J. Bamboo and Rattan, Vol.7, Nos. 3&4, pp. 219-234 (2008)

Aboveground biomass and productivity appraisal of four important bamboo species growing along different altitudinal regimes in Arunachal Pradesh

K. Upadhyaya[1]*, A. Arunachalam[2], K. Arunachalam[2] and A.K. Das[3]
[1]*Department of Forestry, Mizoram University, Aizawl - 796009, Mizoram, India*
[2]*Department of Forestry, North Eastern Regional Institute of Science and Technology, Nirjuli – 791109, Arunachal Pradesh, India*
[3]*Department of Botany, Rajiv Gandhi University, Rono Hills, Doimukh, Itanagar – 791111, Arunachal Pradesh, India*

Abstract: A detailed study on the biomass and productivity of four important bamboo species, *Bambusa balcooa, B. pallida, Phillostachys bambusoides, Arundinaria racemosa* growing at different altitudinal regimes in Arunachal Pradesh was carried out. The biomass of respective bamboo components per culm increased with age except in case of *P. bambusoides* where the culm and branch biomass declined from 2-year to ≥ 3-year old culm. Among the species, the total aboveground biomass was in the sequence of *B. balcooa* >*B. pallida* >*P. bambusoides* >*A. racemosa*. Biomass allocation was maximum in culms (64–81%) and minimum in leaves (5–15%), except in *P. bambusoides* in which minimum allocation of biomass was estimated in its branches (12%). At lower altitudes (in *B. balcooa* and *B. pallida*) foliage biomass was significantly lower as compared to the higher altitude species (*P. bambusoides* and *A. racemosa*). *B. balcooa* had the highest annual litter biomass (24.2 t $ha^{-1}y^{-1}$), followed by *B. pallida* (15.3 t $ha^{-1}y^{-1}$), *P. bambusoides* (5.68 t $ha^{-1}y^{-1}$) and *A. racemosa* (1.76 t $ha^{-1}y^{-1}$). However, litter as per cent of total aboveground biomass was greater in *A. racemosa* (9.79%) and lower in *B. balcooa* (6.41%). Maximum total biomass productivity was obtained from *B. balcooa* (240.38 t $ha^{-1}y^{-1}$), followed by *B. pallida* (114.31 t $ha^{-1}y^{-1}$), *P. bambusoides* (58.36 t $ha^{-1}y^{-1}$) and the minimum was recorded in *A. racemosa* (12.19 t $ha^{-1}y^{-1}$).

Key words: Bamboo, aboveground biomass, biomass productivity, litter biomass.

INTRODUCTION

Utilization of forest resources around their household has been an important livelihood strategy of the people of North-eastern India since time immemorial. Among these resources, bamboo plays an important role in rural socioeconomic development of the indigenous communities (Biswas, 1988). Bamboo thickets have been developed through secondary succession in the hill slopes, which are being denuded by shifting

*To whom correspondence should be addressed; E-mail: kalidaskhanal@yahoo.com

agriculture and/or human encroachment (Bhatt *et al.*, 2004). Gregarious flowering of few dominant bamboo species is the natural threat for the drastic change in their population structure, productivity and young shoot production (Singha *et al.*, 2003). Realizing the threats and potential of bamboo resources in the region, the Government of India has initiated a national programme called National Mission for Bamboo Application with the aim of promoting bamboo as potential source of livelihood opportunity and employment generation. One of the main objectives of this mission is to maintain continuous supply of quality raw material for bamboo-based industries. In this context, estimation of bamboo biomass in natural stand and plantations can be the basis for assessing the demand and capacity of existing areas to cater the raw material demand of such industries.

Moreover, short rotation bamboo plantations that couple intensive management and rapid growth rates are also characterized by high rates of nutrient removal in the harvested biomass (Kumar *et al.*, 2005). The associated high nutrient export potential especially with whole culm harvesting may deplete the nutrient capital in the system (Kumar *et al.*, 1998). This in turn raises concern about long-term site quality and sustainable production. Estimating biomass and productivity can also help in determination of nutrient removal through harvest and also in formulating suitable nutrient management strategy for sustainable production in natural stands as well as in plantations.

In India, most studies are confined to exploration and distribution of bamboo species (Bahadur and Jain, 1983; Gadgil and Prasad, 1984; Haridasan *et al.*, 1987; Beniwal and Haridasan, 1988; Biswas, 1988). In Arunachal Pradesh, which harbours the highest diversity of bamboo (63 species), some species are highly exploited from its natural sources. A few species are also planted and managed by the farmers in the homestead gardens (Beniwal and Haridasan, 1988; Sarkar and Sundriyal, 2002). The present study, therefore, aims to determine the biomass accumulation and productivity of four important bamboo species growing at different altitudes in Arunachal Pradesh.

MATERIALS AND METHODS

Study sites

The study was carried out at three different altitudes covering, *Bambusa balcooa* Roxb. and *B. pallida* Munro in the lower altitudes (181 m a.s.l), *Phyllostachys bambusoides* Sieb. (Zucc.) and *Arundinaria racemosa* Munro in high altitude (1700–3000 m a.s.l). The study on the lower altitude bamboo species was carried out in Nirjuli village (27°10′ N, 93°45′ E and 181m a.s.l) of Papumpare district whereas that of *P. bambusoides* was in the Ziro valley (27°30′ N, 93°50′ E and 1700 m a.s.l) of Lower Subansiri district and *A. racemosa* in the Jang area (27°31′ N, 92°00′ E and 3000 m a.s.l) of Tawang district, in Arunachal Pradesh, India. The physiography and microclimatic characteristics of the study sites are given in Table 1. Soil was acidic to slightly acidic with loamy sand texture. In general, soil physical, chemical and biological properties varied among the study sites (Table 2).

Aboveground biomass

Five bamboo stands (*ca.* 0.2 ha) were randomly selected for estimation of above ground biomass in the three larger diameter species *viz*., *B. balcooa*, *B. pallida* and *P. bambusoides*. Five 10 m x 10 m quadrats were laid out for determining clump and culm densities in each stand. However, in the case of monopodial *P. bambusoides*, which does not form any clump, only the culm density was recorded. The individual culms were categorized into three different age groups *viz*., (i) 1-year culm, (ii) 2-year culm, and (iii) ≥3-year culms. From selected stands of each species 60 bamboos (*i.e.*, 20 bamboos of one age group) were harvested randomly to measure the length and dbh (diameter at breast height) in the month of April, 2007. Fresh weight of leaves, branches, and main culm of each harvested bamboo was measured respectively in the field. Sub-samples were oven-dried for dry matter content. The leaves (including culm sheath, if any) were oven-dried at 60°C for 48 h while branches and culms were dried at 105°C for 48 h. Conversions of total fresh- to total dry-weight were then calculated based on the methods used for the determination of moisture content.

Table 1. Physiography and microclimatic characteristics of study sites

Parameters	Study sites		
	Nirjuli	Ziro	Jang
Physiography			
Latitude	27°102 N	27°302 N	27°312 N
Longitude	93°452 E	93°502 E	91°552 E
Altitude (m a.s.l)	136	1700	3000
Slope (%)	0.5-1	2-5	25-60
Aspect	—	North-West	North-West
Microclimate			
Annual rainfall (mm)	3100	1545	2000
	±91.34	±82.6	±77.3
Air temperature (°C)			
Maximum	33.0	30.6	19.3
	±2.39	±2.54	±2.11
Minimum	18.0	4.0	2.3
	±1.56	±0.87	±0.89
Relative humidity (%)	79	42	62
	±3.56	±2.58	±3.61
Soil temperature (°C)	24.0	17.5	10.3
	±1.01	±0.76	±0.53
Light intensity (Lux)	11300	22000	67700
	±851	±1634	±2480

± SE (n = 10)

Table 2. Soil physico-chemical properties and microbial biomass under different bamboo species

Parameters	Species			
	B. balcooa	*B. pallida*	*P. bambusoides*	*A. racemosa*
Physical properties				
Texture				
Sand (%)	79.67±1.62	79.61±1.14	86.35±2.10	79.67±1.32
Silt (%)	10.79±0.71	11.92±0.68	3.23±0.35	12.54±0.35
Clay (%)	9.54±0.60	8.47±0.32	10.42±0.94	7.79±0.64
Textural class	Loamy sand	Loamy sand	Loamy sand	Loamy sand
WHC (%)	64.06±1.66	51.70±1.03	76.81±2.21	47.63±1.37
Soil moisture (%)	18.58±0.58	19.20±0.88	24.00±1.16	42.50±1.16
Bulk density (g cm^{-3})	0.66±0.05	0.67±0.03	0.04±0.60	0.72±0.02
Chemical properties				
pH (1:2.5 w/v H_2O)	5.99±0.14	6.52±0.17	5.21±0.16	4.90±0.11
Soil organic C (%)	1.05±0.07	1.50±0.09	3.85±0.18	1.47±0.10
Total N (%)	0.036±0.004	0.059±0.007	0.70±0.05	0.24±0.06
Ammonium-N (ig g^{-1})	0.014±0.003	0.016±0.002	0.08±0.006	0.539±0.08
Nitrate-N (ig g^{-1})	5.34±0.23	5.240.31	1.9±0.19	6.30±0.11
Available P (ig g^{-1})	8.89±0.11	10.69±0.19	20.76±0.24	9.70±0.20
C/N	29.17	25.42	5.50	6.13
Microbial biomass (Ig g^{-1})				
Microbial biomass C	155.56±6.79	155.56±7.75	1550.40±18.56	344.91±7.48
Microbial biomass N	2.02±0.26	3.98±0.21	388.63±6.82	76.20±4.99
Microbial biomass P	2.98±0.17	4.23±0.32	4.03±0.26	2.88±0.29
MBC/MBN	75.51	39.09	3.99	4.53
MBC/MBP	52.20	36.78	384.71	129.67
MBN/MBP	0.68	0.94	96.43	28.65

± SE (n = 5); MBC : microbial biomass carbon, MBN: microbial biomass nitrogen, MBP: microbial biomass phosphorus.

Regression equations (for each age category) were worked out for the best fit between dry weight of bamboo components (culms, branches, and leaves) and culm dbh. The best fit was selected based on the minimum standard error and maximum coefficient of determination (r^2). Average dbh for three age categories in the bamboo species were determined by enumerating all the culms recorded in the quadrats. These values were then incorporated in the regression equation to obtain aboveground biomass per culm and then were multiplied with the culm density (ha^{-1}) to estimate the aboveground biomass on a hectare basis. The biomass of all the components of bamboo was added to obtain the total above-ground biomass ha^{-1}.

In case of *A. racemosa*, biomass study was conducted in a large (*ca.* 30 ha) bamboo forest, where *A. maling* was also predominant. Fifteen 10 m x 10 m quadrats were laid out in the study site to record clump and culm densities as well as clump size and culm (clump area, dbh and height of each culm). All the standing culms were categorized into two age classes *viz.*, 1-year and ≥2-year-old culms. Unlike the earlier three species (due to its smaller size) regression equations were not established for this species. However, 20 individual culms in the two age categories were harvested and dry weight of each component was determined. Estimation of biomass per culm was then done by taking the average dry weight of the sampled bamboos for different aboveground components and was later converted on a hectare basis by simple multiplication with culm density (ha^{-1}).

Biomass productivity

Biomass productivity ($t\ ha^{-1}y^{-1}$) was determined as the summation of standing biomass accumulation, annual litter biomass and annual biomass extraction through harvest removal. Standing aboveground biomass accumulation was calculated as follows:
Standing aboveground biomass accumulation = A + B + C
Where, A = Aboveground biomass of 1-year-old culm ha^{-1}
B = Difference between aboveground biomass of 1-year and 2-year culms ha^{-1}.
C = Difference between aboveground biomass of 2-year and ≥3-year culms ha^{-1}.

For estimating annual biomass extracted, it was assumed that only mature culms which were ≥3-year-old (or ≥2-year-old in case of *A. racemosa*), were harvested from the site. Accordingly, the number of culms harvested was determined by counting the number of felled bamboo stumps per quadrat. Annual biomass extracted was then calculated as follows:

Annual biomass extracted = Aboveground biomass of harvested culms/3 (or 2 in case of *A. racemosa*).

In addition, ten plots of 1 m x 1 m was laid out randomly throughout the bamboo stands to estimate annual litter biomass. The litter plots were made permanent by enclosing the area with nylon thread. The contents in the litter plots were collected at sixty days interval for one year and segregated into bamboo litter and others, if any. These were then oven-dried at 60°C for 48 h and the values were represented on a hectare basis.

RESULTS

Growth characteristics

P. bambusoides is a monopodial, non-clump forming species which usually grows as solitary culm. The other three species were clump forming sympodial bamboo. The clump density among the three sympodial bamboo species was in the order of *B. pallida* >*B. balcooa* >*A. racemosa* (Table 3). *B. balcooa* also occupied comparatively

Table 3. Growth characteristics of four bamboo species

Growth characteristics	Species			
	B. balcooa	*B. pallida*	*P. bambusoides*	*A. racemosa*
Clump density (no./ha) (n = 15)	306±10.3	319±9.5	-	237±7.8
Mean clump diameter (m) (n = 15)	4.70±0.41	4.15±0.82	-	3.48±0.37
No. of culms/clump* (n = 15)				
- 1 year	14.0±1.1	19.3±1.6	81.2±6.0	53.3±5.8
- 2 years	20.7±1.3	32.6±2.1	88.0±8.8	87.5±4.9
- ≥ 3 years	26.3±2.3	22.3±1.8	56.4±2.8	-
- Total	61.0±6.5	74.2±6.2	225.6±21.6	140.8±11.7
No. of culms/ha (n = 15)				
- 1 year	4284.0±336.6	6156.7±510.4	8120.0±600.0	12632.1±1374.6
- 2 years	6334.2±397.8	10399.4±669.9	8800.0±880.0	20737.5±1161.3
- ≥ 3 years	8047.8±703.8	7113.7±574.2	5640.0±280.0	-
- Total	18666.0±1989.0	23669.8±1977.8	22560.0±2160.0	33369.6±2772.9
Mean culm dbh (cm) (n = 50)				
- 1 year	9.4±1.81	6.2±0.92	4.8±1.47	2.10±0.34
- 2 years	9.5±1.82	6.5±0.61	5.1±0.86	2.37±0.37
- ≥ 3 years	10.3±2.31	7.0±1.05	4.6±1.07	-
- Average dbh	9.7±2.01	6.6±0.92	4.8±1.15	2.24±0.38
Mean culm height (m) (n = 50)				
- 1 year	17.91±1.61	12.07±1.61	9.42±2.03	3.95±0.44
- 2 years	20.74±1.35	14.04±2.54	9.58±1.20	4.20±0.49
- ≥3 years	21.83±2.14	14.23±2.01	9.81±1.71	-
- Average height	20.16±1.80	13.45±1.89	9.60±1.65	4.08±0.48

± SD; * 10 m x 10 m quadrat was taken for *P. bambusoides*.

more area than the other two species in the same order. However, culm density per clump was the highest in *A. racemosa* (141 culms/clump). Similarly, culm density (ha^{-1}) was maximum in *A. racemosa* (33370) and minimum in *B. balcooa* (18666). In general, *P. bambusoides* and *A. racemosa*, which were found in cooler areas, were smaller in size as compared to other two low altitude species. For instance, *B. balcooa* was the largest (dbh = 9.7 cm and height = 20.16 m), and *A. racemosa* was the smallest (dbh = 2.24 cm and height = 4.08 m) amongst the species studied.

Aboveground biomass

To estimate aboveground biomass an allometric relationship was established between dbh and dry weight of different bamboo components for the three bamboo species *viz.*, *B. balcooa*, *B. pallida* and *P. bambusoides* (Figs. 1-3). For *A. racemosa*, the biomass was determined by multiplying the number of culms with average aboveground biomass of a few harvested culms. The determination of coefficient (r^2) varied from 0.8075 to 0.9902. In most of the bamboo components of different age classes and species, culm recorded greater r^2 value. However, in the 1-year-old culm of *B. balcooa*, the greatest r^2 value was found with the branches (0.9554).

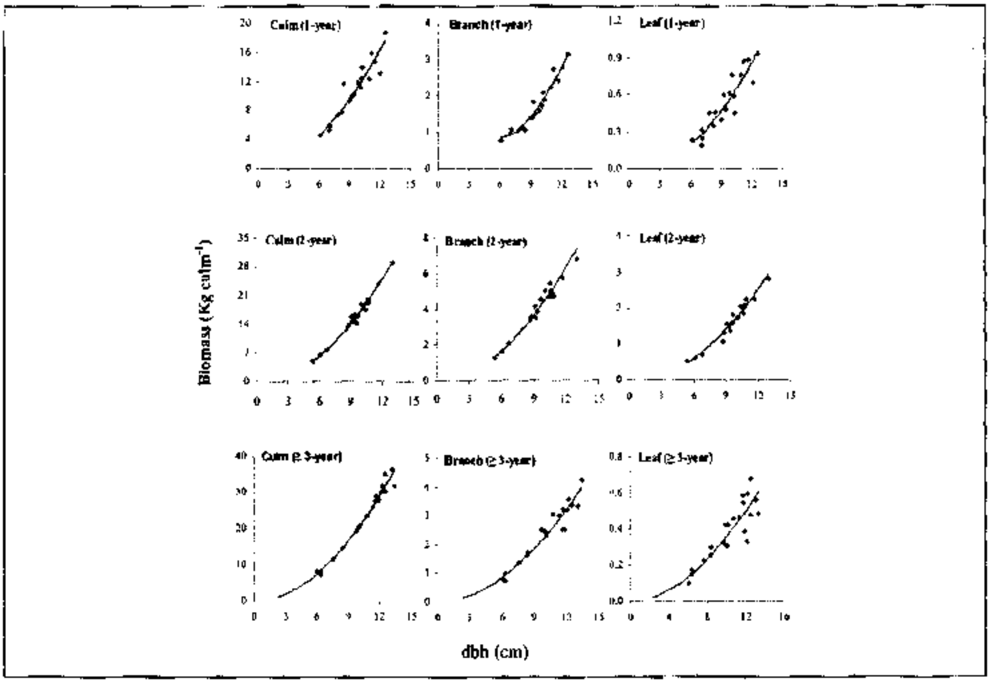

Figure 1. Scattered-plot showing correlation between biomass of different bamboo components and dbh in *B. balcooa.*

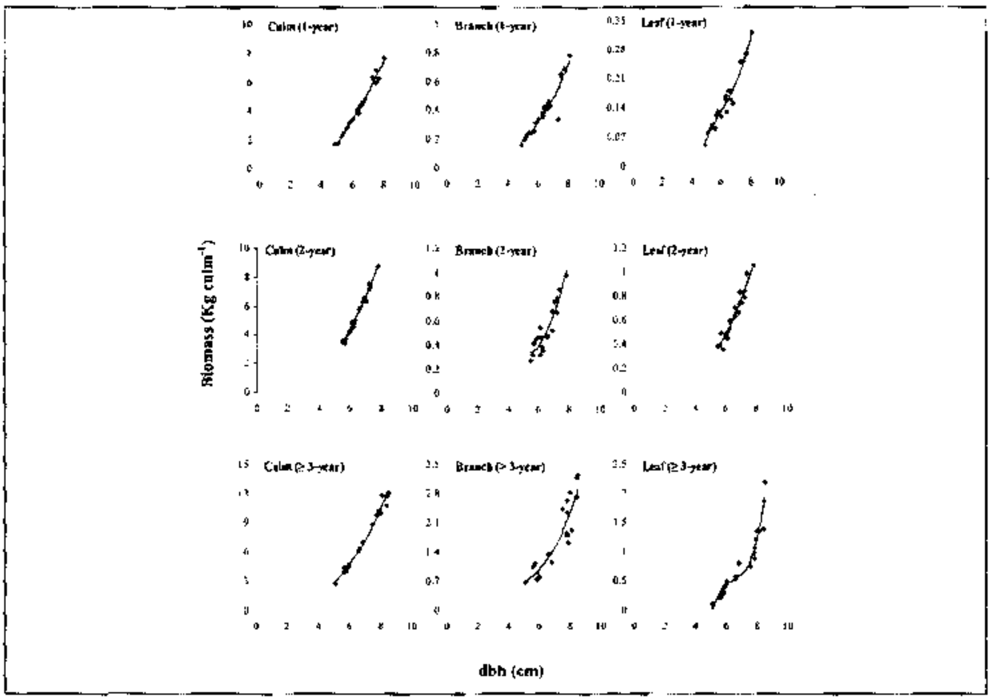

Figure 2. Scattered-plot showing correlation between biomass of different bamboo components and dbh in *B. pallida.*

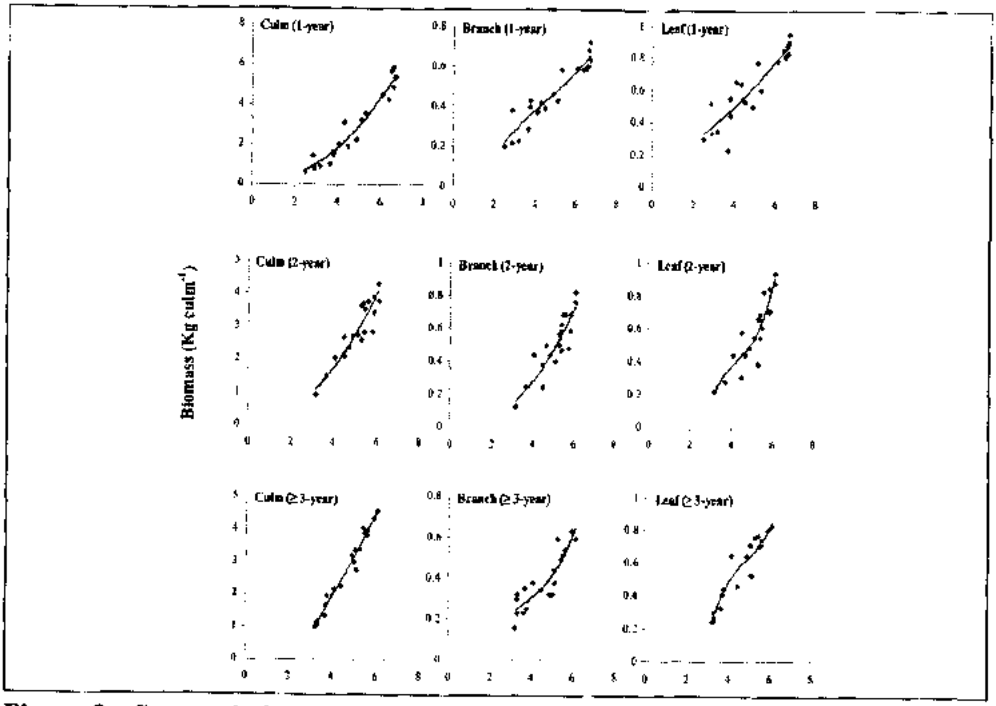

Figure 3. Scattered-plot showing correlation between biomass of different bamboo components and dbh in *P. bambusoides.*

The culm biomass increased with age except in the case of *P. bambusoides*, where the culm and the branch biomass slightly declined from 2-year to ≥3-year-old culm (Table 4). Over all, the aboveground culm biomass was highest in *B. balcooa* and lowest in *A. racemosa* irrespective of culm age.

In this study, the second year culm contributed maximum biomass to total standing aboveground biomass (Table 5). However, among the species, the total aboveground biomass was in the sequence of *B. balcooa* >*B. pallida* >*P. bambusoides* >*A. racemosa.* There appears to be significant difference in biomass partitioning to different culm components in all the four bamboo species. Biomass allocation was maximum in culms and minimum in leaves except in *P. bambusoides* in which minimum allocation of biomass was estimated in branches. Of the four species, highest allocation of culm biomass was found in *B. pallida* and the lowest in *A. racemosa.* On the other hand, allocation to branch and leaves was greater in *A. racemosa*. In both the lower altitude species, biomass allocation to leaves was significantly lower compared to the high altitude species.

Biomass productivity

Biomass productivity ($t\ ha^{-1}y^{-1}$) was calculated by adding standing biomass accumulation, annual litter biomass and annual biomass extraction through harvest.

Table 4. Aboveground standing biomass of four bamboo species (kg culm^{-1})

Species/Component		Culm age		
		1 year	2 year	≥ 3 year
B. balcooa				
	-Culm	10.30±3.97 (83.00)	15.56±5.41 (73.53)	21.57±9.12 (88.62)
	-Branch	1.60±0.66 (12.89)	4.04±1.29 (19.09)	2.39±0.97 (9.82)
	-Leaf	0.51±0.24 (4.11)	1.56±0.56 (7.37)	0.38±0.16 (1.56)
B. pallida				
	-Culm	3.79±1.68 (88.55)	5.50±1.40 (82.83)	7.21±2.92 (77.11)
	-Branch	0.34±0.17 (7.94)	0.51±0.19 (7.68)	1.52±0.81 (16.26)
	-Leaf	0.15±0.07 (3.50)	0.63±0.19 (9.49)	0.62±0.52 (6.63)
P. bambusoides				
	-Culm	2.66±1.74 (71.70)	2.85±1.01 (73.83)	2.65±1.31 (73.61)
	-Branch	0.45±0.17 (12.13)	0.48±0.19 (12.44)	0.36±0.14 (10.00)
	-Leaf	0.60±0.24 (16.17)	0.53±0.23 (13.73)	0.59±0.22 (16.39)
*A. racemosa**				
	-Culm	0.298±0.09 (64.09)	0.370±0.12 (63.36)	-
	-Branch	0.094±0.02 (20.22)	0.122±0.07 (20.89)	-
	-Leaf	0.073±0.01 (15.70)	0.092±0.03 (15.75)	-

± SD (n = 50); values in parentheses are biomass allocation (% of total aboveground biomass).
* Categorized only into two age classes *viz.* 1-year and ≥ 2-year-old culms; categorization into ≥3-year-old culms was not possible due to its smaller culm size.

The bimonthly litterfall accumulation in the bamboo species studied showed a bimodal pattern with a major peak and a minor peak. However, the peak litterfall period varied with the species (Fig. 4). *B. balcooa* had the highest annual litter biomass (24.2 t ha^{-1}y^{-1}), followed by *B. pallida* (15.3 t ha^{-1}y^{-1}), *P. bambusoides* (5.68 t ha^{-1}y^{-1}) and *A. racemosa* (1.76 t ha^{-1}y^{-1}). However, the contribution of litter to the total aboveground biomass was significantly greater in *A. racemosa* (9.79%) as compared to *B. balcooa* (6.41%). Likewise, both accumulation and removal of biomass was greater in *B. balcooa* (143.72 and 36.46 t ha^{-1}y^{-1}, respectively) and the lowest was recorded in *A. racemosa* (8.34 and 2.09 t ha^{-1}y^{-1}, respectively). The total biomass productivity was also greater in *B. balcooa* (240.38 t ha^{-1}y^{-1}), followed by *B. pallida* (114.31 t ha^{-1}y^{-1}), *P. bambusoides* (58.36 t ha^{-1}y^{-1}) and the lowest was recorded in *A. racemosa* (12.19 t ha^{-1}y^{-1}; Table 6).

Table 5. Total aboveground standing biomass of four bamboo species (t ha^{-1})

Species/component		Culm age		
		1 year	2 year	≥ 3 year
B. balcooa				
	-Culm	44.13±3.47	98.56±6.19	173.59±15.18
	-Branch	6.85±0.54	25.59±1.61	19.23±1.68
	-Leaf	2.18±0.17	9.88±0.62	3.06±0.27
	-Total	53.16	134.03	195.88
B. pallida				
	-Culm	23.33±1.93	57.20±3.68	51.29±4.14
	-Branch	2.09±0.17	5.30±0.34	10.81±0.87
	-Leaf	0.92±0.08	6.55±0.42	4.41±0.36
	-Total	26.35	69.05	66.51
P. bambusoides				
	-Culm	21.60±1.60	25.08±2.51	14.95±0.74
	-Branch	3.65±0.27	4.22±0.42	2.03±0.10
	-Leaf	4.78±0.36	4.66±0.47	3.33±0.17
	-Total	30.13	33.97	20.30
A. racemosa				
	-Culm	3.76±0.41	7.67±0.43	-
	-Branch	1.19±0.13	2.53±0.14	-
	-Leaf	0.92±0.10	1.91±0.11	-
	-Total	5.78	12.11	-

± SD (n = 15)

Table 6. Biomass productivity in four bamboo species

Species	Biomass accumulation (t ha^{-1}y^{-1})	Biomass extraction (through harvest)(t ha^{-1}y^{-1})	Total biomass productivity (t ha^{-1}y^{-1})
B. balooca	143.72	36.46	204.38
B. pallida	70.17	28.84	114.31
P. bambusoides	29.98	23.10	58.76
A. racemosa	8.34	2.09	12.19

DISCUSSION

Culms of all bamboo species may complete their growth within 2-3 months after their emergence from the ground, but their diameter and height do not increase further (Banik, 1980; Ueda, 1981; Shanmughavel and Francis, 1996). In the present study too, the bamboo culms attained maximum growth (dbh and height) within 1-year period, thereafter the increase in diameter and height was insignificant in tropical bamboos, *B. balcooa* and *B. pallida*. In the higher altitude bamboo, the reduced mean diameter for ≥3-year culms in case of *P. bambusoides* may be due to the removal of more vigorous culms from the site as this species is extensively harvested at 3-years rotation by the local farmers for house construction, fencing and for making agricultural tools and implements.

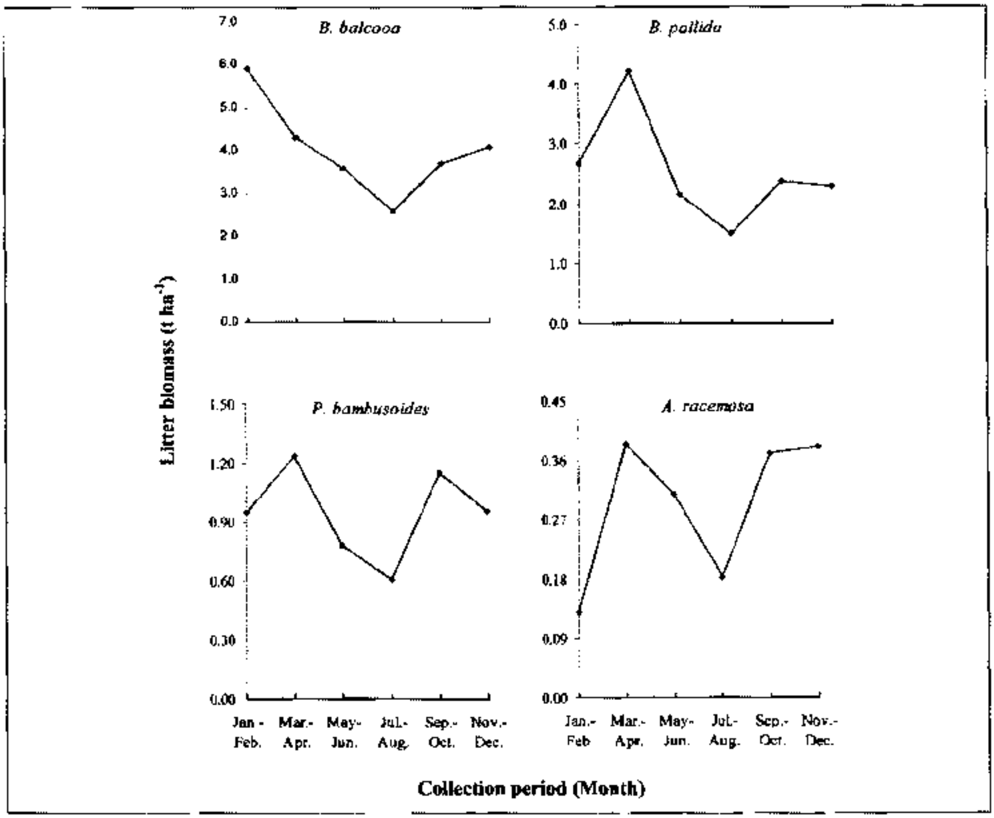

Figure 4. Bimonthly litter biomass accumulation from four bamboo species.

Various regression models have been developed for individual bamboo species by converting easily accessible measurements such as cbh, dbh, height, basal area, *etc.* into biomass estimates. Most researchers (Virtucio *et al.*, 1994; Othman, 1992; Li *et al.*, 1999; Singha, 2006) adopted two measurable growth parameters of individual culms *i.e.*, dbh and culm height. Although, inclusion of height in the regression equations can improve the r^2 values, measuring the culm height is extremely difficult as the culm tops are not properly visible in the stands. Further, in most of the bamboo species, top of the culms usually droop which ultimately leads to a highly underestimated biomass values. Therefore, in the present study, the equations for the three larger diameter species were developed with high significance between biomass (culm^{-1}) and dbh only.

The bamboo species found in tropical lowland areas are usually larger in size and possess more standing biomass when compared to the high altitude or temperate bamboo. For instance, *B. balcooa* and *B. pallida* had comparatively larger culm size and hence accumulated more aboveground biomass irrespective of culm age. Although there was no significant increase in height, there was a significant increase in culm weight as the age increases in all the study species. Ageing of culm is associated with significant chemical and structural changes in parenchyma and fibre tissues that decrease the fibre content (Espiloy. 1994; Sattar *et al.*, 1994) as well as cell wall thickening. This could explain the increasing aboveground biomass in 2-year and ≥3-year culms of the bamboo species studied. However, there is a slight decline in culm and branch biomass in case of *P. bambusoides* after the second year as most of the larger diameter and vigorous mature culms are chosen for harvest from the plantation site. Similarly, branch biomass reduced significantly after the second year of growth in case of *B. balcooa* as the density of mature culms was relatively higher in this bamboo stand which resulted in congested clumps inducing self pruning of most of the lower branches from the main culm. Although leaf biomass did not vary from 2-year culms to ≥3-year old culms in *B. pallida* and *P. bambusoides*, it was significantly low for *B. balcooa* in ≥3-year culms. Perhaps, this reflects that leaf formation may cease with age and growth when the density of mature culms was higher than the new culms.

Among the four species, total aboveground biomass (ha^{-1}) was the highest in *B. balcooa* and the lowest in *A. racemosa*. Great variation in stand biomass among species and among studies within the same species has been reported (Kleinhenz and Midmore, 2001). Accumulation of aboveground biomass in the culms was more in low altitude species compared to the high altitude bamboos. On the other hand contribution of leaf biomass to total aboveground biomass was greater in the later. This might be one of the nutrient conservation strategies for the two bamboo species growing in extreme climatic conditions as the leaves with their higher concentrations make them a major sink of nutrients (Kleinhenz and Midmore, 2001). Biomass partitioning in various components of the four species is at par with the values reported by other workers for different bamboo species (Table 7).

Although annual litter biomass was the highest in *B. balcooa*, its relative contribution to the total aboveground biomass was the lowest among the four bamboo species studied. In *B. pallida* and *A racemosa*, litter as per cent of the total aboveground biomass was higher, while for *B. balcooa* and *P. bambusoides* it was within the reported range of 6-8 per cent obtained for some other bamboo species (Table 8). The present study reveals greater variations amongst different bamboo species in terms of aboveground biomass productivity. In *B. balcooa*, biomass productivity was much higher compared to *B. bambos* plantation (Shanmughavel and Francis, 2001) and tropical and subtropical plantations (Forrest and Ovington, 1970; Madgwick *et al.*, 1977; Prasad *et al.*, 1984; Kadeba, 1991). Except the smaller sized *A. racemosa*, other two medium sized species, *B. pallida* and *P. bambusoides* also showed much higher annual aboveground biomass productivity compared to similar sized bamboos reported by Isagi *et al.* (1993,1997).

Table 7. Aboveground biomass and its allocation in several bamboo species

	Aboveground biomass (t ha^{-1})				
Bamboo species	Culm	Branch	Leaf	Total	Reference
Tropical bamboo					
Sphaerobambos phillipinensis	25.0 (61.0)	5.0 (12.2)	11.0 (26.8)	41.0	Virtucio *et al.* (1994)
S. phillipinensis	112.0 (67.9)	16.0 (9.7)	37.0 (22.4)	165.0	Virtucio *et al.* (1994)
Gigantochloa atter	34.0 (75.6)	6.0 (13.3)	5.0 (11.1)	45.0	Mailly *et al.* (1997)
B. bambos	243.0 (84.7)	40.0 (13.9)	4.0 (1.4)	287.0	Shanmughavel and Francis (1996)
B. balcooa	316.28 (81.03)	51.67 (14.43)	15.12 (4.54)	383.07	Present study
B. pallida	131.82 (81.41)	18.21 (11.25)	11.891 (7.34)	61.92	Present study
Subtropical bamboo					
P. bambusoides	93.0 (83.0)	10.0 (8.9)	9.0 (8.0)	112.0	Isagi *et al.* (1993)
P. pubescens	117.0 (84.2)	16.0 (11.5)	6.0 (4.3)	139.0	Isagi *et al.* (1993)
P. pubescens	49.0 (79.0)	10.0 (16.1)	3.0 (4.8)	62.0	Li *et al.* (1998)
P. bambusoides	61.63 (73.02)	9.91 (11.74)	12.86 (15.24)	84.40	Present study
Melocanna baccifera	25.0 (77.0)	3.5 (10.8)	0.67 (2.1)	32.5	Pynskhem (2007)
P. bambusoides	61.63 (73.02)	9.91 (11.74)	12.86 (15.24)	84.40	Present study
Temperate bamboo					
A. malling	72.5 (91.0)	4.4 (5.5)	2.8 (3.5)	79.7	Singha (2006)
A. racemosa	11.44 (63.63)	3.72 (20.69)	2.83 (15.74)	17.98	Present study

*Values in parentheses are biomass allocation (% of total aboveground biomass).

CONCLUSION

Over all, it can be concluded that generally the bamboo species studied can accumulate substantial aboveground biomass, especially in the culms. The two lower altitude species had significantly greater dry matter production potential as compared to the higher altitude ones. High aboveground biomass productivity in these bamboo species could suggest their potential use in ecorestoration of marginal and degraded lands and shall contribute to the carbon sequestration in terrestrial biomes per se. Nevertheless, whole-culm harvesting, however may lead to considerable nutrient loss

Table 8. Annual litter biomass in several bamboo species

Bamboo species	Annual litter biomass($t\ ha^{-1}y^{-1}$)	Litter as % of bamboo biomass	Reference
Tropical bamboo			
B. bambos	17.8	6.0	Shanmughavel and Francis (1996)
D. strictus	0.5	6.0	Joshi *et al.* (1991)
D. strictus	2.7	8.0	Tripathi and Singh (1994)
G. atter	4.7	6.0	Christanty *et al.* (1996)
S. phillipensis	12.6	8.0	Virtucio *et al.* (1994)
B. balcooa	24.2	6.41	Present study
B. pallida	15.3	9.45	Present study
Subtropical bamboo			
P. pubescens	6.8	4.9	Isagi *et al.* (1997)
P. bambusoides	5.68	6.73	Present study
Temperate bamboo			
A. malling	6.6	8.3	Singha (2006)
A. racemosa	1.76	9.79	Present study

from the site (Kumar *et al.*, 2005) Although, considerably lesser biomass is accumulated in leaves, their high concentration make them nutrient sink and hence leaf biomass and litterfall represent the major source through which nutrient return occurs to and from the living culms. Moreover, significant amount of nutrients can be released to the site if leaves and small twigs are left *in situ* after harvesting resulting in open nutrient cycling in the hill slopes that are vulnerable to leachi l ng and runoff losses.

ACKNOWLEDGEMENTS

The Authors are grateful to Mr. Moharam Ingty for his help during field work.

REFERENCES

Bahadur, K.N. and Jain, S.S. 1983. Rare bamboos of India. An assessment of Threatened Plant. In: K. Jain and R.R. Rao (Eds.). An Assessment of Tthreatened Plant. Botanical Survey of India Publication, Howrah, West Bengal, India: 265-271.

Banik, R.L. 1980. Propagation of bamboos by clonal methods and by seed. In: G. Lessard and A. Chouinard. (Eds.). Bamboo Research in Asia. IDRC, Canada: 139-150.

Beniwal, B.S. and Haridason, K. 1988. Study of bamboos through establishment of bambusetum in Arunachal Pradesh. *Indian Forester* 114: 650-655.

Bhatt, B.P., Singha, L.B., Singh, K. and Sachan, M.S. 2004. Distribution, growth and productivity of commercial edible bamboo species in the three states of eastern Himalaya, India. *World Bamboo and Rattan* 2(3): 22-32.

Biswas, S. 1988. Studies on bamboo distribution in north-eastern region of India. *Indian Forester* 114: 524-531.

Christanty, L., Mailly, D. and Kimmins, J.P. 1996. Without bamboo, the land dies-biomass, litterfall, and soil organic matter dynamics of a Japanese bamboo talon- kebun system. *Forest Ecol. Manage.* 87(1-3): 75-88.

Espiloy, Z. 1994. Effect of age on the physio-mechanical properties of some Philippine bamboo. In: Proceeding of the 4th International Bamboo Workshop on Bamboo in Asia and the Pacific. Chiangmai, Thailand, 27-30 November 1991. Forest Research Support Programme for Asia and the Pacific, Bangkok, Thailand: 180-182.

Forrest, W.G. and Ovington, J.D. 1970. Organic matter changes in an age series of *Pinus radiata* plantations. *J. Appl. Ecol*. 7: 177-186.

Gadgil, M and Prasad, S. N. 1984. Ecological determinants of life history evolution of two bamboo species of India. *Biotropica* 16: 161-172.

Haridasan, K., Singh, N.B. and Deori, M.L. 1987. Bamboos in Arunachal Pradesh - The present status. *Journal of Tropical Forestry* 3(4): 298-301.

Isagi, Y., Kawahara, T. and Kamo, K. 1993. Biomass and net production in a bamboo *Phyllostachys bambusoides* stand. *Ecological Research* 8: 123-133.

Isagi, Y., Kawahara, T., Kamo, K. and Ito, H. 1997. Net production and carbon cycling in a bamboo *Phyllostachys pubescens* stand. *Plant Ecology* 130(1): 41-52.

Joshi, A.P., Sundriyal, R.C. and Baluni, D.C. 1991. Nutrient dynamics of a lower Siwalik bamboo forest in the Garhwal Himalaya, India. *Journal of Tropical Forest Science* 3 (3): 238-250.

Kadeba, O. 1991. Above-ground biomass production and nutrient accumulation in an age sequence of *Pinus caribaea* stands. *Forest Ecol. Manage*. 41(3-4): 237-248.

Kleinhenz, V. and Midmore, D.J. 2001. Aspects of bamboo agronomy. *Advances in Agronomy* 74: 99-149.

Kumar, B.M., George, S.J., Jamaludheen, V. and Suresh, T.K. 1998. Comparision of biomass production, tree allometry and nutrient use efficiency of multipurpose trees grown in woodlot and silvopastoral experiments in Kerala, India. *Forest Ecol. Manage*.12: 145-163.

Kumar, B.M., Rajesh, G. and Sudheesh, K.G. 2005. Aboveground biomass production and nutrient uptake of thorny bamboo (*Bambusa bambos* (L.) Voss) in the homegarden of Thrissur, Kerala. *Journal of Tropical Agriculture* 43(1-2): 51-56.

Li, R., Werger, M.J.A., During, H.J., and Zhong, Z.C. 1998. Carbon and nutrient dynamics in relation to growth rhythm in the giant bamboo *Phyllostachys pubescens*. *Plant and soil* 201: 113-123.

Li, R., Werger, M.J.A., During, H.J., and Zhong, Z.C. 1999. Biomass distribution in grove of the giant bamboo *Phyllostachys pubescence* in Chongqing, China. *Flora* 194: 89-96.

Madgwick, H.A.I., Jackson, D.S. and Knight, P.J. 1977. Aboveground dry matter, energy and nutrient contents of trees in an age series of *Pinus radiata* plantations. *New Zealand Journal of Forest Science* 7: 445-468.

Mailly, D., Christanty, L., and Kimmins, J.P. 1997. Without bamboo, the land dies: nutrient cycling and biogeochemistry of a Japanese bamboo talon-kebun system. *Forest Ecol. Manage*. 91: 155-173.

Othman, A.R. 1992. Culm composition and aboveground biomass of *Gigantochloa scortechinii* stands. Paper presented in the International Symposium on Industrial use of Bamboo. Beijing, China.

Prasad, R., Sah, A.K., Bhandari, A.S. and Choubey, O.P. 1984. Dry matter production by *Eucalyptus camaldulensis* Dehn. plantations in Jabalpur. *Indian Forester* 110(9): 868-878.

Pynskhem, K. 2007. Aboveground Biomass and Nutrient Allocation Pattern in Muli Bamboo (*Melocanna baccifera* Roxb.) in Mizoram. M.Sc. Dissertation, Mizoram University, Aizawl, Mizoram, India: 48p.

Sarkar, J. and Sundriyal, R.C. 2002. Indigenous uses, management and conservation of bamboo resource in Arunachal Pradesh, North East India. *Bamboo Journal* 19: 24-39.

Sattar, M.A., Kabir, M.F. and Battacharjee, D.K. 1994. Effect of age and height position of Muli (*Melocanna baccifera*) and Borak (*Bambusa balcooa*) bamboos on their physical and mechanical properties. In: Proceeding of the 4th International Bamboo Workshop on Bamboo in Asia and the Pacific, Chiangmai, Thailand, 27-30 November 1991. Forest Research Support Programme for Asia and the Pacific, Bangkok, Thailand: 183-187.

Shanmughavel, P. and Francis, K. 1996. Biomass and nutrient cycling in bamboo (*Bambusa bambos*) plantations of tropical areas. *Biol. Fert. Soil* 23(4): 431-434.

Shanmughavel, P. and Francis, K. 2001. Physiology of Bamboo. Scientific Publishers (India), Jodhpur: 154p.

Singha, L.B. 2006. Site Specificity, Growth and Productivity of Rui Bamboo (*Arundinaria malling* Gamble) in Jang Area of Arunachal Pradesh. Ph. D. Thesis, Department of Botany, NEHU, Shillong, Meghalaya, India.

Singha, L.B., Bhatt, B.P. and Khan, M.L. 2003. Flowering of *Bambusa cacharensis* Mazumdar in the southern part of North-east India: a case study. *J. Bamboo and Rattan* 2(1): 57-63.

Tripathi, S.K. and Singh, K.P. 1994. Productivity and nutrient cycling in recently harvested and mature bamboo savannas in the dry tropics. *J. Appl. Ecol.* 31: 109-124.

Ueda, K. 1981. Bamboo Industry in Japan, Present and Future. Proceeding of the XVII IUFRO World Congress, Division. 5, Japan: 244-255.

Virtucio, F.D., Manipula, B.M. and Schlegel, F.M. 1994. Culm yield and biomass productivity of Laak (*Sphaerobambos phillipinensis*). In: proceedings of 4th International Bamboo Workshop on Bamboo in Asia and the Pacific, Chiangmai, Thailand, 27-30 November, 1991. Forest Research Support Programme for Asia and the Pacific, Bangkok, Thailand: 95-99.