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Analysis of landuse and biomass in Khanda watershed, Garhwal Himalaya, using satellite remote sensing data

A.K. TIWARI*[1] ASHITA AGARWAL[2], SUNIL KUMAR[1#] & S.C. TIWARI[2]

[1]*Regional Remote Sensing Service Centre, Indian Space Research Organisation, 4, Kalidas Road, Dehra dun–248001, Uttaranchal, India*
[2]*Department of Botany, H.N.B. Garhwal University, Srinagar, Uttarranchal, India*

Abstract: In the present study, forest biomass mapping and estimates were carried out for a watershed in Garhwal Himalaya using stratified approach. IRS-1B, LISS II data of May 1994 with four spectral bands of spatial resolution 36.25 m were used for forest type and crown cover mapping. The forest type-cum-crown cover map was used as a major base for forest biomass mapping, which was then integrated with 'crown cover-biomass model'. Stand biomass for each site was computed from ground inventory using mean cbh, density and generalized species and interspecies allometric equations. Stand biomass values were related to the crown cover through allometric equations. Using these equations and mean crown cover for each individual class, mean biomass was computed for various components. The total biomass for each forest type was computed by using mean values and the areal extent of the class. Of the total geographical area of 113.50 km^2, non-forested land occupied 54.1% area. Forest cover was distributed in five forest types and stratified into three crown cover classes ranged viz., 21–40%, 41–60% and 61–80%. About 6.8% of the forest area (i.e. 3.1% of total area) was under 61–80% crown cover. Crown cover of >60% was encountered only in mixed conifer forest. The forests with >40% crown cover occupied 78.2% of forest land (i.e. 35.8% of the total area). Total above ground biomass in entire study area including village woodlands was 1217.94×10^3 t out of which 130.31×10^3 t was in village wood-lands. Among different forest types maximum biomass was found in *Pinus roxburghii* forest (315.55×10^5 t).

Resumen: En el presente estudio se llevó a cabo la estimación y el mapeo de la biomasa del bosque para una cuenca en Garhwal Himalaya, usando un enfoque estratificado. Se usaron datos IRS-IB y LISS II de mayo de 1994 con cuatro bandas espectrales de resolución espacial de 36.25 m para el mapeo de tipo de bosque y de cobertura de copa. El mapa de tipo de bosque/cobertura de copa constituyó la base principal para generar el mapa de biomasa forestal, el cual a su vez quedó integrado en el 'modelo de cobertura de copa-biomasa'. La biomasa del rodal para cada sitio fue calculada a partir del inventario de terreno usando la circunferencia promedio a la altura del pecho (cap), la densidad, y ecuaciones alométricas generalizadas para las especies e interespecies. Los valores de biomasa del rodal fueron relacionados con la cobertura de copa por medio de ecuaciones alométricas. Usando estas ecuaciones y la cobertura media de copa para cada clase individual, se calculó la biomasa media para varios componentes. La biomasa total para cada tipo de bosque fue calculada usando valores promedio y la extensión en área de la clase. Del total del área geográfica de 113.5 km cuadrados, la tierra no forestada ocupó 54.1%. La cobertura forestal estuvo distribuida en cinco tipos de bosque y fue estratificada en tres clases de cobertura de copa: 21–40%, 41–60% y 61–80%. Alrededor de 6.8% del área forestal (i.e. 3.1% del área total) quedó en la clase de cobertura de copa de 61–80%. Solamente en el bosque mixto de coníferas se encontró una cobertura de copa > 60%. Los bosques con > 40% de cobertura de copa ocuparon 78.2% del área forestada (i.e. 35.8% del área total). La biomasa aérea total en el estudio entero, incluyendo los arbolados de las aldeas, fue 1227.94×10^3 t, de las cuales 130.31×10^3 t se encontraba en dichos arbolados. Entre los diferentes tipos de bosque la biomasa máxima se encontró en el bosque de *Pinus roxburghii* (315.55×10^5 t).

Resumo: Neste estudo o mapeamento da biomassa florestal e da sua avaliação foi efectuado para uma bacia hidrográfica no Himalaia Garhwal usando uma abordagem estratificada. Os dados de IRS-IB, LISS II datados de Maio de 1994 com quatro bandas espectrais com uma resolução espacial de 36,25 m foram usados para o mapeamento dos tipos florestais e da cobertura de copas. O mapa cumulativo de tipo de cobertura de

**Corresponding Author;* e-mail: rrsscd@nde.vsnl.net.in
#Present Address: Forest, Rangeland and Watershed Stewardship Department, Colorado State University, Fort Callirs, CO 80523, U.S.A.

copas foi utilizado como a base principal para o mapeamento da biomassa, o qual foi depois integrado com "o modelo cobertura de copas-biomassa" A biomassa da parcela para cada estação foi calculada a partir de inventário de terreno usando DAP, densidade e equações alométricas generalizadas para as espécies e inter-específicas. Os valores da biomassa das parcelas estavam relacionados com a cobertura das copas através de equações alométricas. Usando estas equações e a cobertura média das copas para cada classe individual, a biomassa média foi calculada para várias componentes. A biomassa total para cada tipo florestal foi calculada através do uso dos valores médios e a extensão aérea da classe. Da área geográfica total de 113,5 km^2, a área não florestal ocupava 54,1%. A cobertura florestal estava distribuída em cinco tipos florestais e estratificada em três classes de coberto do copado situando-se entre os 21–40%, 41–60% e 61–80%. Cerca de 6,8% da área florestal (i.e.3,1% da área total) situava-se sob os 61–80% de cobertura do copado. A cobertura do copado > 60% encontrou-se somente na floresta mista de coníferas. As florestas com cobertura de copado > 40% ocupavam 78,2% da floresta (i.e. 35,8% da área total). A biomassa aérea total no conjunto da área estudada, incluindo a área da aldeia, foi de 1227,94*10^3 t das quais 130.31*10^3 t eram da floresta da aldeia. Entre os vários tipos florestais encontrou-se que a biomassa máxima estava contida nas florestas de *Pinus roxburghii* (315,55*10^5 t).

Key words: Biomass, crown cover, forest type, Himalaya, landuse, remote sensing.

Introduction

Biomass is one of the very important parameters affecting biosphere-atmosphere interactions. Estimation of woody biomass is a prerequisite for determining the state and flux for biological materials in an ecosystem and for understanding the dynamics of ecosystem (Anderson 1971; Chaturvedi & Singh 1987; Rawat & Singh 1988). Information on biomass is not only important from the standpoint of fundamental ecology, but also relevant to planning for ecologically sustainable development of a region (Singh & Singh 1992). Destructive techniques for biomass estimation procedures are time consuming and expensive in both conventional and short rotation forestry, due to large dimensions and amounts of biomass that have to be processed (Verwijst & Telenius 1999). The majority of ecological literature includes information on the site specific biomass estimations (Crow 1978; Negi *et al.* 1983; Nihalgard 1972; Ogino 1977; Rai 1984; Satoo 1968; Whittaker & Woodwell 1969). Several case studies have been attempted to quantify the biomass accumulation at site level (e.g. Adhikari 1992; Alves *et al.* 1997; Chaturvedi & Singh 1987; Fearnside & Guimaraes 1996; Pereira 1996; Rana *et al.* 1989; Rawat & Singh 1988; Saldarriaga *et al.* 1988; Uhl *et al.* 1988). Most of these studies estimated total aboveground biomass through allometric equations. These equations were derived by using destructively measured dry weights of trees as the dependent variable and field measurements of biometric parameters as the independent variables. Remote Sensing data were used for biomass mapping of rangelands and croplands (Aase & Siddoway 1981; Barnett & Thompson 1983; Steven *et al.* 1983; Tucker & Sellers 1986; Tucker *et al.* 1980, 1981). In the present study, forest biomass mapping and estimates were carried out for a watershed in Garhwal Himalaya using stratified approach as described by Tiwari (1994).

Study area

The study area, Khanda Watershed, lies between 79^0 41' to 79^0 51' longitude and 30^0 7' to 30^0 13' latitude and falls within the administrative district of Pauri and Tehri Garhwal. With an areal extent of 113.50 sq. km., the study area comprises a heterogeneous landscape with respect to topography, micro-climate and natural vegetation. The altitude varies from 650 m (Khanda Village) to 2143 m (Nagdev Reserve Forest) above mean sea level. Natural vegetation of the area includes dominance of *Pinus roxburghii* Sarg. forest in lower altitudes to mixed conifer species like *Cedrus deodara* (Royle ex D. Don) G. Don and *Cupressus torulosa* D.Don in the higher altitudes. Intermediate elevations include Oak (*Quercus leucotrichophora*) and Pine mixed broadleaf forests.

The climate of the area is sub-tropical to temperate on higher elevations. There are three distinct seasons namely rainy (mid June to September), winter (November to February) and summer (April to mid June). The region is influenced by the southwest monsoon with annual precipitation of 1807 mm. Mean monthly temperature fluctuates between 1.3^{0}C (in

Table 1. Transformed divergence between different classes.

Landuse classes			1	2	3	4	5	6	7	8	9	10	11	12
Pinus roxburghii	21–40%	1	0	1728	2000	1994	1980	1980	1903	2000	2000	1803	2000	2000
Pinus roxburghii	41–60%	2		0	2000	1999	2000	2000	1935	2000	2000	2000	2000	2000
Mixed Oak Forest	41–60%	3			0	1922	1957	1989	1995	1999	2000	2000	2000	2000
Pine Mixed Broadleaf	21–40%	4				0	1875	1999	2000	1938	1947	1992	2000	2000
Pine Mixed Broadleaf	41–60%	5					0	2000	1958	2000	2000	1999	2000	2000
Oak Forest	41–60%	6						0	2000	1969	1987	2000	2000	2000
Mixed Conifer Forest	21–40%	7							0	1875	1882	1997	2000	2000
Mixed Conifer Forest	41–60%	8								0	1792	2000	2000	2000
Mixed Conifer Forest	61–80%	9									0	2000	2000	2000
Village Woodland		10										0	2000	1964
Agriculture		11											0	1982
Scrub/Grass		12												0

January) to 41^0 C (in June). The average relative humidity varies from 45% to 87%.

Methods

Forest type and crown cover mapping

For forest type and crown cover mapping, IRS-1B, LISS II data in four spectral bands of spatial resolution 36.25 m were used. Ground truth was collected with the help of topographic maps, forest compartment maps and satellite imagery. Preliminary interpretation of satellite data was done visually on false colour composite in order to stratify forest types.

Possible separability of various land use/land cover types with special reference to vegetation cover was studied using ground collected for land use/land cover of study area. The field survey was carried out across the study area. A total of 50 traverses were surveyed. The ground truth sites, which could be identified on satellite imagery, were used as training sets for classification. Different forest types were recognized based on species dominance.

The divergence (Jenson 1986) between two classes was computed as:

$$D_{cd} = 0.5[(V_c - V_d)\ (V_d^{-1} - V_c^{-1})] + 0.5\ tr\ [(V_c^{-1} - V_d^{-1})\ (M_c - M_d)\ (M_c - M_d)^T]$$

Where, D_{cd} is the divergence between classes c and d, tr is trace of a matrix, V_c and V_d are the co-variance matrices for the two classes c and d, and M_c and M_d are the mean vectors for the classes c and d.

The transformed divergence has been suggested as a better measure of the separability, as it scales the divergence values between '0' and '2000' (Kumar & Silwa 1977). The transform divergence was computed from the divergence as:

$$D_{cd}^T = 2000\ [1 - \exp\ (-D_{cd}/8)\ ]$$

Values of transformed divergence (D_{cd}^T) between different classes are presented in Table 1.

The transformed divergence value of 2000 was considered to be the indicator of excellent separation, 1900 to 2000 as a good separation and 1700 to 1900 as a moderate separation (Jenson 1986; Tiwari *et al.* 1990). The spectral statistics for various classes were used to classify the entire area through maximum likelihood criteria. It was assumed that the assigned discrete crown cover ranges (e.g. 20–40 %) may or may not be true after the classification. In order to remove such errors of classification real crown cover was measured on the ground for each crown cover range, using the line intercept method (Misra 1968; Tiwari & Singh 1984, 1987).

Basal cover and biomass

The forest type-cum-crown cover map was the major base for forest biomass mapping. The forest type cum crown cover map was integrated with the 'crown cover-biomass' model. These models were generated following the technique described by Tiwari & Singh (1984). A total of 50 sites representing all the crown cover classes of various forest types were selected randomly from the classified output. In each site 8–12 quadrats, each 10×10 m in size, were laid down. In each quadrat, each individual tree having circumference at breast height (cbh) >31.5 cm was measured for cbh. In each site crown cover was measured through a line intercept method (Misra 1968) using a 50 m long measuring tape with 10 to 12 replicates. The length of the tape covered by

Table 2. Mean crown cover (ground measured) and area in different forest classes.

Forest Type/Crown Cover	Mean Crown Cover	Area (ha)	Area (%)
Forest			
Pinus roxburghii Forest			
21–40%	23 ± 3%	564.5	10.84
41–60%	53 ± 2%	1247	23.96
Mixed Oak Forest			
41–60%	54 ± 7%	888	17.06
Pine Mixed Broadleaf			
21–40%	34 ± 5%	271	5.21
41–60%	47 ± 5%	284	5.45
Oak Forest			
41–60%	52 ± 4%	876	16.83
Mixed Conifer Forest			
21–40%	34 ± 4%	298	5.72
41–60%	55 ± 3%	417	8.02
61–80%	74 ± 6%	359	6.89
Total		5204	99.97
Non-Forest			
Village Woodland	16 ± 3%	2435	39.61
Agriculture		1713	27.86
Scrub/Grass		2000	32.53
Total		6148	100

the tree crown was measured. By averaging all 10 replicates, percent crown cover for that site was computed. Mean crown cover was obtained by pooling data from various sites of each crown cover class of each forest type. The mean crown cover and area of different classes are presented in Table 2.

Stand biomass for each site was computed using mean cbh, density and generalized species and interspecies allometric equations, of the form:

$$\ln Y = a + b \ln X$$

where, Y is the biomass per tree and X is the circumference at breast height, Intercept (a), slope (b) and r^2 values for these equations are given in Table 3.

Stand biomass values were related to the crown cover through allometric equation of the form:

$$\text{Log}_{10} Y = a + b\ \text{Log}_{10} X$$

where, Y is the biomass (kg 100 m^{-2}) and X is the crown cover (%); Intercept (a), slope (b), r^2 and $S_{y.x}$ values of above relationship are presented in Table 4.

Using above equation and mean crown cover for each individual forest class, mean biomass was computed for various components, viz., bole, branch, twig, foliage and total above-ground biomass. The mean biomass was multiplied with area under the class to compute total biomass. Bole biomass, branch biomass, twig biomass, foliage biomass and total above ground biomass values were regrouped into discrete classes with interval of 40 t ha^{-1}, 25 t ha^{-1}, 10 t ha^{-1}, 8 t ha^{-1} and 80 t ha^{-1} respectively. All the classes falling within similar ranges were regrouped through multi-layer modeling programme of EASI/PACE software, to generate bole biomass, branch biomass, twig biomass, foliage biomass and total aboveground biomass maps.

Table 3. Allometric relationship between biomass of the tree components (Y, kg per tree and cbh (X, cm) according to lnY= a + b lnX).

Component	Intercept (a)	Slope (b)	r^2	$S_{y.x}$
Pinus roxburghii				
Bole	-0.2391	0.9612	0.87	0.063
Branch	0.0512	0.8025	0.89	0.057
Twig	-1.2531	0.6212	0.91	0.067
Leaf	-1.1739	0.5623	0.088	0.093
Quercus leucotrichophora				
Bole	-0.5238	1.1032	0.92	0.082
Branch	-1.1591	0.9125	0.93	0.075
Twig	-0.3215	0.8126	0.86	0.092
Leaf	-0.0232	0.7251	0.95	1.125
Cedrus deodara				
Bole	1.4721	1.0108	0.93	0.321
Branch	0.0421	1.8732	0.59	0.052
Twig	-0.0114	0.7315	0.88	0.039
Leaf	-0.0625	1.6719	0.87	0.215
Cupressus torulosa				
Bole	0.2071	1.2113	0.98	0.072
Branch	-0.1215	0.9312	0.92	0.065
Twig	-0.4125	0.8321	0.86	0.012
Leaf	-0.8926	0.8103	0.86	0.121
Interspecies				
Bole	1.1351	1.2139	0.91	0.132
Branch	1.0162	0.8132	0.91	0.912
Twig	-0.7125	0.8162	0.88	0.101
Leaf	-0.5932	0.7161	0.86	0.212

Classification accuracy

The accuracy of landuse/vegetation map was calculated following Story & Congalton (1986). For evaluation of accuracy of the classified output, the minimum number of sample points for comparison of classified output with ground was calculated to be 205 for an expected accuracy of 85% and allowable error of 5%, using the formula on binomial distribution (Fitzpatrick–Lines 1980).

Table 4. Allometric relationship between crown cover (X, cm) and biomass (Y, t ha^{-1}) according to $\log_{10}Y = a + b \log_{10}X$

Forest type	Intercept (a)	Slope (b)	r^2	$S_{y.x}$
Pinus roxburghii				
Bole	0.1981	1.1443	0.93	0.081
Branch	0.1098	0.7949	0.88	0.072
Twig	-0.8259	1.1757	0.87	0.035
Leaf	-1.009	1.244	0.83	0.043
Mixed Oak Forest				
Bole	0.5591	0.8849	0.96	0.075
Branch	0.3531	0.9035	0.87	0.043
Twig	0.1031	0.9562	0.88	0.037
Leaf	-0.1926	0.8227	0.85	0.027
Pine Mixed Broadleaf				
Bole	0.4764	0.8987	0.89	0.075
Branch	0.0744	1.0162	0.91	0.052
Twig	-0.7944	1.3735	0.87	0.043
Leaf	-0.7341	1.2348	0.82	0.027
Oak Forest				
Bole	0.7011	0.8123	0.93	0.045
Branch	0.5350	0.8135	0.91	0.032
Twig	-0.2866	1.0669	0.88	0.028
Leaf	-0.4156	1.0865	0.85	0.027
Mixed Conifer Forest				
Bole	0.3671	0.8813	0.91	0.051
Branch	0.2073	0.9316	0.91	0.032
Twig	-0.1533	0.8659	0.92	0.027
Leaf	-0.5702	1.0598	0.88	0.025
Open Woodland/V.W. Land				
Bole	-0.0510	1.2372	0.89	0.041
Branch	-0.1574	1.0513	0.82	0.072
Twig	-0.3743	1.0371	0.81	0.042
Leaf	-0.3688	0.9358	0.81	0.022

$$N = 4\,(p.q)/E^2$$

where, N= the minimum number of points to be examined, p= the expected accuracy of the map, q=(100–p), and E= the allowable error. The sample points were selected randomly on classified image.

Results

Spectral separability

As depicted by the transformed divergence between classes (Table 1), the separability between the crown cover classes of each forest types was of a moderate nature (i.e. D_{cd}= 1800–1900). While, the separability between the forest types was good to excellent (D_{cd}= 1900–2000). The data used in the present study was for the summer season. The phenological stages of the forest types were significantly different which was mainly responsible for the inter-class separability. Coupled with the phenological stages was the remarkable geographical distribution of the forest types with reference to terrain topography. For example, *P. roxbourghii* dominated forest were found on elevation range between 700 m to 1800 m mainly on drier slopes (southern aspect). Higher elevations were mainly dominated by oak and mixed conifer forests, out of which oak forests were found mainly on North and North west aspects.. Eight land use/land cover classes have been delineated in the classified output and area of individual classes was calculated.

Table 5. Area under different Land use and Land cover.

Land use Class	Area (km^2)	forest/non-forest area	% of total geographical area
Forest			
Pinus roxburghii Forest			
21–40%	5.65	10.84	4.97
41–60%	12.47	23.96	10.98
Mixed Oak Forest			
41–60%	8.88	17.06	7.82
Pine Mixed Broadleaf			
21–40%	2.71	5.21	2.38
41–60%	2.84	5.45	2.51
Oak Forest			
41–60%	2.76	16.83	7.72
Mixed Conifer Forest			
21–40%	2.98	5.73	2.63
41–60%	4.17	8.02	3.67
61–80%	3.59	6.89	3.16
Total Forest	52.04	100	45.84
Non-Forest			
Village Woodland	24.35	39.61	21.45
Agriculture	17.13	27.86	15.09
Scrub/Garss	20	32.53	17.62
Total Non-Forest	61.48	100	54.16
Total Area	113.5		

Landuse and vegetation

Spatial distribution of various forest types is presented in Fig. 1(a). Forest occupied 52.04 km^2

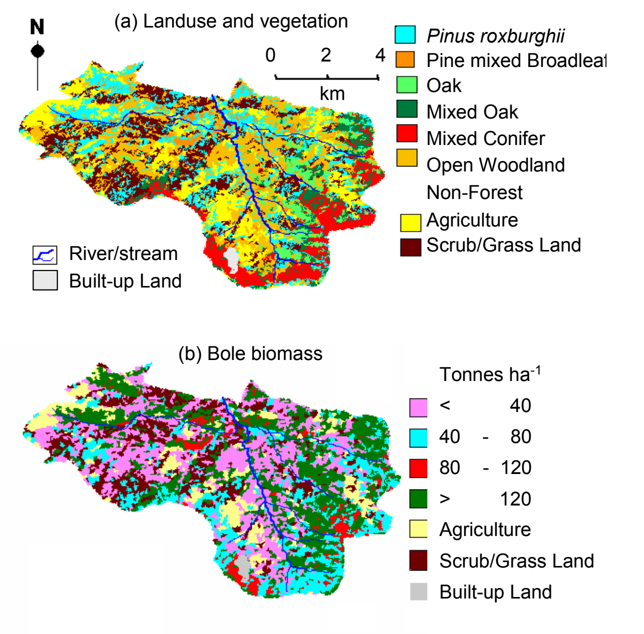

Fig. 1. Landuse /Vegetation and bole biomass maps of Khanda watershed. Branch and twig biomass maps of Khanda watershed.

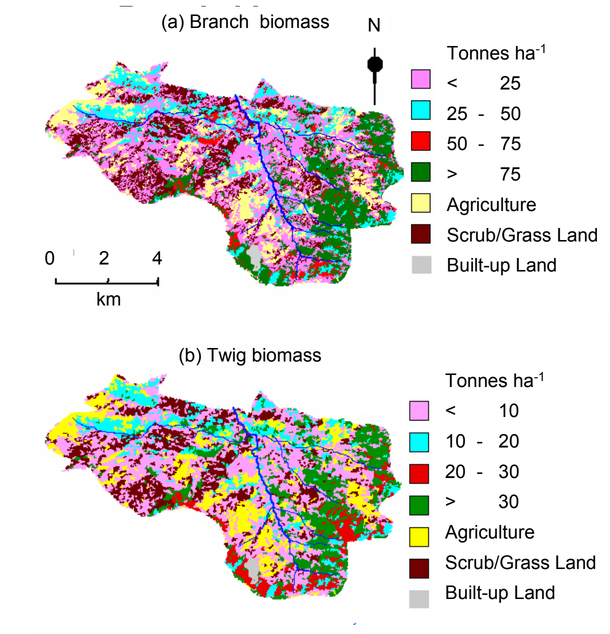

Fig. 2. Foliage and total aboveground biomass maps of Khanda watershed.

of total geographical area. (Table 5), about 54% of the total area was under non-forest uses.

Forest

P. roxburghii Forest: The *P. roxburghii* forest occurred mostly between the altitude of 700 to 2000 m, covering 18.12 km^2 of total geographical area. This forest exhibited two crown cover classes, namely 21–40% and 41–60%, out of which 21–40% crown cover class was spread over 5.64 sq. km and 41–60% crown cover class pertains 12.47 km^2 of the total geographical area. This forest represents only 34.7% of total forest area and 15.9% of the total geographical area.

A single species *P. roxburghii* was dominated with an Importance Value Index (IVI) 259. Associated species were *Quercus leucotrichophora* A. Camus, *Aesculus indica* (Colebr. ex Camb.) Hook., *Madhuca indica* Gmel., *Mallotus philippensis* Muell.-Arg. and *Syzygium cumini* (L.) Skeel., and shrub layer is dominated by *Rhus parviflora* Roxb., *Asparagas racemosus* Willd., *Berbaris asiatica* Roxb. ex DC. and *Pyracantha crenulata* (Don) Roem.

Mixed Oak Forest: This forest extended over a total area of 8.88 km^2 showing co-dominance of *Q. leucotrichophora* and *Rhododendron arboreum* Sm., which together form the upper story of forest vegetation. This forest extends only on 17.0% of forest land and 7.8% of total geographical area. Important companion species were *Myrica esculenta* Buch.-Ham. ex D. Don, *P. roxburghii*, *C. deodara*, and *Litsea glutinosa* (Lour.) Robinson. In 17.0% of its areal extent, crown cover was only 41–60%. The main associated species of shrub layer was *B. asiatica*, *P. crenulata*, *Cotoneaster microphyllus* Wall. ex Lindl. and *Eupatorium cannabinum* L.

Pine Mixed Broadleaf: This forest accounted for 4.9% (5.55 km^2) of the study area. A marked variation of species dominance was observed from site to site (*P. roxburghii-M. esculenta*, *M. esculenta-P. roxburghii* and *P. roxburghii-Q. leucotrichophora*). In other sites the dominance was shared jointly by a number of species e.g. *M. esculenta*, *R. arboreum*, *Cupressus torulosa*, *Cedrus deodara*, *M. indica* and *Terminalia belerica* (Gaertn.) Roxb. The shrub layer was mainly *B. asiatica*, *Cotoneaster microphyllus*, *Pyracantha crenulata*, *Asparagas racemosus* Willd. and *Lantana camara* L.

Within the forest, 5.2% area was under 21.4% crown cover, and 5.4% under 41.6% crown cover. Greater than 60% crown cover was absent.

Oak Forest: *Q. leusotrichophora* forest occupied 16.8% of the forested land and had 41.6% crown cover. *Q. leucotrichophora* dominated in all sites with highest IVI. The other co-dominant species were *P. roxburghii*, *M. esculenta*, *C. deodara* and *R. arboreum*. This forest occupied only 7.7% of the total geographical area. Major shrubs in this forest were *B. asiatica*,

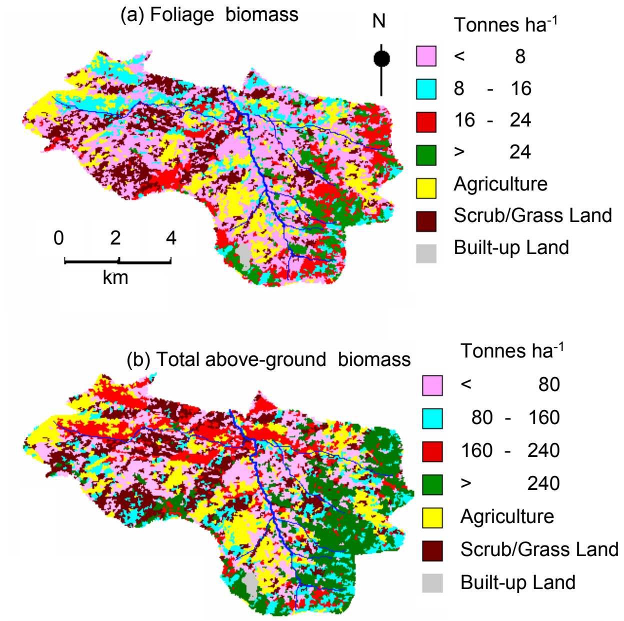

Fig. 3. Relationship between the bole biomass computed in present study and that computed through conventional method.

C. microphyllus, *E. cannabinum* and *Rosa brunonii* Lindley.

Mixed Conifer Forest: This forest was dominated by *C. torulosa*, *P. roxburghii* and *C. deodara*, and occupied 20.6% area of total forest land. Out of 10.74 km² area, 2.98 km² was occupied by 21–40% crown cover, 4.17 km² by 41–60% and 3.59 sq.km by 61–80% crown cover. Other associated species were: *Lyonia ovalifolia*, *M. esculenta*, *Q. leucotrichophora* and *R. arboreum*.

Shrub layer was made up of mainly *B. asiatica*, *E. cannabinum*, *C. microphyllus* and *P. crenulata*.

Non–forest land

A total of 61.48 km². of the catchment was non-forested (Table 5). About 24.35 km² (i.e. 39.6% of total non-forested area) land was under village woodland. A total of 17.13 km² (i.e. 27.8%) land was under agriculture and 20.0 km² (i.e. 32.5%) was under wasteland (including scrub and grasses), which included scattered trees of *P. roxburghii*, *Dalbergia sissoo* Roxb., *Mallotus philippensis*, *Mangifera indica* L., *Syzygium cumini* (L.) Skeels and *M. esculenta*.

Biomass mapping

Maps of bole biomass, branch biomass, twig biomass, foliage biomass and total above ground biomass are shown in Figs. 1 to 3. Mean biomass values for different components in various forest types and crown cover classes are presented in Table 6. Bole biomass varied from 68.55 t ha⁻¹ (*P. roxburglii* forest, 21–40% crown cover) to 124.62 t ha⁻¹ (Mixed Oak Forest, 41–60% crown over). The Oak Forest with same (41–60%) crown cover also exhibited comparable bole biomass (123.62 t ha⁻¹) values. In spite of higher crown cover, the mixed conifer forest (61–80% crown cover) exhibited bole biomass (103.38 t ha⁻¹) lower than that for oak and mixed oak Forest. The lowering of biomass is associated mainly with the high specific density of oak wood than that of conifers. Maximum branch biomass (88.88 t ha⁻¹) was recorded for mixed conifer forest with 61–80% crown cover, followed by oak and mixed oak forests, both with 41–60% crown cover. Minimum

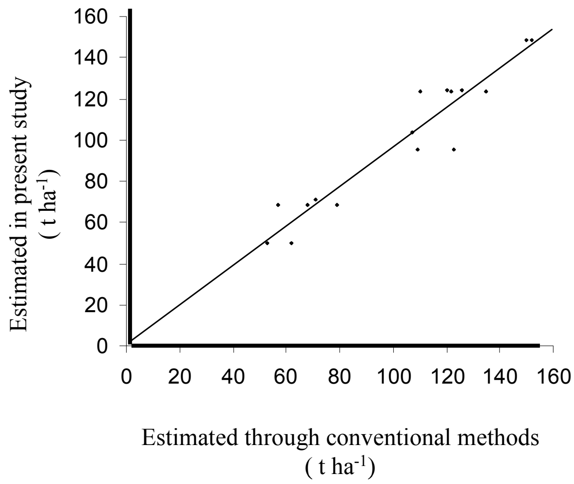

Fig. 4. Relationship between the total above ground biomass computed in present study and that computed through conventional method.

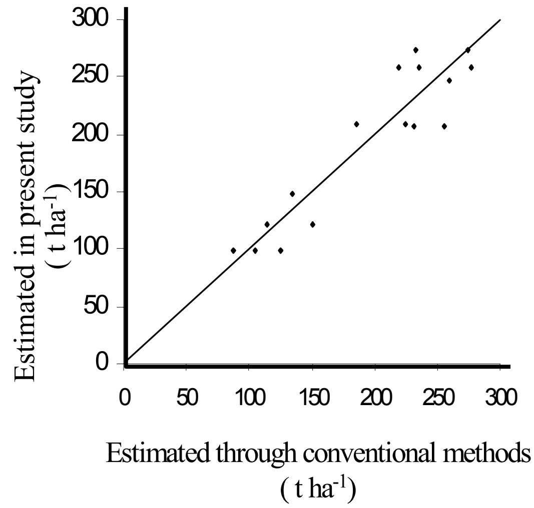

Fig. 5. Relationship between the total above ground biomass computed in present study and that computed through conventional method.

Table 6. Mean biomass (t ha^{-1}) in various components of different forest categories.

Forest type/Crown cover	Bole Biomass	Branch Biomass	Twig Biomass	Foliage Biomass	Total Above ground Biomass
Pinus roxburghii Forest					
21–40%	68.55	17.68	7.19	5.91	99.34
41–60%	148.31	30.23	15.89	13.67	208.12
Mixed Oak Forest					
41–60%	123.62	82.83	35.75	17.09	259.091
Pine Mixed Broadleaf					
21–40%	71.24	42.72	20.37	14.35	148.69
41–60%	95.31	59.37	31.78	21.41	207.87
Oak Forest					
41–60%	124.45	85.31	35.01	28.11	272.88
Mixed Conifer Forest					
21–40%	52.09	43.06	14.88	11.29	121.33
41–60%	79.61	67.42	22.57	18.81	188.40
61–80%	103.38	88.88	29.19	25.74	247.21
Village Woodland	27.46	12.83	7.49	5.73	53.52

Table 7. Total Biomass (×10^3 t) in various components of different forest categories.

Forest type/Crown cover	Bole Biomass	Branch Biomass	Twig Biomass	Foliage Biomass	Total above ground Biomass
Pinus roxburghii Forest					
21–40%	38.66	9.97	4.05	3.33	56.03
41–60%	184.95	37.69	19.81	17.05	259.52
Mixed Oak Forest					
41–60%	109.77	73.55	31.75	15.17	230.07
Pine Mixed Broadleaf					
21–40%	19.31	11.57	5.52	3.88	40.29
41–60%	27.06	16.86	9.02	6.08	59.03
Oak Forest					
41–60%	109.02	74.73	30.66	24.62	239.04
Mixed Conifer Forest					
21–40%	15.52	12.83	4.43	3.36	36.15
41–60%	33.19	28.11	9.41	7.84	78.56
61–80%	37.11	31.91	10.47	9.24	88.75
Total Forested Land	574.59	297.22	125.12	90.57	1087.44
Village Woodland	66.86	31.26	18.24	13.95	130.31
Grand Total	641.45	328.47	143.35	104.52	1217.75

branch biomass was found in *P. roxburghii* forest (21–40% crown cover). Twig foliage and total aboveground biomass exhibited similar trend (Table 6).

Total aboveground biomass in entire study area including village woodlands was 1217.9 ×10^3 t out of which 130.3×10^3 t was in village woodlands. Among different forest types maximum biomass was found in *Pinus roxburghii* forest (315.5×10^3 t) (Table 7).

In general, conifer dominated forests *(P. roxburghii,* Pine mixed broadleaf and Mixed conifer) exhibited nearly one and half times higher total biomass than that for broad-leaved forest (Oak and Mixed Oak). The average density of biomass in forest types is presented in Table 8. For total aboveground biomass the average density was 208.96 t ha^{-1} of forested land. Among various forest types, village woodlands exhibited lowest biomass density, whereas, highest biomass density was recorded for mixed oak forest.

Classification accuracy

The results of classification accuracy estimations are summerised in Table 9, which indicates high accuracy for classification of forest types. The producers accuracy ranged between 100% (oak forests) to 88% (village wood land and Pine-

Table 8. Average density (t ha^{-1}) of biomass in different forest types (i.e. total biomass in forest type/total area under forest type).

Forest Type	Bole Biomass	Branch biomass	Twig Biomass	Foliage Biomass	Total Above ground biomass
Pinus roxburghii Forest	123.43	26.31	13.17	11.25	174.16
Mixed Oak Forest	123.61	82.84	35.75	17.08	259.28
Pine Mixed Broadleaf	83.56	51.24	26.22	17.94	178.96
Oak Forest	124.45	85.31	35.00	28.11	272.87
Mixed Conifer Forest	79.91	67.83	22.64	19.03	189.41
Village Woodland	27.45	12.84	7.49	5.73	53.51
Total Forested Land	110.42	57.12	24.04	17.41	208.99

mixed broad leaved forests. The overall classification accuracy was 96% (Table 9). The accuracy and acceptability of the crown cover-biomass models generated in the present study can be assessed through the r^2 and $S_{y.x}$ values (Table 3).

Discussion

Of the total geographical area of 113.5 km^2, non-forested land occupied 54% land. Forest land was distributed in five forest types. About 6.8% of the forest area (i.e. 3.1% of total area) was under 61–80% crown cover, The crown cover of greater than 60% was encountered only in mixed conifer forest. The forests with >40% crown cover occupied 78.2% of forest land. This indicates an overall lower crown cover level of the forests of the region. The average density of biomass (208.96 t ha^{-1}) in the area is very close to the average density recorded for entire Indian Central Himalaya (210.2 t ha^{-1}) for the base year 1972–73 (Tiwari *et al.* 1985). However, it was marginally higher than that recorded for Pauri Garhwal district (182.9 t ha^{-1}) for base year 1972–73.

The biomass maps and estimates generated in the study form a base line data for evaluating the productive potential of the forests. The total biomass estimates can easily be converted into carbon equivalents to estimate total storage of C in the forests. The estimates of foliage and twig/branch biomass provide the data on total availability of fodder and fuel wood in the area. Such estimates can be used for working out demand/supply ratio of fodder and fuel for the area.

The accuracy of these estimates is dependent on two parameters: (i) accuracy of classification and; (ii) accuracy of cover-biomass models. Accuracy of classification includes the errors caused by preprocessing (Smith & Kovalick 1985), by interpretative techniques both manual (Congalton & Mead 1983) and automated and by techniques for sampling, calculating accuracy, and comparing results (Aronoff 1982; Ginevan 1979; Hord & Brooner 1976). The accuracy of the classification achieved in the present study is much higher than the expected accuracy of 85%. The high classification accuracy associated with high r^2 values of cover-biomass models provided confidence to the study.

Table 9. Errors and accuracies of vegetation classed estimated through field checks.

Forest Type	Omission error (%)	Comission error (%)	Producers accuracy (%)	Users accuracy (%)
Pinus roxburghii	4	17	96	83
Mixed Oak	8	4	92	96
Pine-mixed Broadleaf	12	8	88	92
Oak	0	4	100	96
Mixed Conifer	0	4	100	96
Village Woodland	12	1	88	99
Agriculture	0	0	100	100
Scrub/grass	8	6.12	92	93.88

Independent estimation for bole and total aboveground biomass was carried out for a total of 16 sites in the study area. The biomass was computed through conventional techniques, as described by Chaturvedi & Singh (1987) and Rawat & Singh (1988). Crown cover, bole biomass and total above ground biomass for these sites are presented in Table 10. These values were plotted against the values obtained for corresponding crown cover classes in the present study (Figs. 4 and 5). Both the data sets exhibited a close agreement with r^2 values of 0.91 and 0.86 for bole and total aboveground biomass respectively. The closeness of slope of the relationships to '1' (0.929 for bole and 0.948 for total above ground biomass) provided further confidence to the study estimates.

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