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Bamboo-based agroforestry system (*Dendrocalamus strictus* + *sesame–chickpea*) for enhancing productivity in semi-arid tropics of central India

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Abstract Bundelkhand region of central India is characterized by erratic rainfall with high frequency of drought. The region has undulating topography, poor groundwater resources and shallow soils with low soil fertility, resulting in frequent crop failures. A study was undertaken to assess the potential of bamboo-based agroforestry system to enhance productivity and economic returns at the research farm of ICAR-Central Agroforestry Research Institute, Jhansi (Uttar Pradesh), India, which lies in the Bundelkhand region of central India. The 7-year study (2007–2015) recorded 2906 number of bamboo culms ha^{-1} at 10 m × 10 m spacing compared to 2409 culms under 12 m × 10 m spacing. Averaged over 3 years (5th, 6th and 7th year), bamboo culm yield from agroforestry (*Dendrocalamus strictus* + *Sesamum indicum–Cicer arietinum*)/(bamboo + sesame–chickpea) was higher by 3.20 and 4.96% over sole bamboo in 12 m × 10 m and 10 m × 10 m, respectively. The intercrop productivity started declining from 3rd year onwards, and the extent of reduction in productivity was to the tune of 26.1, 23.7, 24.2, 17.4 and 17.4% during the 3rd, 4th, 5th, 6th and 7th year, respectively. From 5th year onwards, the harvested bamboo culms contributed to the improvement in the system productivity and it was 29 and 236% higher than the sole crops and sole bamboo, respectively, during the 7th year. Financial analysis showed that bamboo-based agroforestry system (bamboo + sesame–chickpea) planted at 12 m × 10m spacing was having high land equivalent ratio (1.95–2.14) and was more profitable than arable cropping and sole bamboo. Therefore, the *Dendrocalamus strictus*-based agroforestry system can be a potential alternative to arable cropping in semi-arid tropics of central India to enhance productivity and economic returns.

Keywords Agroforestry · *Dendrocalamus strictus* · Productivity · Returns · Semi-arid region

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Introduction

The Bundelkhand region of central India is having a geographical area of 7.08 m ha and characterized by undulating and rugged topography, highly eroded soils with poor soil fertility, scarce groundwater resources and erratic rainfall with poor irrigation facilities leading to frequent droughts and crop failures (Gupta et al. 2014). This region falls in semi-arid, subtropical climate, which receives an average annual rainfall of 867 mm, maximum part of which (more than 90%) is received only during 3 months, i.e. July to September (Singh et al. 2014; Tewari et al. 2016). Sometimes uneven rainfall distribution patterns create difficulties to sustain the farming in the region. There are reports of mass migration, hunger and distress sale of animals in the region (Dogra 2015). Heavy biotic pressure on forests, community lands and declining of vegetation cover resulted in scarcity of fodder and fuelwood in the region, which adversely affected livelihood security (Dev et al. 2016, 2018).

Climate change and variability are considered to be one of the biggest threats to agriculture particularly for the developing countries where significant population depends on the agriculture sector (IPCC fifth assessment report). It is predicted that the rising temperatures, variability and the extreme events are going to reduce the consumable food calories up to 1% in prominent crops in several developing countries (Ray et al. 2019).

Climate smart agriculture aims at sustainably increasing agricultural productivity, adapts and builds resilience to climate change and to minimize greenhouse gas emissions and enhance carbon sequestration (FAO 2013). Under such situations, agroforestry practices can be a potential option to sustain the livelihood of the farmers. Agroforestry is a land-use system, which can contribute substantially to these three aspects and thus contribute to strengthen systems ability to cope with the adverse impacts of climate change (Dhyani et al. 2016, 2020). Besides carbon sequestration, it will also help to conserve the natural resources and to enhance farm productivity and profitability (Ofori et al. 2014). Due to fast growth of bamboo, its integration in the farming systems can be a source of income in the Bundelkhand region in India. Reclamation of ravine lands and highly degraded lands has been reported through bamboo-based agroforestry models (Gupta et al. 2018; Behari et al. 2000). Bamboo plantations on bunds, sloped lands and terraced lands have been found effective means of soil and water conservation (Varmah and Bahadur 1980). Natural resource conservation through bamboo plantations has also been advocated by various researchers (Lawler 1993; Yanhui and Yongmin 1995).

Although, India is world's second-largest bamboo grower, but its bamboo products capture only 4% of the global market. India with its vast resources of bamboo has the potential to increase its share in the international market and can also address a number of global challenges, including rural poverty, land degradation, deforestation, urban development, unsustainable resource use, cottage industry, employment and climate change. To harness the full potential of bamboo, there is a need to promote its plantation at massive scale and National Bamboo Mission can play an important role in its promotion at larger scale and the mission has already initiated various steps to increase the availability of quality planting material and to strengthen the marketing of bamboo products.

Bamboo is one of the fastest growing and among the world's most important and versatile plants (Kleinhenz et al. 2003; Chauhan and Kumar 2005). The bamboos are widely distributed in India and provide livelihood support to millions of people. Bamboo has the potential to be incorporated into agroforestry systems in the semi-arid tropics due to their diverse adaptability, multiple utility and quick returns. *Dendrocalamus strictus* (Roxb.) (local name "*Lathi Baans*"; English name "*Male bamboo*") is the most commonly found bamboo species in semi-arid India specifically Uttar Pradesh, Madhya Pradesh, Odisha and Western Ghats (Saxena and Dhawan 1999), and it accounts 53% of the India's total bamboo area. It can tolerate temperatures as low as − 5 °C and as high as 45 °C (Das et al. 2017). This species is extensively used in pharmaceutical, paper, agricultural/other industrial implements, fuel, flooring, screens, soil conservation, coal and even human consumption in tender stage (Kumar and Sikka 2014). The bamboo has very high potential to enhance the farm income, but its potential has not been harnessed fully under agroforestry systems in the region due to many reasons such as lack of awareness among the farmers about the utilization and economic potential of *D. strictus*, non-availability of quality planting material, limited market in nearby areas. Although its wood is utilized for various domestic purposes, but some myths are also associated with bamboo such as its wood is not used as a fuel for cooking. Moreover, the success stories of bamboo-based agroforestry system in the region are limited, as it is being grown in AFS at few farmers' fields.

Globally, bamboo is extensively cultivated as part of forest plantation development programs in view of its short gestation period, widespread usage for construction, pulpwood, flooring, panel products and furniture (Partey et al. 2017) and wide range of socio-economic and environmental benefits (INBAR 2014). India grows bamboo on estimated area of 15.69 million ha mainly in forest area (FSI report, 2017). To promote the bamboo cultivation on non-forest land, Government of India has amended the Indian Forest Act (IFA) 1927 in year 2017 and exempted the bamboo from tree category (Section 41 of IFA); thereby, felling/transit permit for bamboo grown on private land has been relaxed. At present, India imports about 18.01 million cubic metres of timber and allied products such as pulp, paper and furniture worth US$ 6 billion (Press Information Bureau, Government of India, 23 November 2017). However, little efforts were made towards integration of bamboo into the existing cropping systems in various ecological regions, particularly in the semi-arid regions, which are distributed globally in about 15% of earth surface (Huang 2016) and distributed in an area of about 95 m ha in India. There is a need to assess the impact of integration of bamboo into the predominant crops of Bundelkhand region. We hypothesized that integrating bamboo will enhance productivity and profitability and minimize the impact of variable rainfall on the system productivity particularly in rainfed regions receiving a rainfall less than 900 mm. Keeping in view the above, a study was undertaken to develop and standardize bamboo-based agroforestry system suitable for semi-tropic environments.

Materials and methods

Site description

The study on *Dendrocalamus strictus*-based agroforestry system (AFS) was carried out at ICAR-Central Agroforestry Research Institute (25° 30′–25′ 32° N latitude and 78° 32′–78° 34′ E longitudes with an altitude of 272 m above mean sea level), Jhansi, Uttar Pradesh, India, during 2007 to 2015. The average annual rainfall of the area is around 867 mm. The potential evaporation is quite high and is in the range of 1400–1700 mm with moisture index value of − 40 to − 50. Mean maximum temperature ranges from 23.5 °C (January) to 47.4 °C (June), and mean minimum temperature ranges from 4.1 °C (December) to 27.2 °C (June), where May and June are the hottest months (Shukla et al. 2017). Soils of the experimental site were mixed red and black and low in fertility. Initial soil characteristics of experimental site were as pH 6.54, EC 0.180 dSm^{-1}, OC 0.39%, available N 213 kg ha^{-1}, available P 5.28 kg ha^{-1} and available K 185 kg ha^{-1}.

Layout and design

The *D. strictus*-based agroforestry system was laid out in randomized block design with five treatments, viz. T_1: 10 m x10m (*Dendrocalamus strictus* + *Sesamum indicum*–*Cicer arietinum*) bamboo + sesame–chickpea; T_2: 12 m × 10 m bamboo + sesame–chickpea; T_3: sole bamboo 10 m × 10 m; T_4: sole bamboo 12 m x10m; and T_5: sole crop (sesame–chickpea), and three replications. The gross plot size was 1200 m^2 (spacing-10 m × 10 m) and 1440 m^2 (spacing-12 m × 10 m). In the experiment, 12 clumps plot^{-1} (3 × 4: rows × clumps) having 100 clumps ha^{-1} (10 m × 10 m) and 84 clumps ha^{-1} (12 m × 10 m) were maintained. For seed and stover yields of sesame–chickpea crops, samples were taken from six replications.

Rainfall pattern during bamboo growth period

A total annual rainfall of 558.1 mm (2007), 578 mm (2009), 718.4 mm (2010), 825.5 mm (2012), 629.5 mm (2014), 1238.3 mm (2008), 1289.2 mm (2011) and 1374.8 mm (2013) was received in the area. However, the rainfall received during the particular year was not evenly distributed and most of it was confined to the rainy season, i.e. June–September. The rainfall data indicated that out of 8 years, the area received less than the average rainfall (851 mm) during 5 years (2007, 2009, 2010, 2012 and 2014) and very high rainfall during 3 years (2008, 2011 and 2013). Bundelkhand region of central India is infamous for frequent drought, water shortage and high migration of the residents. Pandey (2011) reported that in eighteenth–nineteenth century, frequency of drought was once in 16 years; however during 1968 to 1992, the region experienced droughts in every 5 years. The situations worsen in twenty-first century, as more droughts are experienced as compared to earlier period.

Bamboo

Planting material and transplanting

Seedlings of *D. strictus* were procured from the Agroforestry Research Centre, G.B. Pant University of Agriculture & Technology, Pantnagar (Uttarakhand), India. Pits of 60 cm × 60 cm × 60 cm (length, width and depth) dimension were dug during second week of September 2007. Each pit was filled with the mixture of 15 kg FYM + top soil of same field + 100 g DAP +2 g chlorpyrifos (as an anti-termite treatment). The seedlings of *D. strictus* were planted on 25 September 2007 as per treatments. A basin of 1.0 m around the plant and a mound of 15 cm high around the seedling were made after plantation. Each plant was given about 60 L of water immediately after plantation for proper establishment and regular weeding, and soil forking was done for better growth of the plants. The plantation was protected against damage by rodents, grazing and browsing animals. The plants were irrigated by providing 60 litres of water per irrigation at fifteen days interval only for initial 3 months.

Growth observations

Five clumps were randomly selected (marked with paint) in each treatment for data recording. The numbers of culms in these selected clumps were counted. Observations were made for culm height (m), internodal length (cm) and culm diameter at sixth internode. The height of all the culms in selected clumps and internodal length were measured with measuring tape. Diameter of culm was measured at sixth internode from base with vernier caliper. Leaf biomass was harvested every year during September–October, and fresh weight was taken in field. Average of five nodes was taken as internodal length. The culm harvesting commenced from 5th year onwards, and each year one-third of the bamboo culms (mature) were harvested.

Sesame–chickpea (Sesamum indicum–Cicer arietinum) cropping system

Sesame (rainy season)–chickpea (winter season) intercrops were taken in six replications in agroforestry system and as sole crop for 7 years as per standard package of practices. To evaluate yields of sesame and chickpea, sampling was done with quadrat of 0.5 m × 0.5 m area at different distances (1.0, 2.0, 3.0 and 4.0 m) from bamboo clump spaced at 10 m × 10 m, 12 m × 10 m and averaged them. Both the crops were harvested for economic and biological yields. The crop residues were not incorporated in the experimental field, but the bamboo litterfall was not removed and allowed to decompose in the field itself.

System productivity

Since, the seed yield of sesame and chickpea and bamboo yields (bamboo leaves and culms) and their respective market price was different; hence, their combined (system) productivity was computed by converting their yield into chickpea equivalent yield. Afterwards, the chickpea equivalent yield of sesame and bamboo was added to chickpea seed yield to compute the productivity of the system. In bamboo, only leaf yield was considered for chickpea equivalent yield during first 4 years. The chickpea equivalent of sesame and bamboo was computed as:

$$\text{Chickpea equivalent yield of sesame (kg/ha)} = \frac{\text{Sesame yield (kg per ha)} \times \text{price of 1 kg sesmae}}{\text{Price of 1 kg chickpea}}$$

$$\text{Chickpea equivalent yield of bamboo (kg/ha)} = \frac{\begin{array}{c}\text{(Bamboo leaf yield (kg per ha)} \times \text{price of 1 kg leaf)+}\\ \text{(No. of harvested bamboo culms (per ha)} \times \text{Price of 1 culm)}\end{array}}{\text{Price of 1 kg chickpea}}$$

Land equivalent ratio (LER)

The land equivalent ratio (LER) is the effective way to quantify the intercropping benefits and defined as ratio between the relative yield of each tree and crop species in an agroforestry system in comparison with the yield of the same tree and crop species in a monoculture over the same period (Mead and Wiley 1980; Seserman et al. 2018). It is calculated as follows:

$$LER = \frac{\text{Yield of crops (sesame} - \text{chickpea) in AFS}}{\text{Yield in sole cropping (sesame} - \text{chickpea)}} + \frac{\text{Yield of bamboo in AFS}}{\text{Yield in sole bamboo}}$$

Here, yield of crops and bamboo was given as chickpea equivalent yield. While LER ≤ 1 means that there is no productivity advantage of agroforestry over sole cropping, a LER > 1 suggests that the production in the agroforestry system is higher than the sole system.

Soil fertility analysis

Soil samples were collected before the start of the experiment and after 7 years from each treatment with the help of soil augur from 0 to 15 cm soil depth and were analysed for available N (Subbiah and Asija 1956), available P (Olsen et al. 1954), 1 N ammonium acetate exchangeable K (Hanway and Heidel 1952) and organic C (Walkley and Black 1934). The pH of soil was estimated using pH meter (1:2.5 soil and water ratio). Before the soil analysis, soil samples were air-dried, ground in a wooden pestle and mortar and passed through 2 mm stainless sieve.

Financial analysis

Among the various financial indicators available to examine viability of any agroforestry models, emphasis was focused on four most important indicators such as net present value (NPV), benefit–cost ratio (B–C), annual equivalent value (AEV) and land expectation value (LEV). Net present value was determined by discounting all revenues and costs to the present; the benefit/cost ratio was calculated by dividing the sum of discounted revenues by the sum of discounted costs; the annual equivalent value is an indicator that expresses NPV in annual equivalents distributed equally over the years of the lifespan of the investment; and land expectation value was interpreted as the maximum amount of money a landowner can pay for the land and still earn the minimum acceptable rate of return of an agroforestry investments. Year-wise production of field crops and respective minimum support price (announced by Government of India every year) for the same has been used to calculate the yearly economic returns from the system. To know the prevailing bamboo culm price, bamboo growers and traders of the region were contacted. Annual cost and returns from the system for 7 years period, i.e. 2007–08 to 2014–15, were adjusted at a discount rate of 12% to get the NPV.

Statistical analysis

Data on bamboo growth/production and crop's (sesame–chickpea) yields were subjected to analysis of variance using SPSS 17.0 statistical software following the randomized block design. Differences in treatment means were compared at the $p \leq 0.05$ level of significance.

Results and discussion

Growth parameters of bamboo

Culm height

Average culm height in sole bamboo and bamboo grown in agroforestry systems (AFS) remained statistically ($p \leq 0.05$) at par during 1st year; however 2nd year onwards, bamboo grown with sesame–chickpea cropping system showed significantly longer culms as compared to sole bamboo. No significant differences were observed in average culm height when bamboo was grown at different spacing, viz. 10 m $\times$ 10 m and 12 m $\times$ 10 m either in agroforestry or in sole bamboo system. The culm height increased up to 7th year, but growth rate was maximum up to 2nd year, and after 5th year, negligible culm height increment was observed irrespective of land use (Table 1).

Table 1 Average culm height and internodal length of *D. strictus* under *D. strictus* + sesame–chickpea AFS

Treatments	Culm height (m)							Internodal length (cm)						
	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year
T_1: 10 m × 10 m bamboo + sesame–chickpea	2.59	4.24	5.49	6.17	6.99	7.02	7.05	6.72	9.69	12.46	14.24	16.43	16.46	16.53
T_2: 12 m × 10 m bamboo + sesame–chickpea	2.51	4.13	5.37	6.08	6.92	6.95	6.98	6.63	9.48	12.23	14.02	16.28	16.32	16.35
T_3: 10 m × 10 m sole bamboo	2.12	3.69	4.52	5.80	5.98	6.05	6.10	6.24	8.73	10.48	12.71	14.68	14.64	14.75
T_4: 12 m × 10 m sole bamboo	2.16	3.53	4.46	5.53	5.84	6.02	6.05	6.17	8.16	10.02	12.62	14.42	14.62	14.60
T_5: sole crop (sesame–chickpea)	–	–	–	–	–			–	–	–	–	–	–	–
SEm±	0.07	0.12	0.14	0.09	0.13	0.12	0.11	0.11	0.19	0.37	0.32	0.40	0.35	0.41
LSD ($p \leq 0.05$)	NS	0.41	0.47	0.29	0.47	0.37	0.33	NS	0.66	1.29	1.10	1.37	1.30	1.39

Internodal length

In 1-year-old bamboo, internodal length was not affected significantly due to spacing or land use. However, 2nd year onwards internodal length of bamboo grown in agroforestry system (sesame–chickpea) significantly increased as compared to sole bamboo (Table 1). The maximum internodal length growth was found when bamboo was planted in agroforestry system at 10 × 10 m spacing. It increased from 6.42 cm (1-year-old culms) to 16.53 cm (7-year-old culms). Maximum internodal length growth was observed up to 4 years; thereafter, growth was minimal.

Culm diameter

It was observed that 2nd year onwards culm diameter of bamboo grown in agroforestry system (bamboo + sesame–chickpea) was significantly ($p \leq 0.05$) higher over the sole bamboo. After 2nd year, nearly 20.12 to 28.12% more culm diameter was observed in bamboo grown in agroforestry system over sole bamboo plantation under different spacing. The diameter growth increased with increasing rate up to 4th years, and thereafter, the diameter increased but with a decreasing rate. At 7th year, the difference in diameter of bamboo grown in agroforestry system over sole plantation was narrowed down to 13.83–15.31% (Table 2). However, bamboo grown either as sole or with crops (AFS) in 10 m × 10 m or in 12 m × 10 m spacing remained statistically at par.

Culm yield

The maximum numbers of culm were found in 10 m × 10 m spacing irrespective of land-use system. The matured culms were harvested after 5th, 6th and 7th years of plantation. After 7 years of bamboo plantation, a higher number of cumulative matured culms (2982 culms ha^{-1}) were harvested from the bamboo planted at 10 m × 10 m in agroforestry system followed by bamboo planted at same spacing in sole bamboo (Fig. 1). Average per clump yield of matured bamboo was 9.94 and 9.43 in 10 m × 10 m and 12 m × 10 m spacing, respectively, in agroforestry system. The corresponding values for both the spacing in sole bamboo were 9.89 and 9.22. Results showed no significant effect of land use on number of culms per

Table 2 Culm diameter and no. of culm (before harvesting) of *D. strictus* under *D. strictus* + sesame–chickpea AFS

Treatments	Culm diameter (mm)							No. of culm ha^{-1}						
	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year	1st year	2nd year	3rd year	4th year	5th year	6th year	7th year
T_1: 10 m × 10 m bamboo + sesame–chickpea	3.21	9.43	19.82	31.15	35.42	35.22	35.40	375	1439	2134	2860	3105	3208	3315
T_2: 12 m × 10 m bamboo + sesame–chickpea	3.42	9.84	20.25	31.87	36.08	35.85	35.62	323	1235	1808	2417	2596	2711	2851
T_3: 10 m × 10 m sole bamboo	2.92	7.85	16.86	26.95	30.47	31.02	31.10	356	1390	1865	2700	2946	3136	3247
T_4: 12 m × 10 m sole bamboo	3.11	7.68	16.45	26.47	29.98	30.54	30.89	302	1167	1507	2283	2422	2647	2703
T_5: sole crop (sesame–chickpea)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
SEm ±	0.07	0.28	0.61	0.81	1.02	1.05	0.95	10	40	61	63	78	82	89
LSD ($p \leq 0.05$)	NS	0.96	2.10	2.82	3.54	3.44	3.35	NS	139	212	216	269	257	281

clump. Averaged upon 3 years (5th, 6th and 7th year) irrespective of land-use bamboo grown at a spacing of 10 m × 10 m (sole and with intercrop) recorded significantly ($p \leq 0.05$) 20.60% more harvested culms as compared to 12 m × 10 m (sole and with intercrops).

It was observed that most of the growth parameters of *D. strictus*, viz. culm height, culm diameter, internodal length and leaf biomass, were recorded significantly higher in bamboo grown in agroforestry system as compared to sole bamboo irrespective of spacing. This might be due to the benefits drawn by bamboo from various agricultural inputs, viz. tillage, irrigation, fertilizers, etc. (Dev et al. 2016, 2017).

Banerjee et al. (2015) also reported the higher growth of *Bambusa tulda* and *Bambusa balcooa* in agroforestry system as compared to sole bamboo plantation. Nutrients released from bamboo leaf litter decomposition are beneficial to both bamboo and intercrops (Baruah and Borah 2019). It was observed that under rainfed semi-arid environment, 5th year onwards bamboo gets maturity and can be harvested (Dev et al. 2016). The numbers of culm harvested from 10 m × 10 m spacing were found significantly higher over 12 m × 10 m spacing irrespective of land use. This might be due to closer spacing and about 20% more clumps in 10 m × 10 m spacing as compared to 12 m × 10 m spacing. The culm yield of *D. strictus* at 5th year of plantation was recorded between 2422 and 3105 culms (84–100 clumps ha^{-1}) in rainfed region of Bundelkhand (India). However, culm productivity of *D. strictus* was lower as compared to culm productivity of *D. strictus* in humid region of Kerala (11,000 culms ha^{-1}, Kittur et al. 2016) and irrigated light soils of Punjab, India (10,803 culms ha^{-1}, Singh et al. 2018).

Yields of intercrops

Sesame

During 1st and 2nd year, the sesame yield from agroforestry system, i.e. T_1: 10 m × 10 m and T_2: 12 m × 10 m, was at par with T_5: sole crop. In 3rd year, seed yield was significantly higher in sole crop as compared to the seed yield from agroforestry system (T_1 and T_2); however, seed yield in T_1 and T_2 was at par with each other. Similar trend was observed during subsequent years. In T_1: 10 m × 10 m treatment,

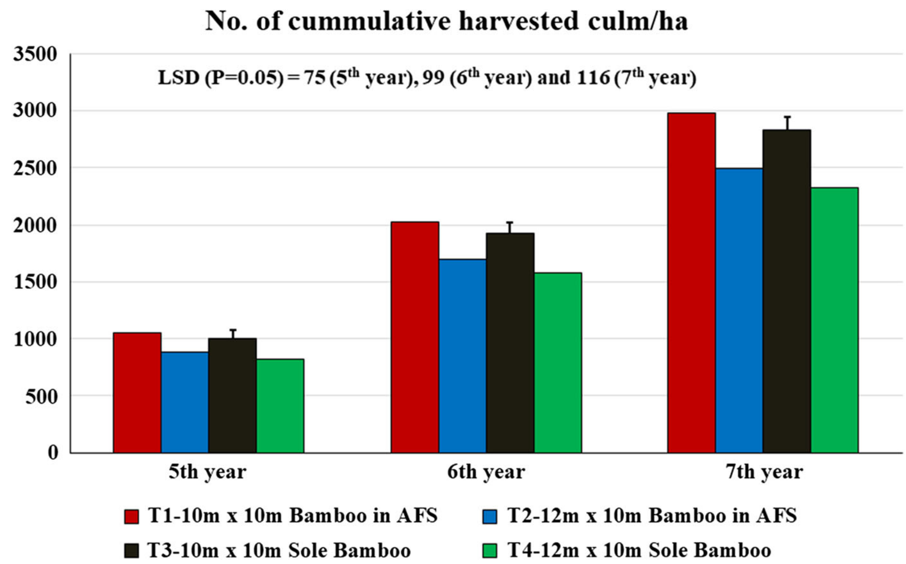

Fig. 1 No. of harvested culm of *D. strictus* under bamboo + sesame–chickpea AFS

12.08, 9.61, 17.45, 14.26 and 14.34% less yield of sesame was recorded as compared to sole crop in 3rd, 4th, 5th, 6th and 7th year, respectively. Likewise in T_2: 12 m × 10 m treatment, 10.86, 6.23, 11.91, 5.96 and 6.52% less yield of sesame crop was recorded in respective period (Table 3).

Chickpea

The seed yield of chickpea in bamboo-based agroforestry system (T_1: 10 m × 10 m and T_2: 12 m × 10 m) remained statistically at par with sole crop during 1st and 2nd year of study. However, during 3rd year seed yield in sole crop (1850 kg ha^{-1}) was significantly higher as compared to two spacing in agroforestry system (1370 kg ha^{-1} in T_1 and 1460 kg ha^{-1} in T_2). The similar trend was observed during 4th, 5th, 6th and 7th year of study. Averaged upon 7 years, 16.80 and 12.29% higher chickpea yield was obtained in T_5 over the T_1: 10 m × 10 m and T_2: 12 m × 10 m agroforestry system, respectively (Table 3).

The reduction in seed yields of sesame and chickpea under bamboo-based AFS may be due to allelopathic effect of bamboo or reduced photosynthetic active radiation (PAR) under bamboo canopy (Kittur et al. 2016) and competition for various other resources, viz. water, nutrients, space, etc., in comparison with sole crop of sesame and chickpea. Inhibitory effect of leaf leachates of *D. stocksii* was reported by Rawat et al. (2018) on growth of groundnut and of *D. strictus* by Nema and Reddy (2016) on growth of wheat and soybean. Growth of intercrops in agroforestry is influenced highly by availability of light. Gao et al. (2013) observed that the PAR at 0.5 m and 1.5 m distance to the tree row was reduced by 17.9 and 10.4% in apple–soybean intercropping system, respectively, and was reduced by 17.8 and 5.4% in apple–peanut intercropping system. Qiao et al. (2019) reported 61.5, 42.2 and 63.6%, reduction in mean daily light intensity in east-, inter- and west-row positions, respectively, in 10-year-old apricot-based agroforestry system as compared to monocropped wheat. Singh et al. (2016) reported micro-environmental changes under canopy of different tree species. All the yield contributing characteristics and major nutrient content in wheat was decreased in apricot-based agroforestry system. Similar results were also reported by Makumba et al. (2007) for gliricidia/maize; Jose et al. (2000) for walnut/maize and Kittur et al. (2016) for bamboo/turmeric in different agroforestry systems. Rahangdale et al. (2014) also reported the lower seed yields of various crops (soybean, paddy, green gram and sesame) under bamboo-based AFS. Bamboo as well as other agroforestry species becomes more competitive with advancement of age and consequently decreases the crop yields (Ahlawat et al.

Table 3 Seed yields of sesame and chickpea under *D. strictus* +sesame–chickpea agroforestry system

Treatments	Sesame seed yield (kg ha^{-1})							Chickpea seed yield (kg ha^{-1})						
	2008	2009	2010	2011	2012	2013	2014	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15
T_1: 10 m × 10 m bamboo + sesame–chickpea	558	540	502	508	492	475	460	1800	1750	1370	1330	1270	1244	1304
T_2: 12 m × 10 m bamboo + sesame–chickpea	538	547	509	527	525	521	502	1760	1770	1460	1470	1410	1345	1388
T_3: 10 m × 10 m Sole bamboo	–	–	–	–	–	–	–	–	–	–	–	–	–	–
T_4: 12 m × 10 m Sole bamboo	–	–	–	–	–	–	–	–	–	–	–	–	–	–
T_5: sole crop (sesame–chickpea)	551	535	571	562	596	554	537	1810	1760	1850	1810	1700	1550	1608
SEm±	8.0	4.6	6.9	6.9	12.8	10.1	10.5	44	42	32	47	45	33	31
LSD ($p \le 0.05$)	NS	NS	21.8	21.6	40.3	31.9	32.9	NS	NS	101	149	141	103	97

2008). However, after 5 year of plantation age, one-third of the culms were harvested from bamboo clumps, and it reduced the competition for resources up to some extent. As compared to 4th year, lesser quantity of leaf fall was received on the adjoining field which resulted lesser allelopathic effect on the sesame and chickpea crops.

System productivity (bamboo + sesame–chickpea)

The system productivity expressed in terms of chickpea equivalent yield (Table 4) varied in the range of 836 to 1015 kg ha^{-1} (sole bamboo), 3088 to 3129 kg ha^{-1} (bamboo-based AFS) and 2405 kg ha^{-1} (sole crops) during 7th year of study. However, during first 4 years, system productivity was observed relatively much higher in agroforestry system (T_1 and T_2) and sole crop (T_5) as compared to sole bamboo (T_3 and T_4). First harvesting of matured culms was done in 5th year in both the land uses, and thus, system productivity increased in 5th, 6th and 7th year of study. Averaged upon 7 years, T_1, T_2, T_3, T_4 and T_5 resulted 2584, 2636, 303, 252 and 2612 kg ha^{-1} chickpea equivalent yield, respectively. Higher productivity in bamboo-based agroforestry system was mainly due to utilization of interspace for sesame and chickpea production. It shows that 5th year onwards bamboo-based agroforestry systems are commercially more viable as compared to sole crops. Rawat et al. (2002) also reported economic feasibility of *D. strictus*-based agroforestry system.

Land equivalent ratio (LER)

Land equivalent ratio showed considerably higher (1.92 to 2.14) in both the bamboo spacing (T_1 and T_2) in agroforestry system (Table 4). Except 1st year, all the values for LER were obtained higher in T_2 treatment as compared to the T_1 treatment. However, both (T_1 and T_2) the agroforestry treatments (bamboo + sesame–chickpea) have greater advantages over the sole cropping (sesame–chickpea). Results of the study corroborate the greater efficiency of land use, i.e. high LER when bamboo was integrated with sesame–chickpea cropping system rather than grown as sole crops. Seserman et al. (2018) also reported the LER values between 2.0 and 2.9 in the agroforestry systems (Poplar + wheat/mustard) in Forst and

Table 4 System productivity (*D. strictus* +sesame–chickpea) and land equivalent ratio (LER) of *D. strictus*-based agroforestry system

Treatments	System productivity (Chickpea equivalent yield, kg ha^{-1})						
	2008–09	2009–10	2010–11	2011–12	2012–13	2013–14	2014–15
T_1: 10 m × 10 m bamboo + sesame–chickpea	2767 (2.13)	2661 (2.13)	2238 (1.92)	2197 (1.92)	2995 (1.92)	3045 (1.95)	3129 (1.95)
T_2: 12 m × 10 m bamboo + sesame–chickpea	2691 (2.12)	2692 (2.14)	2338 (1.95)	2366 (1.97)	3029 (2.01)	3038 (2.05)	3088 (2.03)
T_3: 10 m × 10 m sole bamboo	7	18	36	39	863	962	1015
T_4: 12 m × 10 m sole bamboo	6	18	35	38	716	791	836
T_5: sole crop (sesame–chickpea)	2757	2642	2790	2719	2593	2381	2405

Values in parentheses are land equivalent ratio (LER)

Wendhausen (Germany) and LER value between 3.3 and 3.7 were reported by Fadl (2013) in *Acacia senegal* + sorghum/sesame/roselle and between 1.0 and 1.8 by van der Werf et al. (2007).

Soil fertility

Irrespective of spacing, bamboo-based agroforestry system had higher organic carbon (OC), available N and P in the soil surface (0–15 cm) in comparison with sole crop after 7 years of plantation. After 7 years of study, the highest increase (60.2% OC; 27.7% available N; 12.7% available P; and 5.9% available K) in soil nutrients were recorded in T_1 (bamboo spaced at 10 m × 10 m in sesame–chickpea cropping system) followed by in T_2 (58.7% OC, 24.4% available N, 9.8% available P and 5.4% available K) (Table 5). However, no clear cut trend was observed with respect to the soil pH under these systems. This could be attributed to addition of organic matter through leaf litter and fine root decomposition into the soil through litterfall and sloughing off roots in the bamboo-based agroforestry systems than seasonal cropping. Bamboo leaf litter and fine root decomposition have enhanced the soil organic matter and other nutrients (N, P and K) in bamboo-based AFS as compared to sole crop. Similar observations have earlier been recorded by Singh et al. (2004); Yadav et al. (2008); and Nath and Das (2012). The increase in soil nutrients in order of N > P > K has also been supported by the study of Jagadish et al. (2015) on bamboo litter decomposition and nutrient release study. Reddy et al. (2011) reported the increase in microbial activities in soil due to bamboo litter addition. Bamboo litter not only adds nutrients to soil but also helps in maintaining soil ecological and ecosystem processes (Ge et al. 2014).

Financial analysis of the bamboo-based AFS

The results of financial analysis of 7-year bamboo-based agroforestry system revealed that the highest NPV, B:C ratio, AEV and LEV were recorded in T_2 (12 m × 10 m bamboo + sesame–chickpea), followed by T_1 (10 m × 10 m bamboo + sesame–chickpea). It is verified that T_2 treatment was financial viable and significantly more profitable than other treatment combinations (Table 6). Hence, this model is suitable for adoption in semi-arid region. Results showed that the seed yield of chickpea and sesame was

Table 5 Changes in soil fertility in *D. strictus*-based AFS after 7 years of the study

Treatments	pH	OC (g kg^{-1} soil)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
Initial status (2007)	6.54	3.92	213.0	5.28	185.0
Final status (2015)					
T_1: 10 m × 10 m bamboo + sesame–chickpea	6.52	6.28	272.0	5.95	196.0
T_2: 12 m × 10 m bamboo + sesame–chickpea	6.53	6.22	265.0	5.80	195.0
T_3: 10 m × 10 m sole bamboo	6.60	6.13	247.0	5.58	203.0
T_4: 12 m × 10 m sole bamboo	6.56	6.11	244.0	5.54	200.0
T_5: sole crop (sesame–chickpea)	6.59	5.44	234.0	5.52	183.0
SEm±	0.11	0.13	6.0	0.10	4.0
LSD ($p \leq 0.05$)	NS	0.40	18.8	0.31	12.0

Table 6 Financial analysis of *D. strictus* + sesame–chickpea agroforestry system (2007–08 to 2014–15)

Treatments	Year							Total (US $)
	2008	2009	2010	2011	2012	2013	2014	
	Total costs (US $ ha^{-1})							
T_1: 10 m × 10 m bamboo + sesame–chickpea	297	272	284	298	337	372	402	2262
T_2: 12 m × 10 m bamboo + sesame–chickpea	288	272	284	298	337	379	397	2256
T_3: 10 m × 10 m sole bamboo	53.2	2.80	3.50	4.20	28.0	32.18	35.0	159
T_4: 12 m × 10 m sole bamboo	44.36	2.80	3.50	4.20	28.0	32.2	35.0	150
T_5: sole crop (sesame–chickpea)	244	270	281	294	309	346	362	2106
	Gross income (US $ ha^{-1})							
T_1: 10 m × 10 m bamboo + sesame–chickpea	619	645	552	645	1173	1278	1357	6269
T_2: 12 m × 10 m bamboo + sesame–chickpea	602	651	575	695	1186	1275	1340	6325
T_3: 10 m × 10 m sole bamboo	1.54	4.48	9.0	11.33	338	404	440	1208
T_4: 12 m × 10 m sole bamboo	1.40	4.48	8.68	11.2	280	332	363	1001
T_5: sole crop (sesame–chickpea)	617	639	687	799	1016	1000	1043	5801

Table 6 continued

Treatments	Year							Total (US $)
	2008	2009	2010	2011	2012	2013	2014	
	Net benefits (US $ ha^{-1})							
T_1: 10 m × 10 m bamboo + sesame–chickpea	322	372	267	347	836	907	956	4006
T_2: 12 m × 10 m bamboo + sesame–chickpea	314	379	291	397	849	897	943	4069
T_3: 10 m × 10 m sole bamboo	− 51.63	1.68	5.46	7.14	310	371	405	1050
T_4: 12 m × 10 m sole bamboo	− 42.96	1.68	5.18	7.00	252.48	300	328	851
T_5: sole crop (sesame–chickpea)	373	370	406	505	707	653	681	3696

Table 7 Financial indicators for *D. strictus*-based agroforestry system (2007–08 to 2014–15)

Treatments	Net present value (NPV) (US $ ha^{-1})	Benefit–cost (B:C) ratio	Annual equivalent value (AEV) (US $ ha^{-1})	Land expectation value (LEV) (US $ ha^{-1})
T_1: 10 m × 10 m bamboo + sesame–chickpea	2360.0	2.6	517.1	4309.3
T_2: 12 m × 10 m bamboo + sesame–chickpea	2403.7	2.7	526.7	4389.1
T_3: 10 m × 10 m sole bamboo	511.0	6.0	112.0	933.1
T_4: 12 m × 10 m sole bamboo	414.4	5.4	90.8	756.7
T_5: sole crop (sesame–chickpea)	2277.8	2.7	499.1	4159.2

higher under wider spacing (12 m $\times$ 10 m) than closer spacing (10 m $\times$ 10 m), which resulted in higher net income under T_2 treatment (Table 7). Kittur et al. (2016) also reported the 58% reduction in turmeric yield in closely spaced (4 m $\times$ 4 m) bamboo as compared to wider spacing (12 m $\times$ 12 m). Returns from sole bamboo (in both the spacing) were very low because of underutilization of land resource, whereas under agroforestry, sesame and chickpea crops were raised, which enhanced the overall productivity of the system. Kaushik et al. (2015) also reported that although in agroforestry systems, crop yields are reduced due to competition of above and below ground resources, agroforestry systems gives overall higher economic returns due to supplemental timber/wood yield from tree components.

Conclusion

Dendrocalamus strictus-based agroforestry system produced leaf biomass, bamboo stock as well as sustained crop production over the years. The study suggests that there is ample scope of bamboo-based agroforestry because of the low requirement of capital investment and its ability to cope up with frequent drought in Bundelkhand region of central India. Since sesame crop is not liked by stray cattle (which is major problem for Bundelkhand region in kharif season), it could be concluded that bamboo (12 m $\times$ 10 m)-based AFS (bamboo + sesame–chickpea) could be one of the best livelihood options for semi-arid region. Government should promote this system for better economic returns to the farmers in semi-arid tropic region under drought and uncertain weather conditions. Sesame and chickpea both are low water requiring crops; hence, research on potential of other crops and other bamboo species may also be conducted. Moreover, 7 year is not the ultimate harvesting age of bamboo; rather, it is continuous process, old culms are removed, new ones regenerate and process will continue.

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