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Culm dynamics, carbon sequestration and potential for electrical energy from *Dendrocalamus strictus* Nees plantation in South-eastern Bihar, India

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Abstract: Out of many forms of renewable energy, bio-energy could solve the village energy needs through distributed generation to a great extent. An attempt is made to analyse carbon capture and carbon credit generation from bamboo plantations. The total energy stored as biomass by a 5-year-old plantation of *Dendrocalamus strictus* was 2.375 TJ ha^{-1} and that by 7-year-old plantation was 3.579 TJ ha^{-1}. Energy capture efficiency for the above-ground and total clump vegetation after 5 and 7 years was 1.32 per cent, 1.41 per cent, 1.74 per cent and 1.87 per cent respectively. The total carbon storage in standing biomass of 5-year-old and 7-years-old bamboo plantations varied from 56.75 to 84.51 Mg ha^{-1}, of which 48 per cent was distributed in stem, 14 per cent in branches and 25 per cent in below-ground biomass. The total biomass was 118.23 Mg ha^{-1} in the 5-year-old and 176.31 Mg ha^{-1} in the 7-year-old plantations. The number of culms produced per clump varied from 58 to 88. The recruitment to culm population varied between 20 and 21 per cent and shoot mortality between 4 and 5 per cent per year. Net accumulation of green culms between 4^{th} and 5^{th} year was 2,160, and between 6^{th} and 7^{th} year 3477 ha^{-1}. Energy stored in biomass of 5-year-old culms from 9,283 ha, or biomass of 7-year-old culms from 6,253 ha is sufficient to operate a 50 MW generating station for one year. Total energy production in 5- and 7-year-old culms from 1 ha of *D. strictus* is sufficient to meet energy needs (in terms of electrical energy) of an average household of Bihar, India for 21.5 and 31.3 years respectively.

Key words: Biomass, bioenergy, carbon sequestration, electrical energy, *Dendrocalamus strictus*.

INTRODUCTION

Indian economy has shown impressive growth in the recent past and it is expected that it will continue to do so for several decades to come. Growth in economy has to be accompanied by growth of primary energy and electricity consumption. Estimates indicate that the domestic fossil resources would not be able to meet the rising energy demands and the country has to go in for large imports of fossil fuels. In the coming years, biomass-based energy and nuclear technologies will compete with each other for their share.

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Bamboo is a very fast growing species. Biomass production and carbon sequestration rate of this species are very high due to its high energy capture efficiency. Biomass is one of the productivity indicators of any species and carbon capture in plants is an indication of reduction of atmospheric carbon dioxide that can help minimize the potential danger of global warming. *Dendrocalamus strictus* Nees is a very common bamboo that occurs in deciduous forests and drier regions of India except in North Bengal, Assam and moist regions of West Coast (Troup, 1921; Varmah and Bahadur, 1980). In Bihar it is a very common species of homestead forestry, farm forestry and rural forestry. The quality of growing races of *D. strictus* is so high that its plantation was raised by Taiwan in 1912 by obtaining seeds from Bihar. *D. strictus* is a deciduous densely tufted bamboo. Culms grow to 8-16 m in height and 2.5 to 8 cm in diameter and is largely planted by the Forest Department since it is a source of raw material for bamboo cottage industry of the State. The total extent under *D. strictus* is estimated as 16,000 ha (40% of total bamboo growing area of the State). The districts which are rich in bamboo resources include Kisanganj, Araria, Purnea, Supaul, Madhepura, Saharsa, Mungerr, Jamui, Banka, Bhagalpur and Katihar. However, *D. strictus* is dominant in Bhabhua, Rohtas, Aurrangabad, Gaya, Nawada, Jamui and Banka districts (Jha, 2006).

Bamboo is a good substitute for fossil fuels and has a number of desirable fuel characteristics such as low ash content and alkali index. The heating value is higher than many wood species like beech, spruce, eucalypts, poplar and most of the agricultural residues, grasses and straw. Bamboo is high in biomass productivity and is self regenerating. It can thus provide power on a sustainable and environment-friendly basis. The net calorific value of *D. strictus* is in the range of 19.3-20.8 MJ/kg. The present study deals with culm dynamics, carbon sequestration and electrical energy potential of *D. strictus* plantation in southeastern Bihar, India.

MATERIALS AND METHODS

The bamboo plantation investigated in this study was located at Krishi Vigyan Kendra, Munger, Bihar, India (24 °23' N latitude and 85 °35' E longitude). The climate was characterized by hot summer with heat waves, cold winter and moderate to low rainfall. The mean annual temperature of the District was about 29 °C. The average daily maximum temperature goes up to 24 °C in February and to about 38 °C in March. Highest temperature was generally around 46 °C during April to June whereas the lowest temperature was between 20 °C and 70 °C in January. The relative humidity during summer was 83 to 93 per cent in the morning and 36 per cent in the afternoon. The average annual precipitation of Munger was 1122 mm, 80 per cent of which was received during monsoon months of June to September. The soil of the experimental site was loam of neutral pH (7.15). The soil contained 0.31 per cent organic carbon, 21 kg ha^{-1} available P_2O_5, 140 kg ha^{-1} K_2O prior to planting. Total mean incident solar radiation on a horizontal surface was 54,400 TJ ha^{-1} $year^{-1}$.

Plantation of *D. strictus* was raised in July 1996 by planting 4-month-old nursery raised seedling in previously dug pits (45 cm x 45 cm x 45 cm) at a spacing of 6 m x 6 m with a total of 275 seedling ha^{-1}. The biomass of different clump components on a unit area basis was estimated through density and biomass estimation equations (Das and Chaturvedi, 2006). Calorific values were determined with an adiabatic bomb calorimeter (Lieth, 1968). Total energy storage was calculated by multiplying the energy value in a component with its corresponding biomass and then summing up values of different components.

Organic C in the soil was determined in triplicate by dichromate oxidation and titration with ferrous ammonium sulphate (Moore and Chapman, 1986). Carbon concentration in different components of bamboo was determined in triplicate using a CHNS/O-Analyser (Perkin Elmer Series 11-2400). The carbon storage in the plantation was computed as the products obtained by multiplying dry weight of biomass and productivity values of different components by their mean carbon concentrations.

RESULTS AND DISCUSSION

Culm dynamics

Distribution of green and dead culms in different diameter classes for 5th and 7th year is given in Table 1. A majority of green as well as old culms were in the 4-6 cm diameter class. Of the total culms, 21 per cent were represented by current year shoots and 55 per cent by old shoots. The recruitment to culm population was 2,160 ha^{-1} between 4th and 5th year and 3477 ha^{-1} between 6th and 7th year. Corresponding values for mortality were 425 culms ha^{-1} and 520 culms ha^{-1}. This resulted in net accumulation

Table 1. Number of culms in different age and diameter classes in *D. strictus* plantations

Plantation	Number of culms (ha^{-1})			
	Diameter class (cm)			
	2-4	4-6	6-8	Total
5-year-old				
Current	212 ± 18	2678 ± 34	0	2890 ± 34
Old	611 ± 32	6759 ± 62	484 ± 23	7854 ± 85
Green	823 ± 19	9437 ± 44	484 ± 23	10744 ± 103
Dead	335 ± 16	3317 ± 27	0	3652 ± 33
Total	1158 ± 41	12754 ± 46	484 ± 23	14396 ± 85
7-year-old				
Current	509 ± 26	3916 ± 49	0	4425 ± 22
Old	849 ± 16	10215 ± 104	619 ± 25	11683 ± 48
Green	1358 ± 88	14131 ± 71	619 ± 25	16108 ± 82
Dead	718 ± 21	4222 ± 77	0	4940 ± 26
Total	2076 ± 25	18353 ± 85	619 ± 25	21048 ± 79

of 1,735 green culms between 4th and 5th year and 2,957 green culms ha^{-1} between 6th and 7th year. The number of culms per clump varied between 58 and 88 and culm diameter and height ranged from 2.5 to 8 cm and 8 to 16 m, respectively. Recruitment of new culms occurred during the rainy season.

The production of new culms is linearly related with the number of old culms in a clump and the majority of new culms are produced by rhizomes of 1-10 years old (Singh and Singh, 1999). In a given site, the production of new culms depends mostly on the degree of congestion, clump age and the rainfall of the previous year (Shanmughavel and Francis, 1996a). Singh and Singh (1999) reported average annual recruitment of culms of *D. strictus* between 18 (between 3rd and 4th year) and 36 per cent (between 4th and 5th year) on mine spoil in a dry tropical region. The annual recruitment in the present plantation, varied from 20 to 21 per cent. In a mature *D. strictus* plantation, the annual mortality is reported to vary between 6.6 per cent and 10.6 per cent (Tripathi and Singh, 1996). Mortality rates were recorded as 3.3 to 5.3 per cent for the present *D. strictus* plantations. Thus the ustochrepts soil of southeastern Bihar proved favourable for growth and survival of *D. strictus*.

Biomass

The range of biomass production of 5- and 7-year-old bamboo clumps is given in Table 2. Average above-ground biomass production was 88.68 Mg ha^{-1} in the 5-year-old to 130.46 Mg ha^{-1} in the 7-year-old plantation while total biomass increased from 118.23 Mg ha^{-1} in 5-year-old to 176.31 Mg ha^{-1} in 7-year-old plantation. Thus, above-ground biomass of *D. strictus* was similar to *Yushania alpina* (110 Mg ha^{-1}) (Embaye *et al.*, 2005) and *Guadua angustifolia* (76 Mg ha^{-1}) (Riano *et al.*, 2002). In this study, production falls within the range of 122-287 Mg ha^{-1} reported for *Bambusa bambos* (Shanmughavel and Francis, 1996b). Above-ground biomass in *D. strictus* reported by Tripathi and Singh (1996) and Singh and Singh (1999) are in the range of 4-22 Mg

Table 2. Biomass and energy value of *D. strictus* plantations at different ages

Components	5-year-old		7-year-old	
	Dry matter (Mg ha^{-1})	Energy (TJ ha^{-1})	Dry matter (Mg ha^{-1})	Energy (TJ ha^{-1})
Foliage	14.19 ± 1.15	0.293 ± 0.023	22.92 ± 2.61	0.479 ± 0.010
Branch	16.56 ± 3.19	0.341 ± 0.065	24.68 ± 4.36	0.513 ± 0.091
Current shoot	9.8 ± 0.15	0.192 ± 0.002	12.66 ± 0.27	0.253 ± 0.005
Old shoot	33.63 ± 1.4	0.677 ± 0.028	50.08 ± 0.92	1.031 ± 0.018
Dead shoot	14.50 ± 0.26	0.297 ± 0.053	20.12 ± 0.38	0.415 ± 0.007
Total shoot stem	57.93 ± 2.6	1.163 ± 0.052	82.86 ± 3.41	1.691 ± 0.069
Rhizome	24.83 ± 2.16	0.489 ± 0.042	38.78 ± 3.82	0.767 ± 0.075
Root	4.72 ± 0.12	0.091 ± 0.002	7.07 ± 0.22	0.136 ± 0.004
Total	118.23 ± 12.32	2.375 ± 0.247	176.31 ± 15.99	3.579 ± 0.324

ha^{-1} and 30-49 Mg ha^{-1}, respectively. These values are very low compared to the present study. Possible reasons could be the stocking density and quality of planting material. Habitat conditions at these two sites were also different. Plantation in the latter case was raised on mine spoil (physically, nutritionally and biologically impoverished) while the former on undisturbed tropical dry soil. There was a marked variation in distribution of biomass in the stems of different diameter classes (Table 3). Majority of biomass resided in the 2-4 and 4-6 cm diameter class.

The contribution of different components of bamboo to total stand biomass was remarkably consistent across the ages. Most of the biomass was contributed by live stems (36.15%) followed by rhizomes (21.49%), branches (13.99%), foliage (12.99%) and roots (3.99%). Thus, 74.52 per cent biomass was located above-ground and 25.48 per cent, below-ground. This is closer to the findings of Riano *et al.* (2002) in *G. angustifolia* (80% and 20%). However, on mine spoil site above-ground production of *D. strictus* is 65 per cent while below-ground production is 35 per cent (Singh and Singh, 1999). Comparatively higher below-ground production may be part of a soil development strategy of the species on this refractory area like coal mine dump. This suggests that *D. strictus* tends to produce more above-ground biomass on comparatively improved soil. However, below-ground accumulation of biomass in this species was much higher as compared to woody species (5-17%) at younger age (5-9 years) and grown in woodlot or agroforestry (Mohan Kumar *et al.*, 1998).

Jha and Das (2007) reported the above-ground and below-ground biomass production in *Albizia procera* as 82.34 per cent and 17.66 per cent in experimental plot of agroforestry at Krishi Vigyan Kendra, Munger, Bihar, India. While reviewing the bamboo biomass, Hunter and Junqui (2003) have also concluded that bamboo invests a sizable proportion of its energy below-ground.

Table 3. Distribution on biomass (Mg ha^{-1}) in different size classes of current, old and dead stems of *D. strictus* plantation at different ages

Year	Stem biomass Mg ha^{-1}			
	Diameter class (cm)			
	2-4	4-6	6-8	Total
5-year-old				
Current	0.489 ± 0.041	9.34 ± 0.11	0	9.8 ± 0.15
Old	1.64 ± 0.83	29.19 ± 0.26	2.8 ± 0.13	33.63 ± 1.4
Dead	0.841 ± 0.04	13.66 ± 0.11	0	14.50 ± 0.26
Total	2.97 ± 0.31	52.19 ± 1.24	2.8 ± 0.13	57.93 ± 2.6
7-year-old				
Current	0.744 ± 0.062	11.92 ± 0.17	0	12.66 ± 0.27
Old	2.31 ± 0.29	44.12 ± 0.44	3.65 ± 0.19	50.08 ± 0.92
Dead	1.87 ± 0.054	18.25 ± 0.33	0	20.12 ± 0.38
Total	4.92 ± 0.406	74.29 ± 2.43	3.65 ± 0.19	82.86 ± 3.41

Carbon capture and sequestration

Total capture of carbon in the standing biomass of *D. strictus* was 56.75 Mg ha^{-1} in 5-year-old and 84.51 Mg ha^{-1} in 7-year-old plantations. Out of this, below-ground biomass was 25.5 per cent and above-ground biomass was 74.5 per cent. Carbon concentration varied in different components. The mean concentrations were: leaf 12.11 per cent, branch 13.94 per cent, stem 47.97 per cent, rhizome 21.51 per cent and root 3.99 per cent. Organic carbon storage in soil to a depth of 60 cm was higher in the older bamboo plantation than in the younger one.

Pandey (2003) arrived at 43.20 Mg ha^{-1} carbon at the end of 10^{th} year in a teak plantation in Madhya Pradesh. In moist deciduous forest region of India this species stores 65 Mg ha^{-1} at the age of 30 years (Jha, 2005). Carbon sequestration potential of *A. procera* plantation is 152.62 Mg ha^{-1} at the end of 9^{th} year in plantation forest of Bihar (Jha and Das, 2007). Temperate plantations can accumulate carbon in vegetation to the tune of 40-80 Mg ha^{-1} (Dewar and Cannell, 1992). This is an indication that, from ecological point of view, *D. strictus* plantation is a more viable option with regard to carbon capture and sequestration. The most striking characteristic of bamboo is vertiginous growth. No other species grows so fast (Singh *et al.*, 2006). Therefore, the advantage of bamboo planting is conversion of atmospheric carbon in shorter time.

Electrical energy

The total amount of energy stored in the bamboo of the present plantation was 2,375 GJ ha^{-1} and 3,579 GJ ha^{-1} at 5 years and 7 years respectively. The distribution of the total energy in different clump components was 48.96 per cent and 47.24 per cent in

Table 4. Carbon storage (Mg ha^{-1}) in different culm components of *D. strictus*

Year	Stem	Branch	Leaves	Rhizome	Roots	Above ground	Below ground	Total
5 year old	27.8 ± 1.2	7.9 ± 0.5	6.8 ± 0.5	11.91 ± 1.13	2.26 ± 0.05	42.5 ± 3.2	14.17 ± 1.18	56.75 ± 5.91
7 year old	39.7 ± 1.6	11.8 ± 2.1	11.01 ± 1.2	18.61 ± 1.83	3.39 ± 0.11	62.5 ± 4.9	22.01 ± 1.94	84.51 ± 6.54

Table 5. Carbon sequestration rate (Mg ha^{-1}) of *D. strictus* plantation in southeastern Bihar, India

Year	Biomass carbon (Mg ha^{-1})	Stem carbon (Mg ha^{-1})	Soil carbon (Mg ha^{-1})	Total carbon (Mg ha^{-1})	N.E.P. Mg /ha/year	Return @ USD 20/tonne/ha	
						Stem	Total
5-year-old	56.75 ± 5.91	27.8 ± 1.2	9.18 ± 1.23	65.93 ± 3.57	11.35 ± 1.18	556	1318.6
7-year-old	84.51 ± 6.84	39.7 ± 1.6	11.64 ± 2.24	96.15 ± 4.54	12.07 ± 0.76	794	1923.1

culms, 14.35 per cent and 14.33 per cent in branches. 12.33 per cent and 13.38 per cent in foliage, 20.58 per cent and 21.43 per cent in rhizome, 3.83 per cent and 3.79 per cent in roots. Thus, the components with highest biomass (culm) stored the highest amount of energy.

Energy capture efficiency (ECE) is computed as the ratio of energy captured by the vegetation to 50 per cent of the incident solar radiation over a given period of time. The amount of annual insolation is 54,400 GJ ha^{-1}. Of this, about 50 per cent would be photosynthetically available. The energy capture efficiency (photosynthetic radiation) of the above-ground portion was 1.32 per cent and 1.41 per cent and that of total vegetation was 1.74 per cent and 1.87 per cent respectively for 5- and 7-year-old of bamboo plantations. However, the upper limit of energy fixation through photosynthesis in a clump is set by the environmental factors particularly temperature, rainfall, edaphic factors, leaf area index and photosynthetic efficiency of the species.

A medium size household with five persons in Bihar needs 7.5 kg bamboo chips per day for fuel. With an average energy value of 20.18 KJ g^{-1}, this is equivalent to 4.5 GJ $month^{-1}$. With a conversion factor of 1 KW= 0.0036 $GJh^{-1}$and assuming a 35 per cent heat conversion efficiency with an operating load of 50 per cent, the equivalent electrical energy utilized is 218.75 KW $month^{-1}$. Energy stored in the above-ground 5-year-old culm biomass from 1 ha (1,163 GJ), and 7-year-old culm biomass from 1 ha (1,691 GJ) is thus sufficient to meet the electrical energy needs of a household for 21.53 years and 31.31 years respectively. The total energy requirement for a 50 MW power station, with the above assumptions is 1032.11 GJ. The energy required to generate this power continuously would require the equivalent of 90,41,285 GJ $year^{-1}$. The energy stored in 5-year-old culms from 9,283 ha and in 7-year-old clums from 6,253 ha is sufficient to operate a 50 MW generating station for one year. Thus a total of 46,413 ha (9,283 × 5) of bamboo plantation needs to be raised with rotation period and felling cycle of five years or 43,768 ha (6,253 × 7) are needed to raise bamboo plantation with a rotation period and felling cycle of seven years, *i.e.*, 928 ha and 875 per MW (from annual production) till clump flowering (40-45 years for this species) by adopting culm-selection silvicultural system. The bio-energy estimated for the present plantation does not however, represent the maximum potential energy storage. The energy yield of the plantation can be optimized by suitable management techniques such as raising the stocking density, fertilizer application, irrigation, plant protection measures and genetic manipulations as argued by Tuskan and Cruz (1982). However, economic feasibilities of the electrical production system need to be carefully studied.

CONCLUSIONS

D. strictus is one of the high biomass producing species. It can store more carbon than longer rotation slow growing species if it is grown repeatedly for that duration. The species is a better option compared to many tropical and temperate plantation species with regard to carbon capture or carbon storage in a given time. It is also a suitable species for high energy production because of high energy capture efficiency and can be used for electricity generation through distributed generation.

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