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Abstract

Bamboo (*Bamusa bambos*) is emerging as an important multiple-use plant both in forests and agricultural lands. However, no clear-cut guidelines have been found developed on optimal harvest levels based on quantitative methods. An attempt made in this direction is reported here based on a State level study initiated in the forests of Kerala.

Twenty two sample plots of size ranging from 30 m x 30 m to 50 m x 50 m were laid in different bamboo growing regions in Kerala. Observations on number of clumps, number of culms on selected clumps and culm height were made in each plot over three years. The status of miscellaneous species was also recorded. Soil samples were collected from each plot yearly and analyzed to evaluate the soil properties. The stand level values for the different attributes were worked out using allometric relations established for different characters with clump diameter. The number of clumps ranged from 72 to 444/ha in the year of establishment of sample plots. The range for number of mature culms was to the order of 1065 to 4197 culms/ha. Height of the tallest culm varied from 10.5 to 22.6 m. The soil properties also showed much variation over the twenty two plots.

Maximum sustainable harvest was worked out using linear programming algorithm implemented on a transition matrix model that depicted the changes in culm numbers of different size classes over time. With the level of natural destruction found occurring on the shoots produced every year, sustainable harvest levels varied from 102 mature culms/ha annually to 832 mature culms/ha every ten years.

Two cutting cycles of intervals three and five years, were evaluated through linear programming which maximized the land expectation value. With an annual discount rate of 9 per cent and average price of Rs 60 for a mature culm, five year cutting cycle was found better than three year cutting cycle especially when the management is poor. The superiority of five year cutting cycle was found retained for values of fixed cost ranging from nil to as high as Rs 10,000/ha. The optimal cutting intensity thus worked out to 50 per cent of the total number of culms in the stand every five years. Every five years, around 464 mature culms can be harvested leaving 102 mature and 357 immature culms in the stand. At the current rates, the harvest value works out to Rs 27,832/ha every five years less costs of harvesting. This happens in the presence of natural destruction of the shoots amounting to 50 per cent every year. If we are able to reduce the extent of this damage, the harvests could be increased correspondingly.

Study on the effect of soil properties on the growth of bamboo showed that increment in diameter of the clumps was not affected by many soil properties except for Aluminium and pH. However, the increment in height was found influenced by gravel and phosphorus content. Additionally, the effect of soil on ingrowth of culms and transformation from immature to mature stage of the culms was investigated. The production of new shoots is seen affected by soil reaction. The transformation from immature to mature shoots reflective of the growth of the stand does not seem to be influenced by soil variables. However, these results are temporary as the estimates are based on a limited number of observations and also the plots were under severe external disturbances. With measurements coming from repeated measurements or larger number of plots, the results may get changed.

1. Introduction

Bamboo plays an important role in the forestry and allied sectors of Kerala by way of its use as pulpwood, use for furniture and for various agricultural purposes. Besides traditional use of construction, furniture, handicrafts and food, bamboo is increasingly being recognized as an environment friendly and cost-effective wood substitute for producing pulp, paper, boards, panels, flooring, roofing, composites and charcoal. Bamboo contributes substantially to the ecological, economic and social development. Ecologically, bamboo plays a critical role in soil and water conservation, maintaining the balance of oxygen and carbon dioxide in the atmosphere, lowers light intensity and offers protection against ultraviolet rays. Its inherent ability to grow on marginal and wastelands makes it one of the preferred crops for greening the wastelands and degraded sites, conservation of soil and moisture and sequestration of carbon.

Although a large quantity of bamboo comes from homesteads, natural stands of bamboo in forests still serve as an important source of bamboo raw material. A study at KFRI (Nair *et al.*, 2001) indicated the following status for bamboo in forest areas in Kerala.

Circle	Area under bamboo (km^2)	Bamboo stock (Dry weight in tonnes)	Percentage of stock (%)
Northern region	200.54	807,151	31
Olavakkod region	235.69	895,130	34
Central region	76.69	234,206	9
High range region	57.89	122,727	5
Southern region	201.01	571,232	21
Total	771.82	2,630,446	100

Currently, the Kerala Forest Department has an extent of around 5,000 ha under bamboo plantations. The Kerala Forest Development Corporation has also started planting bamboo and the species exhibits fast growth. Realizing the high potential of bamboo as a plantation species, it is getting included in more and more developmental schemes. Naturally, there is a need to develop scientific methods of cultivation for the species. One area where scientific information is lacking for this species is stand density management in relation to site conditions and hence was this project. The commonly occurring species *Bambusa bambos* has been considered for the study. The project was taken up with the following specific objectives.

a) To develop a growth simulation model for bamboo stands.
b) To optimize the harvesting schedules based on economic evaluation of alternative management regimes in relation to site conditions.
c) To study the influence of soil on growth of bamboo.

Before providing a detailed reporting of the works executed, some general descriptions about bamboo and its nature was considered appropriate and the following narrative is added to serve as a preamble for the report.

Bamboo is one of the most diverse and primitive groups of plants in the grass family, Poaceae. They usually grow in tropical, subtropical and temperate regions where the annual rainfall ranges between 1200 and 4000 mm and the temperature varies between 16 and 38^{o}C. Bamboos are highly adaptable, some species of which are deciduous and others evergreen. India stands next to China in bamboo resources of the world. Of the 111 genera and 1575 species of bamboos reported to occur in the world, 134 species belonging to 18 genera have been reported from India. Bamboo in India extends over an area of 10.05 million ha, which is about 12.8% of the total forest area of the country.

The Kerala part of the Western Ghat is one of the major diversity centres for bamboo coming only next to the North-eastern states of the country. In Kerala, 25 species of bamboos have been recorded under seven genera. This accounts for about 19 per cent of the total bamboos available in India and 95 per cent of the total species reported from Peninsular India. *Bambusa bambos*, *Dendrocalamus strictus* and *Ochlandra travancorica* are the most widely distributed bamboos within the State.

Bamboos are perennial grasses of gregarious habit, for which the woody stems (the culms) arise from a woody root stock called rhizomes. The stems are the culms and their joints the nodes. There is a scaly rhizome or underground stem which is produced from the base of the seedling plant which grows vertically downwards for a short distance and then curves up again and appears as a small culm. The rhizome system penetrates the soil as it grows and produces larger and larger culms successively. Full size culms are usually produced after a span of 5 to 12 years depending on the species and growing conditions. In majority of cases, in the planes, the rhizomes are more or less densely clustered together and the culms arise as clumps. The culms are jointed and hollow between joints, the thickness of walls varies according to the species. Solid culms are also produced as in the case of *Dendrocalamus strictus*. The new culms arise from the rhizomes during the rainy season, appearing above ground in the form of tender pointed cones covered with sheaths at the nodes. The culms elongate rapidly, reaching full height, in a span of three to four months. Usually the branches develop after the upward growth of the culm is completed. The number of new culms produced varies greatly depending on the species, size and vigor of the clump.

The rudimentary buds are formed on the rhizome especially at the nodal regions, soon after the rains and enlarge slowly taking a few months time while embedded in the soil and emerge out as tender shoots in the shape of pointed cones simultaneous with the pre-monsoon showers of the next year. The rains during June-July influence the sprouting of the tender new shoots and it takes about three to four months to achieve full growth. Branches appear on the culms usually only after the full emergence of the culm, which is a species specific character. At this stage, each culm will have a sheath covering towards its base and at the lower part of each of the internodes. The exposed outer part of the internodes will have a waxy powdery coating and will be covered with very fine stellate hairs. As the culms become older, the coloration of the culms usually gets darker. Bamboo is considered to be the fastest growing woody plant in the world as their growth rate is on an average up to 50 centimeters/day which is due to the unique growth mainly dependent on the rhizome and the fibrous root system. However, the growth is also highly dependent on local soil and climatic conditions.

2. Review of past works

Productivity of bamboo forests in India is far below and can be attributed to over-exploitation, lack of scientific management, recurrent fire, poor natural regeneration and damage by cattle (INBAR, 1991). In India, almost 99% annual bamboo production is from natural stands in the forest and only1% is derived from plantations. Nevertheless increased productivity can be achieved following selection of right species, elite clones or genotypes matching with the site characters and proper management practices (Gielis *et. al*., 2001).

In the case of plantations, seedlings are planted at 6 m x 6 m spacing with a total of about 250 seedlings per ha. The seedlings are irrigated immediately after transplanting. Weeding is generally required during the first year (Shanmughavel *et al.,* 1997). Most villagers generally cultivate bamboos by planting offsets or rhizomes as seeds are not readily available. Rhizomes or offsets are dug out carefully so that the buds are not damaged and then transported to planting sites. Planting work is done immediately after the first showers of the monsoon. Bamboo clump starts production of new culms from the third year of establishment in the field. The plantations are ready for exploitation within 4-12 years, depending upon the prevailing climatic conditions (Negi and Naithani, 1994). The number of culms produced initially will be lesser, smaller and lighter. As the clump matures in a span of 3 to 5 years the productivity usually goes up and will be maximum after about 7 to 10 years (KFRI-Unpublished data). The culm production is species dependent and is very much influenced by the climatic and edaphic conditions of the site. Mature culms can be harvested after about five years of establishment and then onwards periodically with a gap of three years although these practices are not based on any quantitative study.

It is reported that soils with high fertility status supported good bamboo growth and comparatively poor growth was observed on soils with low fertility (Anonymous, 1961). Yadav (1969) correlated the growth performance of bamboo with different soil properties in Bihar and concluded that soils supporting good bamboo possessed higher moisture and organic carbon than those having poor growth. He also claimed that finer textured soils associated with higher nitrogen status and greater phosphorus availability, were helpful in promoting the growth of bamboo plantations. Cai and Wang (1985) reported that height of the young culm in *Phyllostachys* is positively correlated with air and soil temperature and deeper the soil layer, the greater the diameter of the shoots produced. Biswas (1988) was of the opinion that soils high in N, P_2O_5, SiO_2 and CaO promoted the best growth of bamboo. Sujatha (1999) reported that growth performance of reed bamboo (*Ochlandra travancorica)* in Kerala is greatly influenced by soil pH and organic carbon. Li *et al*. (1998) found a strong correlation between growth parameters (height and diameter) of *Phyllostachys glauca* and soil porosity. Significant relation with soil exchangeable Al and bamboo forests was reported by Liang *et al*. (2000) in China. According to Venkatesh *et al.* (2005) all the bamboo species show varying effects on soil properties and *Dendrocalamus giganteus, D hookerii* and *Babusa nutans* were better species for restoring soil fertility status with respect to pH and organic carbon in humid tropics of the NEH region, India.

3. Materials and methods

3.1. Data

A set of 22 semi-permanent sample plots were laid out in bamboo plantations and natural bamboo stands of *Bambusa bambos* during December 2008-May 2009, representing various age groups, stocking levels and site conditions in different parts of the State of Kerala. The plot size varied from 30 m X 30 m to 50 m X 50 m depending upon the age/stocking status of the plots. These plots were remeasured during December 2009-May 2010 and December 2010-May 2011. During each measurement period, observations on clump diameter on all the clumps, height of tallest culm on selected clumps, i.e., smallest, medium, and largest of the clumps and number of culms of different size classes in the selected clumps were recorded from the sample plots.

Figure 1. View of the sample plot laid out at Thiruvizhamkunnu

The status of clumps not selected for detailed observations on any feature was derived through regression analysis. The following equations fitted to the data for the three years, were used for the purpose.

$$\ln N_1 = 0.754 + 0.559 \ln D \quad (R^2=0.267) \tag{1}$$

$$\ln N_2 = 2.084 + 0.991 \ln D \quad (R^2=0.739) \tag{2}$$

$$\ln N_3 = 2.171 + 0.769 \ln D \quad (R^2=0.328) \tag{3}$$

$$\ln H = 2.571 + 0.426 \ln D \quad (R^2=0.483) \tag{4}$$

where N_1 is the number of immature culms in the clump

N_2 is the number of mature culms in the clump
N_3 is the number of cut, dry or damaged culms in the clump
H is the height of the tallest culm in the clump (m)
D is the diameter of the clump (m)

Graphs of equations (1) to (4) are depicted in Figures (1) to (4) along with corresponding observations.

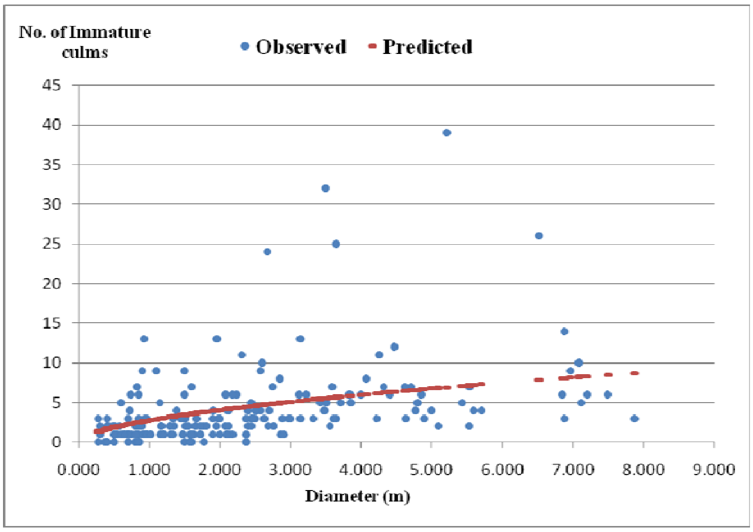

Figure 2. Graph of number of immature culms against diameter of clumps

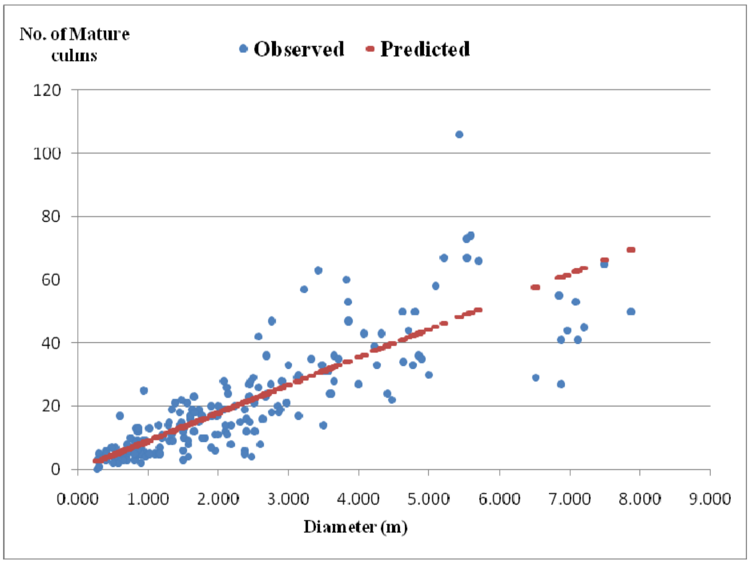

Figure 2. Graph of number of mature culms against diameter of clumps

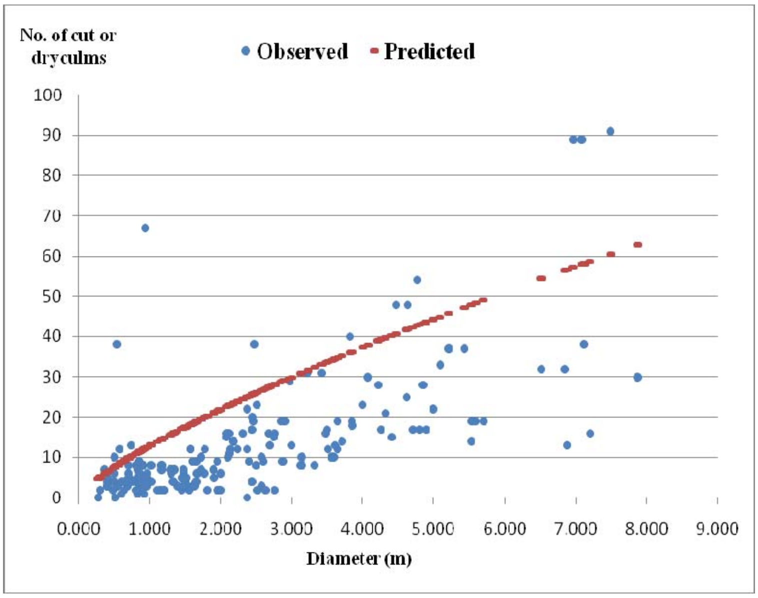

Figure 3. Graph of number of cut or dry culms against diameter of clumps

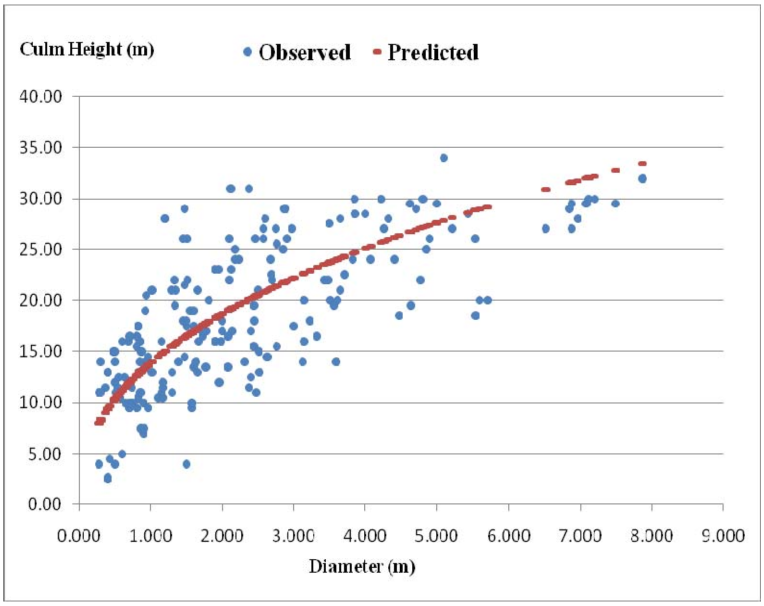

Figure 4. Graph of height of tallest culm against diameter of clumps

For miscellaneous tree species growing in the plots, girth at breast-height and the species identity were also recorded. Geographical position in terms of latitude, longitude, and altitude were recorded along with other site features including the slope of the sample plots.

Soil samples were collected using soil augur from the four quarters within each plot and pooled to make a composite sample for analysis. These samples were collected from 0-10 cm and 10-20 cm depth levels, dried under shade and sieved through 2mm sieve for further analysis.

Various physical and chemical properties *viz.*, gravel, texture (hydrometer method), bulk density (core method), water holding capacity, pH (1:2.5 soil water suspension), organic carbon (sulphuric acid and potassium dichromate wet digestion), available N (alkaline permanganate method), extractable P (Bray II extraction), exchange acidity (1 M KCl extraction), exchangeable Al (1 M KCl extraction) and exchangeable K (ammonium acetate extraction followed by flame photometry) were determined using standard procedures (Jackson, 1958 and Black *et al.*, 1965).

The stand level attributes were worked out using equations (1) to (4) and summary statistics generated. The summary statistics on stand features at plot level for the first, second and third year measurements are reported in Tables 1, 2 and 3.

Table 1. Stand level attributes of the sample plots in bamboo stands in 2008-2009

Plot No.	Location	Mean clump diameter (m)	No. of clumps/ha	No. of immature culms/ha	No. of mature culms/ha	No. of cut or dry culms/ha	Mean height of tallest culm (m)	Basal area of miscellaneous species (m^2/ha)
1	Thozhupadam	0.85	244	585	1607	2465	11.8	4.98
2	Punalur	0.89	206	536	1539	2135	12.6	0.00
3	Punalur	1.41	238	687	2634	3212	14.5	1.46
4	Pampetty	2.79	84	374	1635	2081	18.4	2.61
5	Moodal	1.02	244	773	1815	2596	12.0	6.58
6	Arippa	1.15	322	1088	2940	3994	13.8	1.46
7	Palode	0.87	219	549	1496	2123	12.2	2.20
8	Emangadu	1.68	181	760	2644	3054	17.2	0.21
9	Nellikuthu	2.55	92	416	1926	2180	20.2	8.26
10	Neyyamkayam	1.99	200	771	3048	3708	16.8	3.29
11	Koomankundu	2.70	206	988	4197	4732	19.5	1.54
12	Keekarakuthu	3.70	116	763	3256	3538	22.6	0.71
13	Melekalam	1.93	188	722	2639	3089	16.6	29.38
14	Pulikkunnu	0.75	213	471	1108	1763	10.5	25.01
15	Peralantha	2.48	128	465	2122	2621	17.0	8.35
16	Tholnadai	1.68	144	462	1653	2162	14.9	14.00
17	Amayalthotti	2.00	104	389	1748	2046	17.0	3.62
18	Mamalakandam	1.74	204	688	2832	3506	16.1	9.10
19	Cheenikunnu	3.85	72	361	2217	2080	21.8	2.77
20	Vettingapadam	2.08	72	372	1065	1331	18.4	11.15
21	Pandianpara	1.12	444	1111	3589	4841	12.6	0.00
22	Aayiravallipara	3.11	92	644	2200	2465	21.3	7.03

Table 2. Stand level attributes of the sample plots in bamboo stands in 2009-2010

Plot No.	Location	Mean clump diameter (m)	No. of clumps/ha	No. of immature culms/ha	No. of mature culms/ha	No. of cut or dry culms/ha	Mean height of tallest culm (m)	Basal area of miscellaneous species (m^2/ha)
1	Thozhupadam	0.99	233	579	2085	2544	13.0	5.35
2	Punalur	1.01	213	537	1769	2414	13.4	0.00
3	Punalur	1.49	244	699	2861	3410	14.8	1.56
4	Pampetty	2.86	84	330	1740	2114	18.6	2.86
5	Moodal	1.10	233	575	2088	2637	13.0	7.02
6	Arippa	1.00	322	875	3244	4045	14.1	1.46
7	Palode	0.90	225	519	1670	2248	12.6	1.89
8	Emangadu	1.78	181	652	2966	3664	17.7	0.27
9	Nellikuthu	2.77	88	382	1795	2109	20.5	8.52
10	Neyyamkayam	2.07	206	733	3386	3946	17.3	3.60
11	Koomankundu	2.88	188	817	4315	4642	20.8	2.43
12	Keekarakuthu	3.80	116	602	3543	3596	23.0	1.08
13	Melekalam	2.06	188	634	2900	3221	17.4	33.63
14	Pulikkunnu	0.83	194	397	1243	1792	11.2	25.37
15	Peralantha	2.69	120	474	2256	2689	18.0	7.93
16	Tholnadai	1.79	152	447	1955	2441	15.5	12.73
17	Amayalthotti	2.21	96	365	1828	2044	18.2	3.27
18	Mamalakandam	1.78	196	645	2754	3344	16.0	6.35
19	Cheenikunnu	3.79	68	319	2095	1911	21.7	3.67
20	Vettingapadam	2.23	72	266	1254	1401	18.8	12.64
21	Pandianpara	1.26	444	1233	4334	5618	13.9	0.00
22	Aayiravallipara	3.27	92	423	2568	2555	21.9	7.11

Table 3. Stand level attributes of the sample plots in bamboo stands in 2010-2011

Plot No.	Location	Mean clump diameter (m)	No. of clumps/ha	No. of immature culms/ha	No. of mature culms/ha	No. of cut or dry culms/ha	Mean height of tallest culm (m)	Basal area of miscellaneous species (m^2/ha)
1	Thozhupadam	1.03	222	601	2006	2570	13.7	4.91
2	Punalur	1.02	206	572	1926	2540	13.9	0.00
3	Punalur	1.48	231	737	2898	3538	15.4	1.33
4	Pampetty	3.03	80	349	1797	2027	19.5	2.42

5	Moodal	1.10	211	574	1967	2481	13.7	8.74
6	Arippa	1.24	311	938	3365	4248	14.9	0.11
7	Palode	1.00	219	563	1829	2392	13.1	1.13
8	Emangadu	1.95	181	706	3065	3584	18.1	0.25
9	Nellikuthu	2.88	76	371	1967	1978	21.4	5.99
10	Neyyamkayam	2.21	206	815	3700	4221	18.2	3.82
11	Koomankundu	2.82	175	855	4471	4631	21.5	2.71
12	Keekarakuthu	3.91	116	626	3653	3722	23.0	1.59
13	Melekalam	2.23	181	688	3172	3405	17.5	18.87
14	Pulikkunnu	0.89	181	454	1428	2023	12.9	35.50
15	Peralantha	2.68	116	464	2309	2653	18.2	6.73
16	Tholnadai	1.84	152	493	2078	2529	15.4	11.61
17	Amayalthotti	2.27	96	406	1908	2224	19.2	3.26
18	Mamalakandam	1.83	196	689	2918	3502	16.6	6.95
19	Cheenikunnu	4.05	72	390	2309	2163	23.0	2.59
20	Vettingapadam	2.49	72	301	1444	1547	19.0	11.20
21	Pandianpara	1.33	444	1322	4821	5955	14.7	0.00
22	Aayiravallipara	3.36	92	457	2491	2475	21.7	7.62

The range of the stand level attributes for the three consecutive measurements are shown in Table 4.

Table 4. Range of stand level attributes in three consecutive measurements

Attribute	2008-09		2009-10		2010-11	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Mean clump diameter (m)	0.75	3.85	0.83	3.80	0.89	4.05
No. of clumps/ha	72	444	68	444	72	444
No. of immature culms/ha	361	1111	266	1233	301	1322
No. of mature culms/ ha	1065	4197	1243	4334	1428	4821
No. of cut or dry culms/ ha	1331	4841	1401	5618	1547	5955
Mean.height of tallest culm (m)	10.5	22.6	11.2	23.0	12.9	23.0

The status of soil properties during the first measurement in 2008-09 is shown in Table 5 and 6.

Table 5. Status of soil properties during the first measurement in 2008-09

Plot No.	Plot Name	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Gravel (%)	Bulk density (g/cc)	pH	OC (%)
1	Thozhupadam	0 - 10	78	8	14	31.8	1.24	4.2	1.7
		10 - 20				27.1	1.38	4.3	1.2
2	Punalur	0 - 10	80	11	9	29.0	1.01	4.5	3.2
		10 - 20				19.9	1.09	5.7	1.0
3	Punalur	0 - 10	76	14	10	24.5	0.80	5.6	3.0
		10 - 20				37.2	0.74	4.1	2.6
4	Pampetty	0 - 10	76	13	11	23.5	0.82	5.7	2.6
		10 - 20				34.6	0.90	4.3	2.2
5	Moodal	0 - 10	85	12	3	20.2	0.55	4.3	2.4
		10 - 20				27.0	0.59	5.9	1.2
6	Arippa	0 - 10	76	14	10	8.0	1.11	4.3	2.4
		10 - 20				12.9	1.06	5.9	1.2
7	Palode	0 - 10	89	6	5	20.6	1.45	5.9	1.1
		10 - 20				16.3	1.16	5.9	0.8
8	Emangadu	0 - 10	89	6	5	42.6	0.94	5.8	2.0
		10 - 20				22.3	0.94	4.4	0.8
9	Nellikuthu	0 - 10	76	12	12	15.2	1.14	4.6	3.3
		10 - 20				20.6	1.15	4.7	0.8
10	Neyyamkayam	0 - 10	76	9	15	44.0	0.87	5.3	3.1
		10 - 20				38.3	1.03	5.3	2.2
11	Koomankundu	0 - 10	94	4	2	17.9	0.76	4.6	3.0
		10 - 20				27.7	0.56	4.9	2.3
12	Keekarakuthu	0 - 10	89	6	5	25.7	0.76	6.2	2.4
		10 - 20				14.0	0.77	6.1	3.1
13	Melekalam	0 - 10	87	9	4	52.6	0.69	5.7	3.3
		10 - 20				48.0	0.61	5.8	3.0
14	Pulikkunnu	0 - 10	78	11	11	47.7	1.01	5.7	1.2
		10 - 20				35.3	1.49	5.9	0.9
15	Peralantha	0 - 10	84	11	5	22.9	1.00	5.8	3.4
		10 - 20				33.6	1.39	6.1	3.2
16	Tholnadai	0 - 10	95	3	2	22.9	1.00	4.2	4.1
		10 - 20				18.2	0.99	4.1	2.5
17	Amayalthotti	0 - 10	84	10	6	28.4	0.92	5.6	2.5
		10 - 20				30.4	0.96	4.6	2.1
18	Mamalakandam	0 - 10	93	5	2	24.0	0.80	5.7	3.0
		10 - 20				25.0	0.75	5.3	2.5
19	Cheenikunnu	0 - 10	85	9	6	44.3	0.59	5.3	3.8
		10 - 20				49.1	0.66	5.4	2.4
20	Vettingapadam	0 - 10	86	6	8	7.4	0.96	5.7	2.5
		10 - 20				8.0	0.97	5.5	3.1
21	Pandianpara	0 - 10	87	10	3	44.3	1.24	5.9	3.0
		10 - 20				79.0	0.93	5.8	1.5
22	Aayiravallipara	0 - 10	84	9	5	33.2	0.61	5.9	2.9
		10 - 20				48.9	0.67	6.0	2.0

Table 5 cont...

Plot No.	Plot Name	Depth (cm)	EA (meq/100g)	Av. N (%)	Extr. P (ppm)	Exch. K (ppm)	Exch. Na (ppm)	Exch.Al (meq/100g)
1	Thozhupadam	0 – 10	0.30	0.04	8.53	149.50	38.50	0.00
		10 – 20	0.30	0.02	7.45	71.50	46.50	0.00
2	Punalur	0 – 10	0.90	0.04	7.08	88.00	44.00	0.80
		10 – 20	1.30	0.03	5.49	55.50	41.00	0.60
3	Punalur	0 – 10	1.00	0.06	8.71	168.00	39.50	0.30
		10 – 20	1.90	0.45	22.56	123.50	35.00	1.70
4	Pampetty	0 – 10	0.30	0.03	6.83	203.50	36.00	0.00
		10 – 20	0.40	0.04	5.47	135.00	49.50	0.00
5	Moodal	0 – 10	0.60	0.04	4.28	48.50	50.50	0.30
		10 – 20	0.90	0.04	4.70	79.50	49.50	0.40
6	Arippa	0 – 10	0.60	0.04	4.28	48.50	48.00	0.30
		10 – 20	0.90	0.04	4.70	79.50	48.00	0.40
7	Palode	0 – 10	0.20	0.04	8.98	70.50	33.50	0.00
		10 - 20	0.30	0.02	8.85	79.50	36.50	0.00
8	Emangadu	0 - 10	0.20	0.03	3.81	86.50	45.00	0.00
		10 - 20	0.50	0.03	6.73	82.50	65.50	0.10
9	Nellikuthu	0 - 10	0.30	0.04	4.94	64.00	61.00	0.00
		10 - 20	0.30	0.03	5.45	35.50	59.50	0.00
10	Neyyamkayam	0 - 10	1.10	0.02	4.87	109.00	53.50	0.40
		10 - 20	1.60	0.04	4.80	74.50	55.50	1.00
11	Koomankundu	0 - 10	0.30	0.04	12.89	81.00	42.50	0.00
		10 - 20	0.40	0.03	11.22	53.50	40.50	0.00
12	Keekarakuthu	0 - 10	0.10	0.05	43.13	185.00	22.50	0.00
		10 - 20	0.20	0.04	16.20	258.50	47.00	0.00
13	Melekalam	0 - 10	0.40	0.04	17.02	127.50	53.50	0.00
		10 - 20	0.10	0.03	16.42	110.00	53.00	0.00
14	Pulikkunnu	0 - 10	0.30	0.03	13.17	248.50	42.00	0.00
		10 - 20	0.10	0.04	5.58	373.50	47.50	0.00
15	Peralantha	0 - 10	0.20	0.03	64.58	140.00	46.50	0.00
		10 - 20	0.10	0.04	45.10	106.00	44.50	0.00
16	Tholnadai	0 - 10	0.80	0.03	5.58	101.00	43.50	0.00
		10 - 20	1.30	0.16	5.79	65.50	41.00	0.50
17	Amayalthotti	0 - 10	0.60	0.06	4.30	90.50	49.50	0.30
		10 - 20	0.60	0.04	5.04	55.00	40.50	0.30
18	Mamalakandam	0 - 10	2.80	0.06	4.37	87.00	45.00	2.30
		10 - 20	2.50	0.06	4.85	36.00	42.00	2.20
19	Cheenikunnu	0 - 10	0.50	0.06	4.93	166.00	44.00	0.00
		10 - 20	0.90	0.04	4.38	65.50	47.00	0.70
20	Vettingapadam	0 - 10	0.30	0.04	14.69	183.50	45.50	0.00
		10 - 20	0.20	0.04	26.21	167.50	47.50	0.00
21	Pandianpara	0 - 10	0.40	0.04	7.69	248.50	50.50	0.00
		10 - 20	0.30	0.04	7.58	235.00	69.00	0.00
22	Aayiravallipara	0 - 10	0.20	0.04	14.57	324.50	52.00	0.00
		10 - 20	0.20	0.04	11.43	182.00	51.00	0.00

Table 6. Range of soil variables observed over the sample plots during the first measurement

Characteristics (Unit)	Code	Depth level (cm)	Minimum	Maximum
Sand (%)	Sa	0-20	76	95
Silt (%)	Si	0-20	3	14
Clay (%)	Cl	0-20	2	15
Gravel (%)	Gr_1	0-10	7.41	52.55
	Gr_2	10-20	8.04	78.99
Bulk density (g/cc)	Bd_1	0-10	0.55	1.45
	Bd_2	10-20	0.56	1.49
pH	pH_1	0-10	4.19	6.16
	pH_2	10-20	4.07	6.14
Organic carbon (%)	Oc_1	0-10	1.11	4.14
	Oc_2	10-20	0.75	3.15
Exchange acidity (meq/100g)	Ea_1	0-10	0.10	2.80
	Ea_2	10-20	0.10	2.50
Available N (%)	N_1	0-10	0.02	0.06
	N_2	10-20	0.02	0.45
Extr. P (ppm)	P_1	0-10	3.81	64.58
	P_2	10-20	4.38	45.10
Exch. K (ppm)	K_1	0-10	48.50	324.50
	K_2	10-20	35.50	373.50
Exch. Na (ppm)	Na_1	0-10	22.50	61.00
	Na_2	10-20	35.00	69.00
Exch Al (meq/100g)	Al_1	0-10	0	2.30
	Al_2	10-20	0	2.20

The status of soil properties during the second measurement in 2009-10 is shown in Table 7 and 8.

Table 7. Status of soil properties during the second measurement in 2009-10

Plot No.	Plot Name	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Gravel (%)	Bulk density (g/cc)	pH	OC (%)
1	Thozhupadam	0 - 10	79	12	9	24.1	1.38	5.7	1.2
		10 - 20				25.7	1.44	5.5	0.8
2	Punalur	0 - 10	80	11	9	25.8	1.69	4.9	1.6
		10 - 20				30.7	1.45	5	1.6
3	Punalur	0 - 10	72	17	11	27.9	1.32	5.1	1.8
		10 - 20				31.8	1.08	5.4	1.5
4	Pampetty	0 - 10	79	14	7	20.9	0.81	5.6	2.1
		10 - 20				20.2	1.14	5.6	1.7
5	Moodal	0 - 10	87	10	3	8.2	1.08	5.8	4.6
		10 - 20				11.9	0.85	5.7	4
6	Arippa	0 - 10	82	11	7	13.1	1.51	5.5	1.9
		10 - 20				11.1	1.30	5.2	1.1
7	Palode	0 - 10	90	5	5	27.6	1.97	5.9	1.2
		10 - 20				23.9	1.71	5.5	0.9
8	Emangadu	0 - 10	76	16	8	35.6	1.46	5.5	1.4
		10 - 20				35.8	1.15	5.6	1.3
9	Nellikuthu	0 - 10	82	10	8	13.5	1.42	5.2	1.4
		10 - 20				13.5	1.24	5.7	0.9
10	Neyyamkayam	0 - 10	84	12	4	34.6	1.32	4.7	2
		10 - 20				28.5	1.56	4.8	1.3
11	Koomankundu	0 - 10	83	11	6	32.9	1.43	5.8	2.8
		10 - 20				48.7	1.41	5.8	2.5
12	Keekarakuthu	0 - 10	80	10	10	0	1.56	6.3	2.4
		10 - 20				2.4	1.41	6.1	2.1
13	Melekalam	0 - 10	76	16	8	14.7	1.23	5.9	3.4
		10 - 20				15.4	1.27	5.5	2.6
14	Pulikkunnu	0 - 10	72	17	11	10.8	1.23	6.3	1.4
		10 - 20				34.2	1.15	5.8	1.4
15	Peralantha	0 - 10	86	10	4	14.4	1.04	6.4	3.5
		10 - 20				16.8	1.41	6.3	2.2
16	Tholnadai	0 - 10	92	4	4	18.9	1.29	5.6	4.8
		10 - 20				34.6	0.81	5.5	3.8
17	Amayalthotti	0 - 10	80	13	7	10.6	1.64	5.1	2.6
		10 - 20				9	1.33	5.3	2.4
18	Mamalakandam	0 - 10	74	16	10	2.8	1.43	4.9	3.5
		10 - 20				5.8	1.06	5.1	3.2
19	Cheenikunnu	0 - 10	82	13	5	11.1	0.99	5.6	5.3
		10 - 20				33.9	1.28	5.5	4.7
20	Vettingapadam	0 - 10	80	11	9	16.3	1.72	5.5	0.5
		10 - 20				19.7	1.42	5.1	1.3
21	Pandianpara	0 - 10	83	9	8	15	1.32	6.1	2.1
		10 - 20				18.5	1.62	6	2
22	Aayiravallipara	0 - 10	79	14	7	15.8	1.01	6.5	3
		10 - 20				27.4	1.82	5.8	2

Table 7 cont...

Plot No.	Plot Name	Depth (cm)	EA (meq/100g)	Av. N (%)	Extr. P (ppm)	Exch. K (ppm)	EC (ds/m)	Exch.Al (meq/100g)
1	Thozhupadam	0 - 10	0.70	0.01	7.10	70.80	0.03	0.00
		10 - 20	0.80	0.02	9.70	72.50	0.02	0.00
2	Punalur	0 - 10	1.60	0.01	3.80	45.50	0.03	0.70
		10 - 20	1.40	0.01	1.50	56.50	0.04	0.60
3	Punalur	0 - 10	2.50	0.02	3.10	58.50	0.02	1.10
		10 - 20	2.10	0.02	3.40	87.50	0.03	1.20
4	Pampetty	0 - 10	0.80	0.03	2.30	104.00	0.03	0.10
		10 - 20	0.60	0.02	1.80	76.80	0.02	0.00
5	Moodal	0 - 10	0.40	0.01	6.50	145.00	0.04	0.00
		10 - 20	0.30	0.02	3.90	121.50	0.04	0.00
6	Arippa	0 - 10	0.40	0.02	0.80	122.30	0.08	0.10
		10 - 20	0.30	0.01	1.50	44.30	0.04	0.00
7	Palode	0 - 10	0.40	0.03	24.90	72.80	0.05	0.00
		10 - 20	0.50	0.01	6.00	86.30	0.04	0.00
8	Emangadu	0 - 10	0.60	0.01	4.60	71.30	0.03	0.00
		10 - 20	0.40	0.02	2.40	52.50	0.02	0.00
9	Nellikuthu	0 - 10	0.70	0.03	1.40	41.80	0.04	0.60
		10 - 20	0.90	0.02	3.70	27.80	0.03	0.50
10	Neyyamkayam	0 - 10	0.90	0.02	8.00	84.50	0.03	0.30
		10 - 20	1.20	0.02	4.50	75.80	0.03	0.20
11	Koomankundu	0 - 10	0.30	0.02	3.10	75.30	0.04	0.00
		10 - 20	0.40	0.02	4.00	54.00	0.03	0.00
12	Keekarakuthu	0 - 10	0.40	0.03	43.70	190.00	0.19	0.00
		10 - 20	0.20	0.02	54.80	140.00	0.09	0.00
13	Melekalam	0 - 10	0.30	0.02	2.70	128.80	0.06	0.00
		10 - 20	0.40	0.02	3.80	59.00	0.02	0.00
14	Pulikkunnu	0 - 10	0.90	0.02	0.50	324.80	0.08	0.20
		10 - 20	0.70	0.02	3.80	361.50	0.08	0.00
15	Peralantha	0 - 10	0.60	0.03	54.20	220.80	0.24	0.00
		10 - 20	0.30	0.02	44.30	129.50	0.09	0.00
16	Tholnadai	0 - 10	1.30	0.03	3.00	54.80	0.06	0.50
		10 - 20	1.00	0.02	26.70	35.80	0.04	0.40
17	Amayalthotti	0 - 10	0.70	0.02	4.60	51.50	0.04	0.30
		10 - 20	0.50	0.02	1.10	49.50	0.04	0.30
18	Mamalakandam	0 - 10	3.60	0.03	15.00	60.80	0.04	2.50
		10 - 20	3.00	0.03	1.70	57.00	0.03	2.20
19	Cheenikunnu	0 - 10	0.40	0.03	2.80	153.50	0.07	0.00
		10 - 20	0.20	0.02	3.50	88.00	0.04	0.00
20	Vettingapadam	0 - 10	1.50	0.02	41.80	178.30	0.21	0.00
		10 - 20	1.70	0.02	28.40	95.50	0.12	0.00
21	Pandianpara	0 - 10	0.30	0.02	47.50	197.00	0.13	0.00
		10 - 20	0.50	0.02	0.80	157.80	0.08	0.00
22	Aayiravallipara	0 - 10	0.10	0.03	45.60	272.00	0.20	0.00
		10 - 20	0.30	0.02	18.30	165.30	0.04	0.00

Table 8. Range of soil variables observed over the sample plots during the second measurement

Characteristic (unit)	Code	Depth level (cm)	Minimum	Maximum
Sand (%)	*Sa*	0-20	72	92
Silt (%)	*Si*	0-20	4	17
Clay (%)	*Cl*	0-20	3	11
Gravel (%)	Gr_1	0-10	0.00	35.60
	Gr_2	10-20	2.40	48.70
Bulk density (g/cc)	Bd_1	0-10	0.81	1.97
	Bd_2	10-20	0.81	1.82
pH	pH_1	0-10	4.70	6.50
	pH_2	10-20	4.80	6.30
Organic carbon (%)	Oc_1	0-10	0.50	5.30
	Oc_2	10-20	0.90	4.70
Exchange acidity (meq/100g)	Ea_1	0-10	0.10	3.60
	Ea_2	10-20	0.20	3.00
Available N (%)	N_1	0-10	0.03	0.49
	N_2	10-20	0.03	0.42
Extr. P (ppm)	P_1	0-10	0.50	54.20
	P_2	10-20	0.80	54.80
Exch. K (ppm)	K_1	0-10	41.80	324.80
	K_2	10-20	27.80	361.50
Exch Al (meq/100g)	Al_1	0-10	0	2.50
	Al_2	10-20	0	2.20
Electric Conductivity (ds/m)	*Ec1*	0-10	0.02	0.24
	Ec2	10-20	0.02	0.12

3.2. Statistical analysis

3.2.1. Growth modelling and simulation

The following model structure was adopted for the purpose of growth simulation (Buongiorno and Gilless, 2003) after suitable modifications.

$$\mathbf{y}_{t+1} = \mathbf{G}\mathbf{y}_t + \mathbf{c} \tag{5}$$

The column vector $\mathbf{y}_t$ designates the state of the bamboo stand at time t and **G** and **c** are matrices of constant parameters as shown below.

$$\mathbf{y}_t = \begin{bmatrix} y_{1t} \\ y_{2t} \end{bmatrix}, \qquad \mathbf{G} = \begin{bmatrix} a_1 \; b_1 \\ a_2 \; b_2 \end{bmatrix}, \qquad \mathbf{c} = \begin{bmatrix} R_t \\ 0 \end{bmatrix} \tag{6}$$

where y_{1t} is the number of immature culms/ha at time t
y_{2t} is the number of mature culms/ha at time t
a_1 is the fraction of live immature culms at time t that are still remaining at time t+1
a_2 is the fraction of live mature culms at time t that are still remaining at time t+1
b_1 is the fraction of live immature culms at time t that becomes mature at time t+1
b_2 is the fraction of live mature culms at time t that grows out from the class at time t+1
R_t is the ingrowth or the number of new shoots in immature class/ha during t and t+1

The proportions estimated from the hectare level predictions of culms using equations (1) to (4) are given in Table 9.

Table 9. Proportion of bamboo culms staying, growing up and dying in each size class

Size class	Proportion of culms staying in a class (a_i)	Proportion of culms growing up (b_i)	Proportion of culms dying (1-a_i-b_i)
Immature culms	0.2545	0.2846	0.4609
Mature culms	0.9548	0.0000	0.0452

Obviously, a substantial portion (50 percent) of the new culms produced get damaged or cut illegally. The cutting could not have been a part of regular harvesting because specific instructions were given to the agencies concerned not to disturb the plots during our observation period. Attempts to develop a prediction equation for annual production of new culms (R_t) based on the existing number of culms in the stand as required by model (5) did not lead to a satisfactory equation and hence was assumed to be constant. The mean ingrowth of culms/ha (R_t) worked out to 266.

Substituting R_t in equation (5), the growth equations obtained were as follows.

$$\mathbf{y}_{1t+1} = 266 + 0.2545\mathbf{y}_{1t} \quad (7)$$

$$\mathbf{y}_{2t+1} = 0.2846\mathbf{y}_{1t} + 0.9548\mathbf{y}_{2t} \quad (8)$$

When there is no harvest and the stand is left undisturbed but for the interference from natural forces like damage by elephants, drying up of shoots or illegal removal, the stand will converge to a steady state over time. The steady state is independent of the initial conditions and depends only on the growth parameters. This undisturbed steady state is found by solving this system of linear equations,

$$\mathbf{y}_{t+1} = \mathbf{G}\mathbf{y}_t + \mathbf{c} \quad (9)$$

At the steady state, $\mathbf{y}_{t+1} = \mathbf{y}_t$.

This system has a unique solution, which can be found by linear programming, with the above equations and $\mathbf{y}_t \geq 0$ as constraints and with an arbitrary objective function, such as minimizing y_{1t} where y_{1t} is the number of culms in the youngest class.

At stable condition, as obtained through the Excel Solver, the stand composition worked out to be of 2247 mature culms and 357 immature culms, the latter constituting around 14 % of the total number of culms. The total number of culms/ha (2604) at steady state reflects also the carrying capacity of the stands subject to the natural forces like damage or illicit removal or drying up of shoots. The corresponding stand development is shown in the following graph. Although it takes around 120 years for the complete stabilization, proximate values comparable to the terminal stage are achieved within less than 10 years. The projection ignores the intervention due to natural flowering and subsequent perishing of the plants till regeneration occurs.

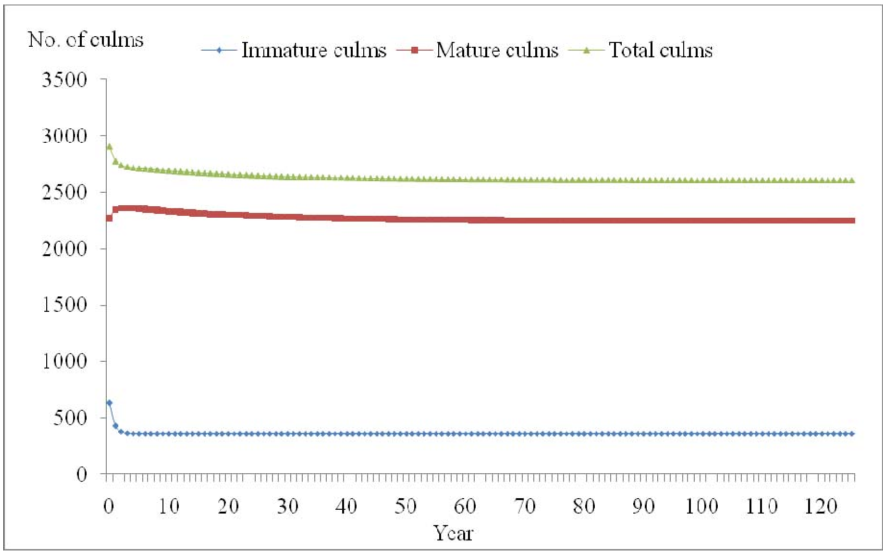

Figure 6. Stand development of bamboo under undisturbed conditions

It was found that nearly 50 percent of the shoots produced get removed from the stand due to natural forces operating like fire, damage due to elephants, illicit removal or drying up. It would be of interest to know what if the extent of this damage is reduced. Consequence of such a state of affairs was studied by altering the transition probabilities as follows restricting the annual loss of shoots to around 25 per cent as shown below.

Size class	Proportion of culms staying in a class (a_i)	Proportion of culms growing up (b_i)	Proportion of culms dying ($1-a_i-b_i$)
Immature culms	0.2545	0.5346	0.2109
Mature culms	0.9548	0.0000	0.0452

The results of simulation are shown in Figure 6. At stable condition, the stand composition worked out to 4220 mature culms and 357 immature culms, the latter constituting around 8 per cent of the total number of culms. Although it takes around 170 years for the complete stabilization, proximate values comparable to the terminal stage are achieved in less than 60 years.

Even after reducing the loss due to natural factors to 25 per cent, the number of immature culms in the steady state did not get altered and remained at 357 culms/ha (Figure 7). The reason could partly be due to the constant production of new shoots (266 culms/ha), assumed due to the poor R^2 for the corresponding prediction equation. Coupled with the fraction of culms remaining stationary in the same class, the terminal value got fixed at 357 culms/ha.

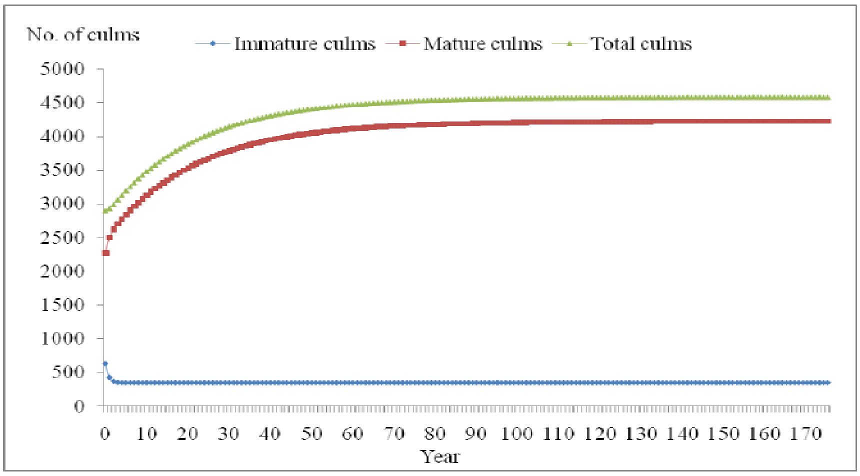

Figure 7. Stand development of bamboo under undisturbed conditions with annual loss of shoots restricted to 25 per cent

3.2.2. Maximizing periodic production

Recursive equation allows prediction of the stand state at any point in the future, starting from a particular initial state y_0 and subject to a specific sequence of harvests: h_0, $h_1, \ldots, h_t$:

$$
\begin{aligned}
\mathbf{y_1} &= \mathbf{G}(\mathbf{y}_0 - \mathbf{h_0}) + \mathbf{c} \\
\mathbf{y}_2 &= \mathbf{G}(\mathbf{y}_1 - \mathbf{h}_1) + \mathbf{c} \\
&\;\;\vdots \\
\mathbf{y}_t &= \mathbf{G}(\mathbf{y}_{t-1} - \mathbf{h}_{t-1}) + \mathbf{c}
\end{aligned}
\tag{10}
$$

The sustainable regime that maximizes production per unit of time is found by solving a linear program with the following objective function and constraints:

Objective function is the constant periodic production:

$$\max_{h_t, y_t} Z_Q = h_t \tag{11}$$

where h_t is number of culms to be harvested from the mature category. The harvest from immature class was set to zero.

Growth equation: $\mathbf{y}_{t+1} = \mathbf{G}(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{c}$
Steady-state constraints: $\mathbf{y}_{t+1} = \mathbf{y}_t$
Cut less than stock, and nonnegative: $h_t \le y_t$, $h_t \ge 0$

The results of optimization are depicted in Table 10 which gives the maximum possible harvest under steady state for annual or longer intervals between harvests.

Table 10. Maximum sustainable harvest levels with various cutting cycles

Interval between harvests (year)	Number of immature culms in the stand (culms/ha)	Number of harvestable culms (culms/ha)
1	357	102
2	357	199
3	357	291
4	357	379
5	357	464
6	357	544
7	357	621
8	357	695
9	357	765
10	357	832

The maximum sustainable harvest varied from 102 mature culms/ha annually to 832 culms/ha with a 10 year cutting cycle. Nevertheless the number of immature culms remained stationery at equilibrium point regardless of the interval between harvests. This could be because the 357 culms/ha is the target value under steady state conditions under undisturbed conditions and the stand attains this target value at equilibrium state for any value of the cutting cycle. It may be noted that these figures correspond to the equilibrium stage on an average and there could be considerable stand to stand and year to year variation during the developmental stages.

3.2.3. Economic optimization of harvests

Through economic optimization, optimal cutting cycle and intensity can be determined. To study the effect of different cutting cycles, it is convenient to write the growth equation (10) in the following form.

$$\mathbf{y}_{t+1} = \mathbf{G}(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{c} \tag{12}$$

where $\mathbf{y}_t$ is the state of the stand at time t, $\mathbf{h}_t$ is the harvest at time t, and $\mathbf{G}$ and $\mathbf{c}$ are the constant parameters.

Assume a two year cutting cycle instead of annual harvest. This means that there is a harvest at time t, but no harvest at time $t+1$. Therefore, the state of the stand at time $t+2$ is:

$$\mathbf{y}_{t+2} = \mathbf{G}\mathbf{y}_{t+1} + \mathbf{c} \tag{13}$$

The steady state constraints require that the stand state be the same at the beginning and at the end of the cutting cycle; i.e.:

$$\mathbf{y}_{t+2} = \mathbf{y}_t \tag{14}$$

In addition, the harvest must be less than the stock:

$$\mathbf{h}_t \le \mathbf{y}_t \tag{15}$$

and the harvest cannot be negative:

$$\mathbf{h}_t \ge \mathbf{0} \tag{16}$$

The object is to find the harvest $\mathbf{h}_t$ and the growing stock $\mathbf{y}_t$ that satisfy constraints specified while maximizing the land expectation value (LEV),

$$LEV = P_h - V_s = V_h + \frac{V_h}{(1+r)^D - 1} - V_s \tag{17}$$

with

$V_h = \mathbf{wh}_t$ and $V_s = \mathbf{wy}_t$

where **w** is the vector of unit commercial values for culms of each size class.
r is the interest rate
D is the length of cutting cycle

However, the expression of the land expectation value changes with the fixed costs (*F*) if any associated with the harvest operations. The LEV then takes the form,

$$LEV_F = (V_h - F) + \frac{V_h - F}{(1+r)^D - 1} - (V_s - F) \quad (18)$$

This simplifies to:

$$LEV_F = V_h + \frac{V_h - F}{(1+r)^D - 1} - V_s = LEV - \frac{F}{(1+r)^D - 1} \quad (19)$$

Thus, the land expectation value with a fixed cost is equal to the land expectation value without a fixed cost, minus a constant that depends only on the fixed cost, the interest rate, and the cutting cycle. As a result, for a given cutting cycle, the harvest that maximizes land expectation value is the same with and without fixed cost. However, the land expectation value will be different for different cutting cycles.

The results of optimization through linear programming are given in Table 11 for two cutting cycles, *viz.*, three and five years. An interest rate of 9 per cent was assumed for the financial calculations. The price of a mature culm was assumed to be Rs 60 on an average for computing the values of stock as well as harvests any time. The results show that a five year cutting cycle is better than three year cutting cycle. The superiority of five year cutting cycle was found retained for values of fixed cost ranging from nil to as high as Rs 10,000/ha.

Table 11. Optimal harvest regime for different cutting cycles

Attribute	Cutting cycle	
	3 Year	5 Year
No. of immature culms in the stand/ha	357	357
No. of mature culms in the stand/ha	102	102
No. of harvestable culms/ha	291	464
Percentage of harvest (%)	38.8	50.3
Harvest value (Rs/ha)	17,465	27,832
Forest value (Rs/ha)	76,662	79,504
Stock value (Rs/ha)	6,093	6,093
Land Expectation value (Rs/ha)	70,569	73,411

The optimal cutting intensity thus works out to 50 per cent of the total number of culms in the stand every five years. Every five years, around 464 mature culms can be harvested leaving 102 mature and 357 immature culms in the stand. At the current rates, the harvest value works out to Rs 27,832/ha every five years less costs of harvesting. This happens in the presence of natural destruction of the shoots amounting to 50 per cent every year. If we are able to reduce the extent of this damage, the harvests could be increased correspondingly. The current practice is understood to be to remove around 60 per cent of the total number of culms that are harvestable leaving the remaining culms in the stand which include both immature and a few mature culms. We are not able to strike a range for harvests as it is highly influenced by the level of damage suffered by the stands.

3.2.4. Relation between soil and growth parameters

The effect of soil properties on the growth of bamboo was investigated by fitting the following equations on increment in clump diameter and increment in height through stepwise regression, after forcing in certain stand variables. The equations were run at the stand level after clubbing the observations on increments for the two intervals considered for the study.

$$\ln I_D = 1.034 + 0.328\ln D - 0.087\ln C - 0.175\ln M + 0.059\ln B - 0.535 Al_1 - 0.405\,pH_1$$
(R^2=0.4740)

$$\ln I_H = 2.380 - 1.643\ln H - 0.477\ln C - 0.037\ln M + 0.002\ln B - 0.026 P_2 + 0.048 Sa + 0.021 Gr_2$$
(R^2=0.4730)

where I_D is the increment in the mean clump diameter (m)
I_H is the increment in the mean height of the tallest culm (m)
D is the mean initial diameter of the clumps (m)
C is the initial number of bamboo clumps/hectare
M is the number of miscellaneous trees/hectare
B is the basal area of miscellaneous trees/hectare (m^2/ha)
H is the mean initial height of the tallest culm (m)
Al_1 is the *Al* in the soil at the depth 0-10 cm
pH_1 is the *pH* in the soil at the depth 0-10 cm
P_2 is the Potassium in the soil at the depth 10-20 cm
Sa is the Sand in the soil
Gr_2 is the gravel percentage in the soil at the depth 10-20 cm
ln indicates natural logarithm

Increment in diameter of the clumps does not seem to be related to many soil properties except for Al and pH. However, the increment in height is influenced by subsoil gravel and phosphorus content other than the forced in variables *viz*., initial height of the clumps, initial number of clumps and the status of miscellaneous species.

Additionally, the effect of soil on ingrowth of culms and transformation from immature to mature stage of the culms was investigated. The results were the following.

$$\ln R_t = 1.419 + 0.894 \ln N_t + 0.128 \ln B_t - 0.732\, pH_2$$
(R^2=0.2030)
$$\ln N_{t,t+1} = 1.588 + 0.390 \ln N_t + 0.113 \ln B_t$$
(R^2=0.0510)

where

R is the increment in total number of culms
$N_{t,t+1}$ is the number of immature culms at time t that becomes mature at time $t+1$
N_t is the total number of culms at time t
B_t is the basal area of miscellaneous trees/hectare (m^2/ha) at time t
pH_2 is the pH in the soil at the depth 10-20 cm
ln indicates natural logarithm

The production of new shoots is seen affected by the soil reaction in subsurface layer. The transformation from immature to mature shoots reflective of the growth of the stand does not seem to be influenced by soil variables. However, these results are temporary as the estimates are based on a limited number of observations and also the plots were under severe external disturbances. With measurements coming from repeated measurements or larger number of plots, the results may get changed.

3.2.5. Changes in soil under bamboo

It would be interest to see the changes in the soil happening with bamboo growing on top of it. The mean changes happening between the first two and the last two measurements are depicted in Table 12 and 13. Significant changes as revealed by paired t test are also shown in Table 12 and 13. It may be noted that the soil properties in Table 12 are based on 22 plots whereas those in Table 13 are based on just 10 plots because of fire that occurred in the remaining plots.

Table 12. Mean changes in soil properties of bamboo stands over a year

Characteristic (unit)	Depth level (cm)	I year (n=22)	II year (n=22)	Change (II-I)	Significance at P=0.01
Sand (%)	0-20	83.95	80.82	3.14	*
Silt (%)	0-20	9.00	11.91	-2.91	*
Clay (%)	0-20	6.95	7.27	-0.32	NS
Gravel (%)	0-10	28.65	17.94	10.71	*
	10-20	30.60	22.70	7.89	NS
Bulk density (g/cc)	0-10	0.92	1.36	-0.44	*
	10-20	0.94	1.31	-0.37	*
pH	0-10	5.29	5.63	-0.34	*
	10-20	5.26	5.54	-0.27	NS
Organic carbon (%)	0-10	2.73	2.46	0.27	NS

	10-20	1.92	2.08	-0.15	NS
Exchange acidity (meq/100g)	0-10	0.56	0.88	-0.32	*
	10-20	0.70	0.80	-0.11	NS
Available N (%)	0-10	0.04	0.02	0.02	*
	10-20	0.06	0.02	0.04	*
Extr. P (ppm)	0-10	12.24	14.86	-2.63	NS
	10-20	10.73	10.44	0.29	NS
Exch. K (ppm)	0-10	137.23	123.82	13.40	NS
	10-20	114.75	95.20	19.55	*
Exch Al (meq/100g)	0-10	0.21	0.29	-0.08	NS
	10-20	0.36	0.25	0.11	NS

*Significant at P=0.01

Table 13. Mean changes in soil properties of bamboo stands over an year

Characteristic (unit)	Depth level (cm)	II year (*n*=10)	III year (*n*=10)	Change (III-II)	Significance at P=0.01
Sand (%)	0-20	80.30	81.00	0.70	NS
Silt (%)	0-20	12.30	11.40	-0.90	NS
Clay (%)	0-20	7.40	7.60	0.20	NS
Gravel (%)	0-10	18.92	12.29	-6.63	NS
	10-20	22.38	9.60	-12.78	*
Bulk density (g/cc)	0-10	1.38	1.33	-0.04	NS
	10-20	1.39	1.52	0.14	NS
pH	0-10	5.80	5.62	-0.18	NS
	10-20	5.57	5.54	-0.03	NS
Organic carbon (%)	0-10	1.84	2.46	0.62	NS
	10-20	1.55	2.20	0.65	*
Exchange acidity (meq/100g)	0-10	0.67	0.56	-0.11	NS
	10-20	0.61	0.54	-0.07	NS
Extr. P (ppm)	0-10	18.64	30.24	11.6	NS
	10-20	11.73	32.35	20.62	*
Exch. K (ppm)	0-10	148.86	123.4	-25.46	NS

	10-20	113.37	107.29	-6.08	NS
Exch Al (meq/100g)	0-10	0.07	0.11	0.04	NS
	10-20	0.03	0.08	0.05	NS

*Significant at P=0.01

Results indicate that among the various soil properties studied, content of sand, silt, gravel, bulk density, pH, exchange acidity and available N were found affected significantly during the first year while only gravel, organic carbon and extractable P were affected during the second year. But on considering the cumulative changes from initial year of the study to the third year, significant changes were observed only with gravel content and bulk density.

4. Discussion

4.1. Sivicultural aspects

The study has shown some results of value in the management of bamboo stands. The mean composition of the population under study in terms of number of culms/ha was as follows.

Number of immature culms : 601 /ha
Number of mature culms : 2458 /ha
Number of cut, dry or damaged culms : 2908 /ha
Total number of culms : 5967 /ha

Number of clumps : 177 /ha
Number of culms /clump : 39 /clump

The maximum sustainable harvest worked out to 102 mature culms/ha annually which changed to 464/ha for a five year cutting cycle and to 832 culms/ha for 10 year cycle (Table 10). It was also found that nearly 50 percent of the shoots produced get removed from the stand due to natural forces operating like fire, damage due to elephants, illicit removal or drying up. Had these damages been avoided, the possibility exists for nearly doubling the harvests. The optimization exercise has ignored the fact of gregarious flowering found in bamboo. Long term projections made in this report are subject to major biological interventions like flowering in this case whereby the entire growth process stops till a new start is made through natural or artificial regeneration.

In any case, annual harvests are not practical in the case of planted stands managed by government agencies. Long gaps between harvests will result in loss of shoots due to external factors. Optimization of cutting cycle with or without fixed costs associated with harvests indicated a five year cutting cycle to be the best. Every five years, we shall be able to harvest 464 mature culms/ha, leaving back 102 mature and 357 immature culms in the stand. The mature culms that are retained should be evenly distributed over the clumps. Retaining this many culms is essential as they will act as supports for the new sprints/ culms during the ensuing growing season. At the current rates, the harvest value worked out to Rs 27,832/ha every five years less costs of harvesting. This happens in the presence of natural destruction of the shoots amounting to 50 per cent every year. If we are able to reduce the extent of this damage, the harvests could be increased correspondingly.

4.2. Relation between soil and growth

Since the bamboo plots selected for the present study represent various age groups, stocking levels and site conditions a wide variation in soil properties did occur naturally during the initial year of the study (Table 6). And these variations were continued during the following year also (Table 8). Any vegetation starts exerting its influence on soil only after having established well on that soil. Usually root penetration, root exudates, plant residues, nutrient uptake, nutrient release etc. are the major factors contributing to changes in soil characteristics due to vegetation. Since the soils in this study are with various age groups and stocking levels of bamboo, any soil variable showing significant change in all the sites could be chalked out only after continuous measurements over a long period of time. Still, on relating the growth of bamboo with soils, some variables such as pH, exchangeable Al, content of K, sand , gravel etc. were found highly correlated. Significant relation with soil exchangeable Al and bamboo forests was also reported by Liang *et al*. (2000) in China. So also Sujatha (1999) reported the influence of soil pH on growth of reed bamboo (*Ochlandra travancorica)* in Kerala.

Although it is too early to make any conclusions regarding the changes happening in the soil under bamboo, the study has given some indications. It requires continued observations to confirm the results. The requirement of a control plot devoid of bamboo adjacent to every plot under observations was indicated but was found not practical under natural conditions. Hence one may have to depend on the continuity of observations to decipher any changes in soil properties over time. It has to be noted that the changes indicated are average over the twenty two plots distributed in different parts of bamboo growing regions in the State.

4.3. Limitations and future works

One of the major limitations of the study has been that observations on the number of culms of different size classes were restricted to just three selected clumps within each plot under the expectation that the status of the remaining clumps could be predicted based on the diameter measured on those clumps. However, the relation between diameter and number of culms worked out to be weak and this affected all further calculations.

The other major constraint was that the stands were under heavy disturbance due to external factors. This was one of the major reasons for weak allometric relations and also lack of relation of growth parameters with soil.

It is recommendable to continue the study avoiding the above limitations to the extent possible and also to understand the dynamics of soil under bamboo.

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