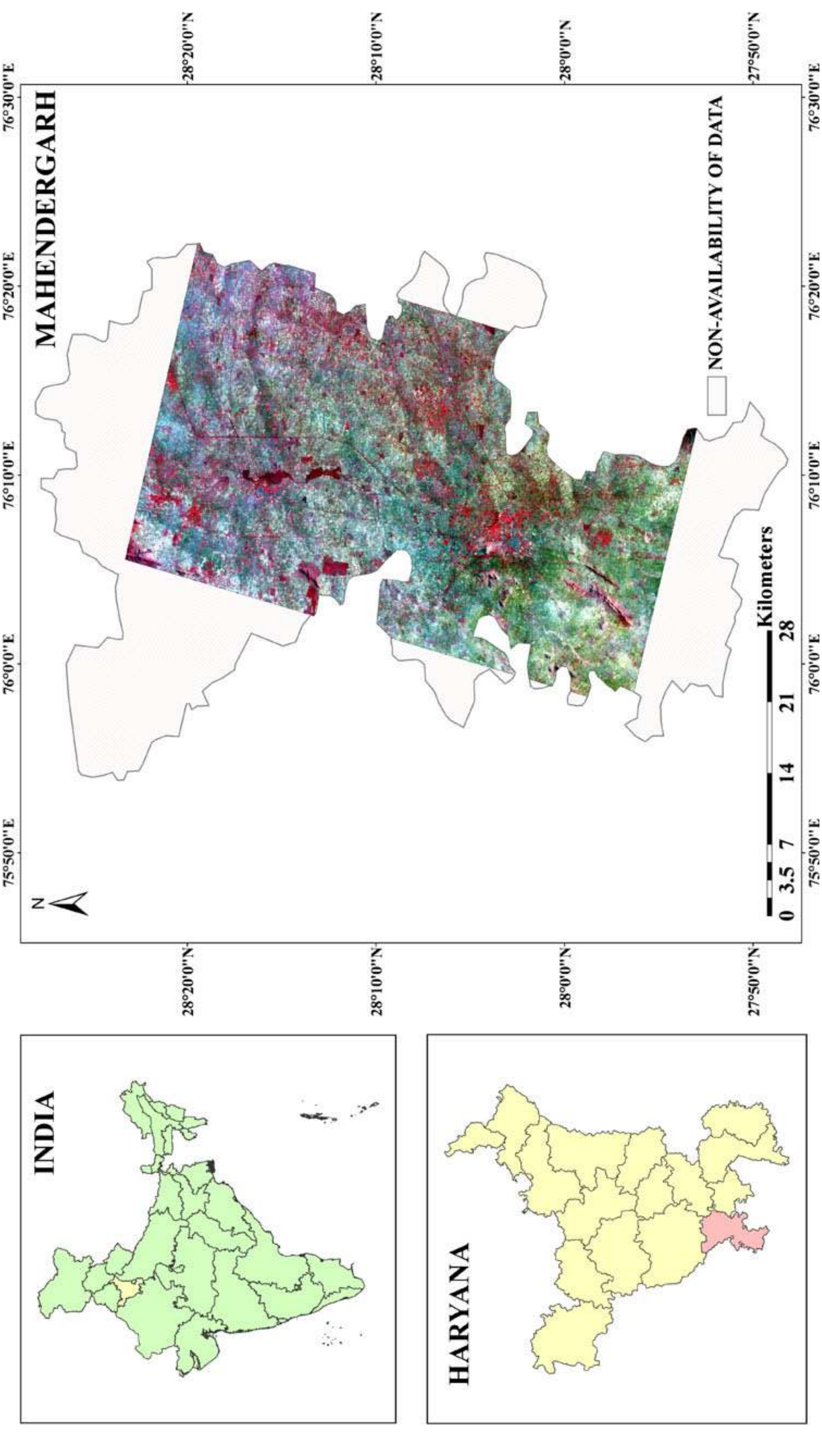

Figure 1. Location of the study area, part of Mahendergarh District in semi-arid zone of southern Haryana (false colour composite of IRS-P6 LISS IV).

done in Erdas Imagine 9.2 software where ArcGIS 9.2 was used for creating and merging the spatial and non-spatial database. The well defined and evenly distributed Ground Control Points (G.C.P) from the field and toposheets have been used for the geo-referencing of the raw image. It helped to achieve the RMS error of 0.246, which comes within a pixel. The ancillary datasets such as topographical map, district forest working plan, FRI/FSI publications (2000, 2003, 2007), soil maps, ASTER global digital elevation model (GDEM), forest cover type and density map from FSI (2005) were also used to assist the classification of TOF classes, to know the spatial distribution and characteristics of TOF and to utilize for designing TOF field sample plots.

2.3 *Trees outside forest (TOF) mapping*

Trees outside the forest have a relatively low density that makes assessment by conventional methods costly and time-consuming. The remote sensing data help to provide large area information at reasonable cost with less time. The LISS-IV data have been used to stratify the area, based on the geometrical formation of tree resources, into three classes: block plantation (group of trees), linear plantation and scattered trees (figure 2). Although, the spectral bands for the dataset were limited to green, red and infra red, these are the bands that contribute a maximum to vegetation analysis. The radiometric techniques, i.e., histogram matching and dark object subtraction methods were applied for removing radiometric distortions from the satellite image. It helps to improve the visual impact of a false colour composite (FCC) image to accurately demarcate TOFs. During the classification of TOF from satellite imagery, the reserved forest blocks are considered as the block TOF because the total area of the reserved forest is approximately to large block of the TOF. Intially, the Normalized Difference Vegetation Index (NDVI) has been used to differentiate vegetated and non-vegetated area from the satellite image. Thereafter, the unsupervised ISODATA classification algorithm was applied. The spectral classes obtained after running the ISODATA classification algorithm were grouped into two categories, *viz.*, TOF and Others (non-TOF) based on the tools available with the software, mainly cursor enquiry, colour palette manipulation and spectral enhancement tools. Spectral profile of prominent TOF classes and its confluence point with other classes were also taken into account while recoding. Later, the classified image is visually analysed for editing and refinement for inclusion and omission of misclassified patches. At last, the final TOF classified map is

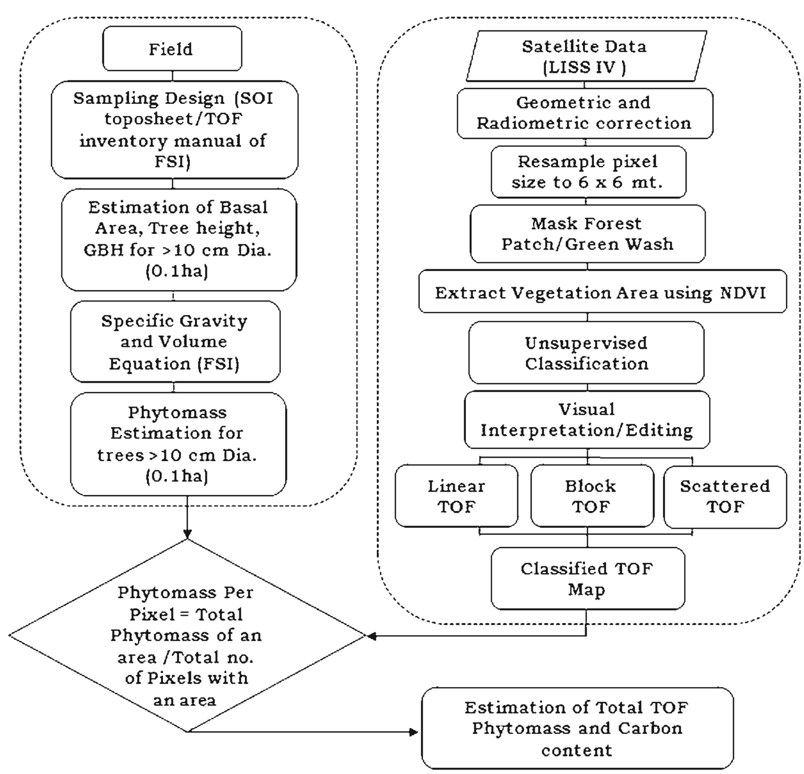

Figure 2. Schematic flow charts of the adopted methodology to classify TOF and estimate TOF phytomass.

generated which has three TOF classes, namely, block, linear and scattered TOF. The classified TOF maps later was used for calculation of total area under each category (stratum) of TOF. The classified raster image was further converted into vector format for enabling GIS analysis of the layer.

2.4 *Field data and tree outside forests (TOF) sampling design*

Remote sensing and field assessments are the main data sources for forest and TOF inventories. While remote sensing provides spatially explicit data for large areas at considerable costs, the number of attributes that can be extracted from remote-sensing imagery is rather limited; thus, field assessments continue to be an essential component of forest and TOF inventories (Köhl *et al.* 2006). The study carried out extensive field work during the mid of March in 2008 to calculate the TOF phytomass and the carbon content from the field. The stratified random sampling scheme has been designed and applied to collect and characterize the data related to TOF. The stratified random sampling design was preferred because it captures each and individual TOF characteristic in the sample and it is likely to be more representative of the each TOF population within individual TOF strata rather than a random sample of the same size. In the field, the non-destructive approach of phytomass estimation was adopted. The most important contribution of satellite data is to provide an opportunity to stratify the TOF in more or less homogeneous areas. The study area is stratified into three strata: block, linear and scattered with the help of remote sensing data and topographical sheets. There were 105 sample plots at 43 sites (figure 3) surveyed during the field for TOF enumeration and collecting other data to estimate TOF phytomass. The optimum plot size and number of samples required for each stratum has been

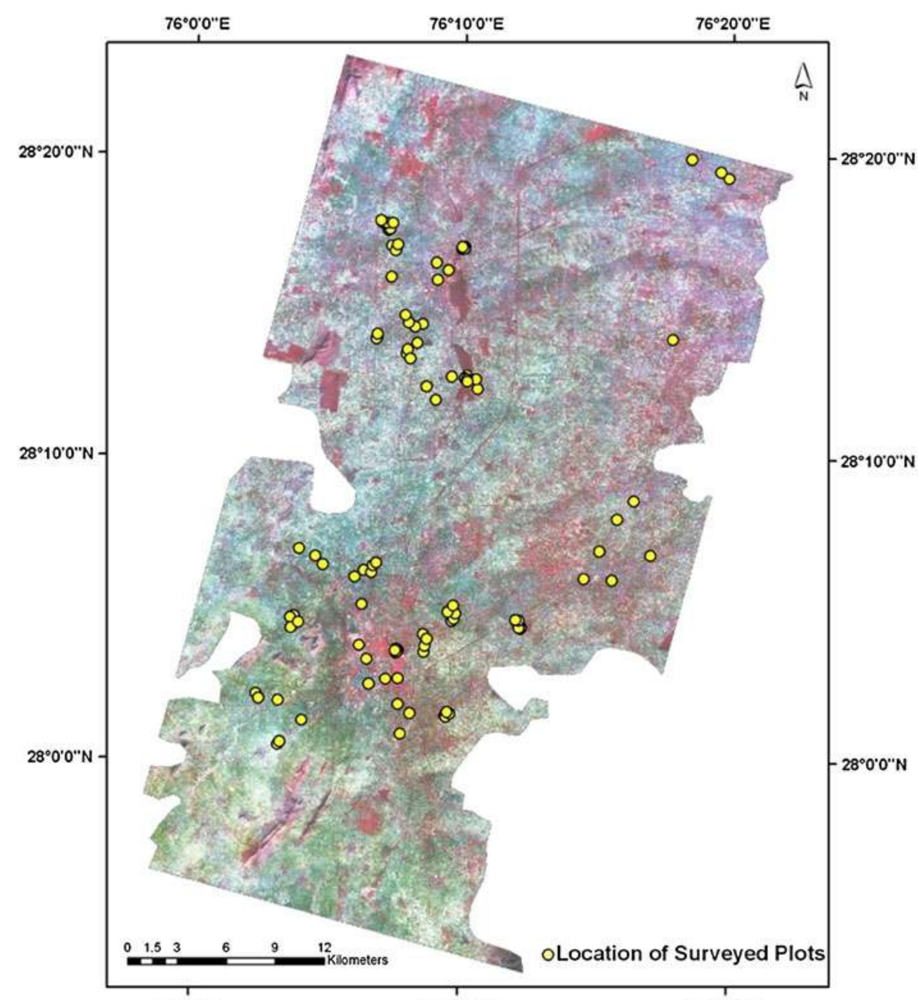

Figure 3. Location of distributed surveyed sample plot in the field to calculate the per plot phytomass.

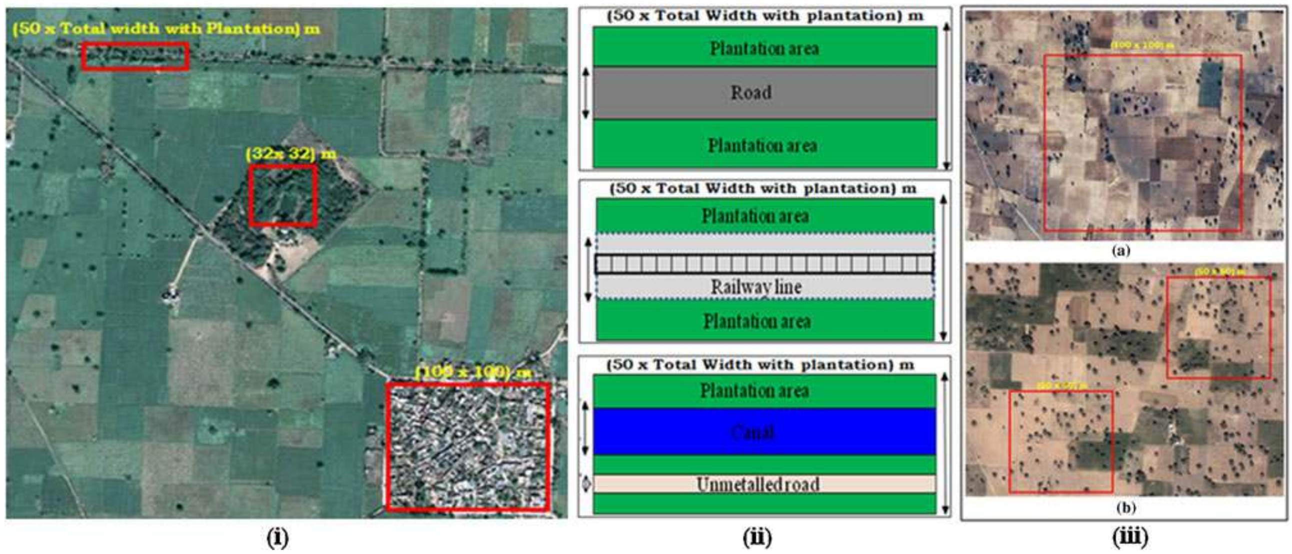

Figure 4. (i) Layout of the surveyed plot in different TOF stratum, (ii) layout of the plot for linear TOF stratum, and (iii) layout of the plot for scattered TOF stratum; (**a**) for sparsely dense tree; (**b**) for dense scattered tree.

determined according to the sampling design and field manual on TOF assessment by FSI (Rawat *et al.* 2005). The dimensions of the sampling plot were taken 32×32 m for the block strata of TOF, 50×50 m (dense scattered tree) and 100×100 m (sparsely scattered trees) for scattered strata and '50×Total width with plantation' for linear strata of TOF, i.e., along the road, canal and railway line (figure 4). The basic idea of layout of the sample plot was adopted from the FSI TOF Rural/Urban field manual, 2005 and learnt from National Carbon Pool Assessment Project under the aegis of ISRO Geosphere Biosphere Program (IGBP), India. Hand handled GPS was used for collecting centre coordinates of each individual plot during the field survey. Detailed data like enumeration of trees, tree species name, average stand height, girth at breast height (G.B.H) and altitude was collected from sample plots (FSI survey manual 2005). Besides, general information like soil type, slope, distance from water sources, road and settlement, etc., were recorded during the field survey to know more about the cause–effect relationship between TOF spatial distribution/characteristics and above-considered factors. During the field survey, various instruments like hypsometer (used to calculate the tree heights), compass, measuring tape, nylon rope, etc., were also used.

2.5 *Plotwise volume and phytomass estimation – ground and satellite-based observation*

Sitewise sample plot field data on plant species of TOF were organized in a spreadsheet and processed in a database environment. Plotwise field data of lat./long., altitude, TOF type, visual evidence of disturbance (lopping, grazing, fire, etc.), the local name of the tree, girth at breast height and tree height were transferred into database environment. Later, the data were converted into required unit as per the volume equations. Wood volume of individual trees was estimated using local species specific volumetric equations using either D.B.H (or G.B.H) (diameter/girth at breast height) and/or height of the trees. The volume was multiplied by species specific gravity to obtain the phytomass. The published and field based compiled literature by Forest Survey of India (FSI), Forest Research Institute (FRI 1996) and ICFRE (1996–2002) was reviewed to find out the site and species-specific volumetric equations and specific gravity for the tree species of the southern Haryana. A total number of 54 sites/region specific volumetric equations and species gravity of tree were found and used. For the remaining species general equations were used (equation 3). Some of the volumetric equations gave negative volume for the trees having G.B.H below 30 cm. The quarter girth formula was applied to calculate the volume for these trees (equation 4). Volumetric equations for some important trees of surveyed TOF class in the field are:

Acacia Nilotica:

$$\sqrt{V} = -0.00142 + 2.61911 * \mathrm{D} - 0.54703 * \sqrt{D} \quad (1)$$

Emblica Officinalis:

$$V = 0.01244 + 0.34322 * D^2 * \mathrm{H} \quad (2)$$

General Equation:

$$V = 0.00471 + 1.79326 * D^2 \quad \text{(for N.E. Rajasthan)} \qquad (3)$$

Quarter Girth formula:

$$V = \left(G^2/4\pi\right) * H \qquad (4)$$

where, V is volume, D is diameter at breast height, H is the height of the tree and G is girth at breast height in meter.

The phytomass of the individual tree was added to find out the total TOF phytomass for the each plot. The mean site TOF phytomass was obtained by dividing the total plot TOF phytomass with total area of TOF sampled plot. Thereafter, per pixel (for LISS-IV satellite image) phytomass was calculated for each TOF class based on calculated field TOF phytomass. For this purpose, Intially LISS-IV image was resampled from 5.8 mt pixel to 6 mt pixel to get the better approximation of the results and to calculate the total number of pixels within the surveyed TOF plots. The total calculated TOF phytomass for an individual surveyed TOF plot was divided by the total number of the image pixel within the corresponding surveyed plot to obtain per pixel TOF phytomass for an individual TOF class from the LISS-IV image. At last, the TOF phytomass occupied in an image pixel by each TOF class was multiplied by the respective classified TOF area from satellite image to obtain the total TOF phtyomass for each classified TOF class.

2.6 *Estimation of carbon content in TOF*

Phytomass has a direct relationship with the amount of carbon present in that plant biomass. Westlake (1963) has observed that there is 47% carbon present in dry plant biomass, while the Intergovernmental Panel on Climate Change (IPCC 1995) reported that the carbon present in plant biomass is 45% of it. Based on the results of different studies related to estimation of carbon in wood, it was observed that carbon varies between 45% and 50% for different ecosystems and thus considering 47.5% carbon in the woody biomass is quite reasonable for regional level carbon pool estimations (Raghubanshi *et al.* 1991). Unfeasible practicality to separate the different phytomass components for variations in carbon content as a function of the phytomass component has led to the usage of universal coefficient of 0.475 for the conversion of the phytomass to carbon. The present study considered the universal coefficient of 0.475 to estimate the carbon content in the TOF by multiplying the total phytomass by a conversion factor 0.475.

3. Results and discussion

3.1 *TOF mapping*

The methodology based on digital image processing, GIS and remote sensing data of IRS-P6 LISS-IV with supplement of visual interpretation and field data can be effectively employed to identify and map the TOF resources in the semi-arid region of India. It is expected to provide better estimates of TOF resources at a larger scale than the one generated through the field surveys only. The present results show a positive perspective regarding the ability to identify the TOFs from LISS-IV image. In addition, the significant differences found in terms of classified TOF types, TOF total area and number of objects of TOF areas can be mainly attributed to the better spatial and geometric resolution of the satellite image. A cursory look of the various classified outputs gives the impression that finer resolutions of LISS-IV could demarcate TOF effectively. Even the scattered and isolated TOF could be classified from its undergrowth vegetation (figure 5). The linear TOF patches as well as block/compact patches were more prominent in the classified datasets. Whereas, plantation along the canal, road or agriculture bunds were mapped separately in the datasets, while few scattered TOF pixels falling along the periphery of the linear feature and in the open area making it difficult to classify scattered TOF due to less foliage and undergrowth. Besides, young plantation species having less chlorophyll content and lopped tree do not have a proper reflectance on the satellite image. The mapping includes TOF patches of size greater than 0.014 ha (i.e., an area of 4 pixels of resample LISS-IV data) wherein during analysis it was also found in the case of small patches of size less than 0.014 ha with high canopy density and more foliage could be picked up in the mapping (figure 6). Ground validation of the classified output of 47 points has shown complete agreement with the ground situation except in few cases for the scattered TOF which covered an area of less than 0.014 hectares. Thus, omission and commission of few scattered TOF patches were noticed in the mapping. It is observed in a number of cases, that the neighbourhood cropped agriculture fields and pasture land had an impact on the classification of the particular type of TOF (along field bunds) and in those cases spectral response

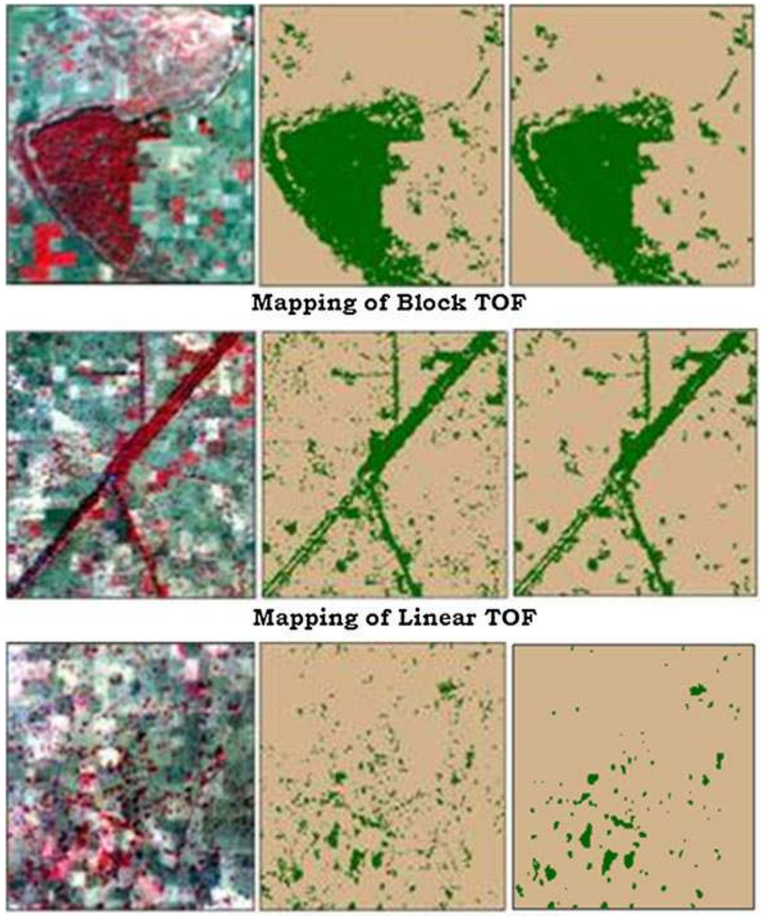

Figure 5. Mapping of TOF classes using LISS-IV image.

and textural information were used to differentiate. The infrared band of the LISS-IV data shows a high contrast which makes the features more distinct and helps to distinguish TOF from non-TOF vegetation area.

3.2 *TOF spatial distribution and characterization*

The total area covered by TOFs is 5142.32 hectares which is 4.19% of the total area considered for the TOF mapping. Among the TOFs, scattered TOF covered the maximum area of 2501.94 hectares and it shows that most of the semi-arid area of southern Haryana is dominated by the scattered TOF, wherein, the linear and block TOF covered an area of 1386.66 and 1253.72 hectares, respectively (figure 6). Although the scattered TOF dominated the study region, the density and crown cover is less as compared to linear and block TOF. Since, in the field, a large variation has been found in the number of trees and tree species among the classified TOFs. The number of trees/ha in linear pattern was varying from 171 to 1556, 478 to 557 and 852 to 1440 along road, railway line and canal, respectively (table 1). In the block plantation, the range varies from 447 to 1200. More trees are present in the rural/urban periphery and fewer number of trees in the centre of an urban area. The Prosopis cineraria (Khejari) is one of the dominant species which contributes more to phytomass content of scattered TOF in agro-forestry and number of trees vary from 64 and 164 trees/ha in scattered TOF. A visual inspection of classified images allows the identification of some spatial patterns of TOF distribution in the study area under investigation. The highest values of TOF density are concentrated in the central-east and central-southern parts of the study site (figure 6), signifying a cluster of TOF in these areas. The scattered TOF is mainly distributed throughout the image except the barren land and in the center of a rural/urban settlement (figure 6). The social and biophysical factors are determining the spatial distribution and characteristics of TOF in the study area, like in

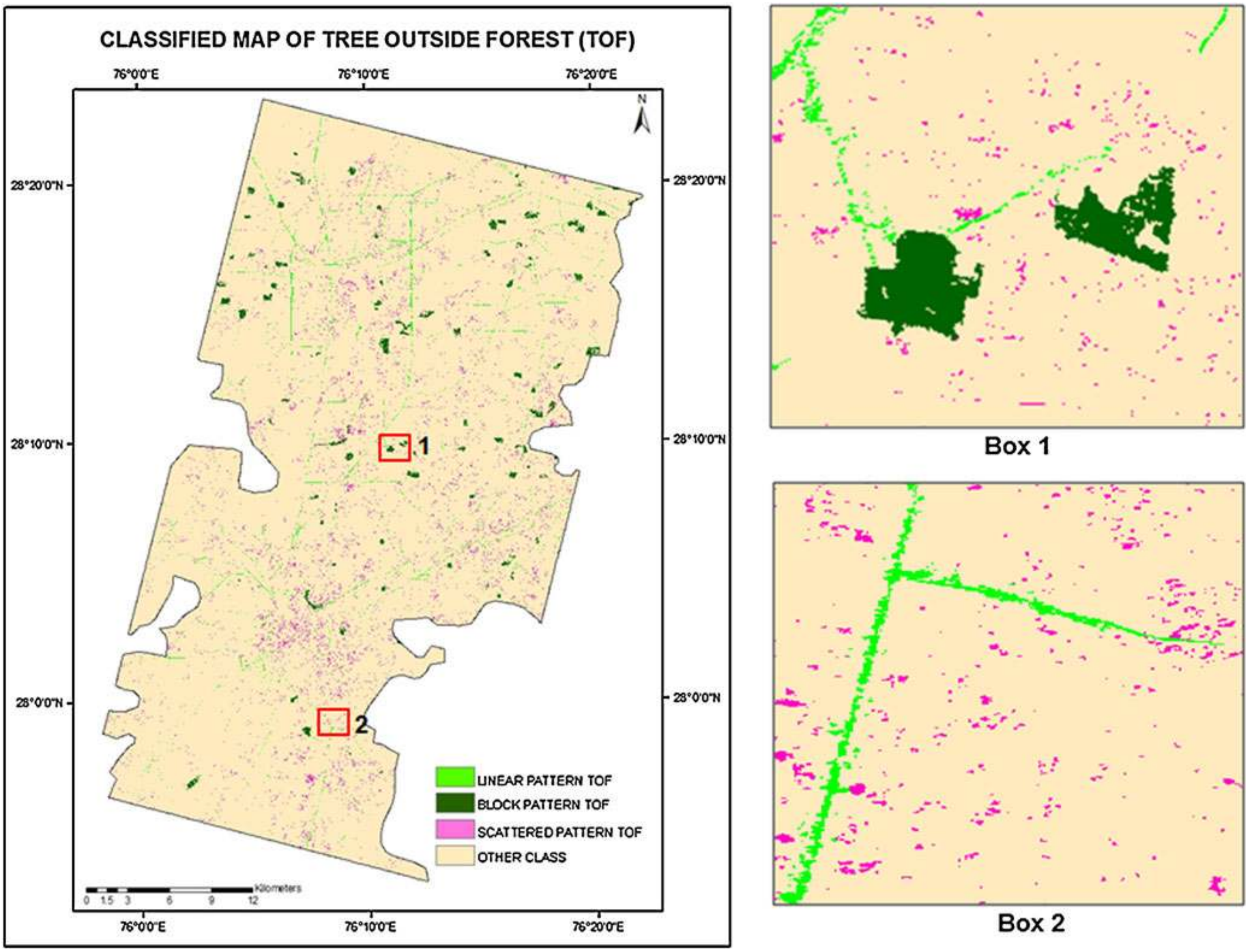

Figure 6. Spatial distribution of TOF classes on classified LISS-IV image; Boxes 1 and 2 show the distribution of block, linear and scattered TOF on a higher scale.

the case of canal and paved roads, the areas presenting the lowest values of TOF density are far away from these linear features. Another important factor determining TOF spatial distribution is the distance to nearest human settlement. TOF presence increases as the distance to human settlements decreases. In agricultural landscapes, it is expected that human settlements surround the farm system and the productive areas are near population centres.

Table 1. *Tree density (as per the TOF classwise).*

Sl. no.	TOF type	Number of trees/hectare
1	Linear	
a)	Road	171–1556
b)	Rail	478–557
c)	Canal	852–1440
2	Block	447–1200
3	Scattered	
a)	Urban	170–416
b)	Rural	132–336
c)	Agro-forestry	64–164

Table 2. *Calculated TOF phytomass (as per the TOF classwise).*

Sl. no	TOF type	Phytomass (tons/hectare)	Phytomass range (tons/hectare)
1	Linear	40.71	
a)	Road	41.59	8.3–91.3
b)	Rail	11.15	8–14.3
c)	Canal	45.21	12.7–92
2	Block	18.24	6.8–64.9
3	Scattered	7.15	
a)	Urban	9.53	1.3–25.4
b)	Rural	6.79	2–13.5
c)	Agro-forestry	6.33	3.3–12.4

3.3 *Estimation of phytomass for TOF*

The average plotwise (N = 105) phytomass of different TOF classes from the field data has been found to be 22.03 tons/ha with ranges from 1.26 tons/ha in the scattered trees in the urban area to 91.5 tons/ha in the dense linear TOF along the canal. It has been found that there is a variation of TOF phytomass in linear, block and scattered TOF. The linear TOF contains phytomass content of 40.71 tons/ha, block TOF contains 18.24 tons/ha and scattered TOF contains 7.15 tons/ha (table 2). The average calculated TOF phytomass for all three TOF classes in the region is 367.04 tons/ha. Besides, the total calculated phytomass content in each class of linear, block and scattered TOF is 207.99, 81.49 and 77.56 tons/ha, respectively (table 3 and figure 7). Calculated per pixel phytomass also vary from 0.15 tons per pixel size (p.p.s) (0.0042 tons/mt) for a linear tree to 0.031 tons/pps for scattered TOF. Besides, the variation in per pixel TOF phytomass for different TOF classes has been also found. The maximum per pixel phytomass was calculated for the TOF along the road (0.17 tons/pps) and canal where it is found comparatively less in the block TOF in urban areas and minimum in scattered TOF (0.023 tons/pps) of the urban/rural and agricultural area. The per hectare phytomass content along linear TOF has been found a maximum due to continuity of maximum tree density and old mature trees along the roads. The phytomass (tons/ha) along the canal also was found maximum due to higher moisture contents in the soil along the canal which favours the rate of growth of trees and the canopy cover. The phytomass range is nearly identical along the road and the canal where the most of TOF type comprises the same tree species. The phytomass (tons/ha) along the railway line has been found less as compared to the other linear patterned TOF, because the tree density along the railway line is comparatively low, which is mainly affected by work to change railway line from meter gauge to broad gauge. TOF phytomass has been found minimum in block TOF as compared to linear TOF because of vegetation type and external factors, i.e., site conditions, mainly either in reclaimed areas of river beds or in lower degraded part of the hills. Besides, the block plantation was found mainly outside of the rural and urban area which was highly affected by many factors like grazing, fire and lopping,

Table 3. *Calculated total TOF phytomass and carbon content (as per the TOF classwise).*

TOF classes	Area (hectare)	Area % to total geographical area	Phytomass per pixel	Total phytomass (tons/hectare)	Total carbon (tons/hectare)
Linear	1386.66	1.13	0.15	207.99	98.79
Block	1253.72	1.02	0.065	81.49	38.71
Scattered	2501.94	2.04	0.031	77.56	36.84

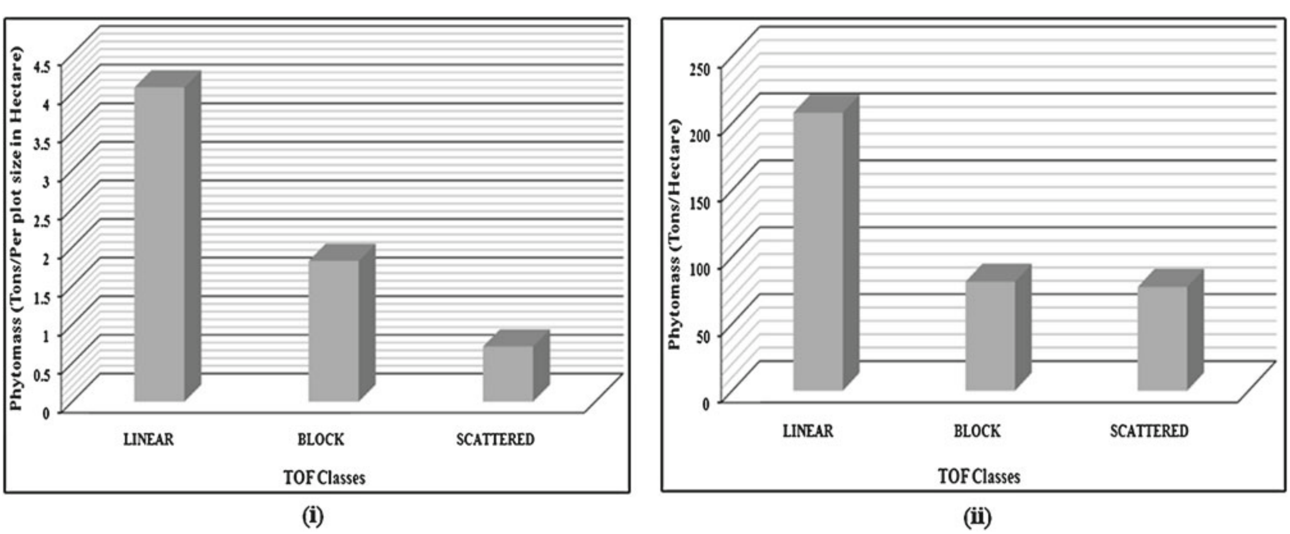

Figure 7. Calculated TOF phytomass shows (i) total calculated TOF phytomass for sample plot; and (ii) total calculated phytomass for different TOF classes in southern Haryana.

etc. Even the area under block pattern of trees has been used for many purposes like solid waste (dung, agriculture wastes) disposal. The scattered TOF, although covers the maximum part of the study area, it has minimum average TOF phytomass (tons/ha) as compared to other TOF. It is mainly due to the low density of trees in urban, rural and agro-forestry systems, the undergrowth of scattered TOF and the less phytomass content in scattered TOF species, i.e., Prosopis Cineraria (Khejari).

3.4 *Estimation of carbon content in TOF*

The content of carbon in phytomass has been reported as 45–50% of the total biomass. Accordingly, a mean value of 47.5% of the phytomass has been considered for carbon estimation. The total carbon content of different TOF classes was estimated by multiplying the total phytomass by a conversion factor 0.475. The plotwise average carbon content varies for all three individual TOF of linear, block and scattered which is 19.34, 8.66 and 3.4 tons/ha, respectively (tables 3 and 4). Besides, the total estimated carbon content store in all the TOF classes of the whole study area is 174.34 tons/ha. Among the TOF classes, the linear TOF stored more carbon content of 98.79 tons/ha as compared to block and scattered TOF which stored 38.71 and 36.84 tons/ha carbon content in it, respectively.

Considering the increasing importance of carbon sequestration studies all over the world, this kind of studies will provide a robust baseline database to assess the TOF phtyomass and carbon content and its change during the period of time, which can be used for different research and management purposes by the forest departments. Although, the differences in the phytomass and carbon content values for TOF's classes has been observed which was mainly due to differences in the plant density, woody part, vegetation thickness (height), canopy moisture level, different environmental site factors of TOF location, existence of distinctive phenological conditions, i.e., young plantation and looped TOF at the time of satellite data acquisition. However, selection of methods to calculate phtyomass during field, selection of general or regional volume equations and site specific gravity are some of the other equally important factors that should be precisely considered in the further study (Patil *et al.* 2011). This study can immensely help in tracking the major carbon sequestration potential zones of the semi-arid region which are less forested. TOF classification allows a more precise analysis of the biophysical and socio-economic factors affecting each class of TOF. This study will be very helpful in making a sampling plan for TOF area which is quite different from the sampling plan for the forest area. In order to accurately quantify the TOF phytomass and the carbon content for the semi-arid region on a large scale under the scenarios of plantation, agro-forestry, deforestation and degradation, the use of remote sensing data is the need of the hour, because the collection of field data for large areas at considerable costs and time will always be a problem. Although, the inability of the hitherto available remotely sensed data to provide TOF specific information, such as identification and measurement of tree cover class and its characteristics, have been some of the limiting factors in the use of remote sensing for TOF work. But, the latest remote sensing datasets of airborne laser altimetry, microwave and high spatial resolution sensors with GIS tools could be used for the TOF inventory, measurement of tree characteristics and volume estimations, for the the future estimation of phytomass/carbon content and its temporal changes in the semi-arid region.

Table 4. *Calculated carbon content (as per the TOF classwise).*

Sl. no.	TOF type	Carbon (tons/hectare)
1	Linear	19.34
a)	Road	19.75
b)	Canal	21.47
c)	Rail	5.30
2	Block	8.66
3	Scattered	3.40
a)	Urban	4.53
b)	Rural	3.22
c)	Agro-forestry	3.10

4. Conclusion

The study concluded that the assessment of phytomass and carbon in TOF can be successfully achieved through the combined approach of GIS techniques, field data and high spatial resolution data of IRS-P6 LISS-IV for the larger areas. The approach adopted here has the following salient features:

- The methodology using digital image processing, GIS and high-resolution satellite imageries can be effectively employed to identify and map the TOF resources in the semi-arid region of India. It is expected to provide better estimates of TOF resources than the one generated through field survey only. The LISS-IV image appears to be a better choice as it can be used effectively to classify TOF patches of minimal dimension (0.014 ha), i.e., those which are located in open fields, along the roadside and field bunds.

- The study reports that above ground TOF phytomass varied from 1.26 tons/ha in the scattered trees in the rural/urban area to 91.5 tons/ha in the dense linear TOF along the canal. The total above ground TOF phytomass and carbon content was calculated 367.04 and 174.34 tons/ha, respectively in the study area.
- TOF classification shows that the socio-economic and biophysical factors play an important role in affecting the spatial distribution and characterization of TOF in the semi-arid region of Haryana.
- The study shows that the TOF plays an important role in carbon sequestration in the semi-arid region of Haryana which is less forested.
- The study suggests that the semi-arid region of Haryana has a vast potential of increasing its tree cover as the state has a large percent of its total geographical area as cultural non-forest area. It will provide a fragmented TOF ecosystem which facilitates exchange of genetic resources.
- The TOF mapping employed as a part of this study should be used for future investigation of the new methods to allow more comprehensive and temporal study on differentiating managed and unmanaged TOF resources and monitoring its temporal change in the semi-arid region of India.

The present approach would offer the opportunity to identify and map the spatial distribution and characteristics of TOF resource and to estimate the above-ground phytomass and carbon content in the TOF resource from LISS-IV sensor of an IRS-6 satellite image by synthesising the field data. This study will further help to locate the area of potential carbon sequestration zone in the semi-arid region which ultimately helps to generate more carbon credit from the TOF resources in the semi-arid region of India.

Acknowledgements

The present study was taken up under the academic project work at the Indian Institute of Remote Sensing (IIRS) and was part of the National Carbon Project (NCP) funded by Indian Space Research Organization, Government of India under its ISRO-Geosphere Biosphere Programme. The authors express their gratitude to IIRS-NRSA-ISRO for data, materials and financial support. The support and encouragement from Programme Director, IGBP are duly acknowledged. Authors acknowledge the support received from Haryana forest officials during the collection of the field data.

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MS received 14 December 2011; revised 19 February 2012; accepted 7 April 2012