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Biochar Application and Soil Carbon Stocks in Semi-Arid Vertisols

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Abstract: Biochar application as a soil amendment has improved crop productivity, soil properties, and long-term carbon (C) storage in soils. In order to ascertain these positive effects of biochar, a six-year study was conducted on deep black soil in a typical semi-arid setup of Karnataka. Biochar (prepared from *Prosopis juliflora*) was applied and mixed at rates ranging from 2.5 to 20 t ha^{-1} to *rabi* sorghum under rainfed conditions before the start of the study. The six treatment combinations were evaluated through their effects on run-off, soil loss, sorghum yields, soil properties, and increase in soil organic carbon (SOC) stock at the end of the study period. Sorghum yield increased with the levels of biochar application, with yields under 10 and 20 t ha^{-1} levels of addition being statistically at par. Soil loss was not significantly affected by biochar application, and so were most of the soil properties. However, there was an increase in SOC stock to the tune of 0.28 and 0.43 t ha^{-1}y^{-1} through biochar application @ 10 and 20 t ha^{-1}, respectively, pointing at the C sequestration potential of biochar. Increased crop yields by applying biochar can be attributed to enhanced soil aggregation and water holding capacity and increased nutrient cycling and uptake by plant roots.

Keywords: *Biochar, soil amendment, carbon stock accumulation, carbon sequestration*

Introduction

Soil organic carbon (SOC) sequestration, *i.e.,* the process of capturing atmospheric carbon-di-oxide and converting it into soil carbon for an extended period, has been considered as a possible solution to mitigate climate change (Minasny *et al*. 2017). The global soil carbon pool (up to one-metre depth) estimated at 2500 Pg C (Lal 2004) is about 2.8 times the atmospheric CO_2 concentration of 415 ppm (https://www.esrl.noaa.gov/gmd/obop/mlo/), or a carbon equivalent of 880 Gt. An increase in soil C stocks can be achieved by: (a) adding C at a higher rate by offsetting atmospheric CO_2 and (b) reducing C emissions (as CO_2) *via* decomposition from soils (Paustian *et al*. 2019). A relatively small increase in C stocks could exert a significant role in mitigating greenhouse gas emissions. Tropical agricultural soils have considerable potential to act as CO_2 sinks through improved land management practices (Ogle *et al*. 2005; Johnson *et al*. 2007) that include the addition of organic manures and the use of altered agricultural waste material/by-products.

One of the approaches for efficient utilization of wastes generated from agriculture, forests, wastelands, and agro-industries involves carbonization of biomass to a highly stable carbon compound known as biochar and its use as a soil amendment first proposed by Lehmann *et*

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al. (2006). Biochar acts as a soil conditioner by improving the physical (*e.g.,* bulk density, aggregation, water retention), chemical (*e.g.,* cation exchange capacity), and biochemical (*e.g.,* microbial activity, nutrient recycling) properties of soils, thereby enhancing plant growth (Sohi *et al.* 2010). The use of biochar in agricultural systems reduces farm waste, improves soil quality and crop yields (Stavi and Lal 2013), and promotes soil carbon sequestration (Forbes *et al.* 2006; Njoku *et al.* 2016) due to its long residence time. The success of biochar as a soil amendment is attributed to its highly porous structure, resulting in increased soil surface area and improved water retention. Short-term assessments of biochar application on the yields of staple grain crops have also been extensively reported (Kimetu *et al.* 2008; Asai *et al.* 2009).

Vertisols, an important soil order in semi-arid agriculture, are more productive soils under proper management. However, they are prone to climatic aberrations, particularly uncertain rainfall and frequent droughts. The primary factor contributing to the productivity of Vertisols in semi-arid environments is their high water-holding capacity; however, high clay content renders these soils sticky and unworkable when wet and very hard when dry. Velayutham *et al.* (2019) suggested an enormous scope for C sequestration in the black soils of arid and semi-arid India due to the large surface area of the soil minerals. Considering the potential benefits of biochar in terms of C sequestration, improvement in soil physical properties, and enhancement of crop yields, a six-year field study was conducted with the following objectives *viz.,* (a) to study the effect of one-time biochar application on run-off and soil loss, sorghum yields, and soil properties, and (b) to assess the changes in quantum of carbon stored in the soil after the completion of the study.

Materials and Methods

Experimental site

A six-year study was conducted from 2013-14 to 2018-19 at the ICAR-Indian Institute of Soil and Water Conservation Research Farm, Ballari, Karnataka (15˚09' N, 76˚51' E), at an altitude of 445 m above mean sea level). The region average annual rainfall is 509 mm received in 32 rainy days with high variability (CV = 33%). The monthly rainfall data shows a bi-modal distribution pattern with peaks in June and September (Fig. 1). Half of the annual rainfall is received during the post-south west monsoon season (September-December), with about 43% alone recorded during the two months of September and October. Probability analysis of weekly rainfall reveals an assured rainfall of about 150 mm (P > 0.60) between meteorological weeks 37 and 44, corresponding to September 10 to November 4. Therefore, pre-*rabi* cropping with high levels of uncertainty under rainfed conditions is the best option for the region.

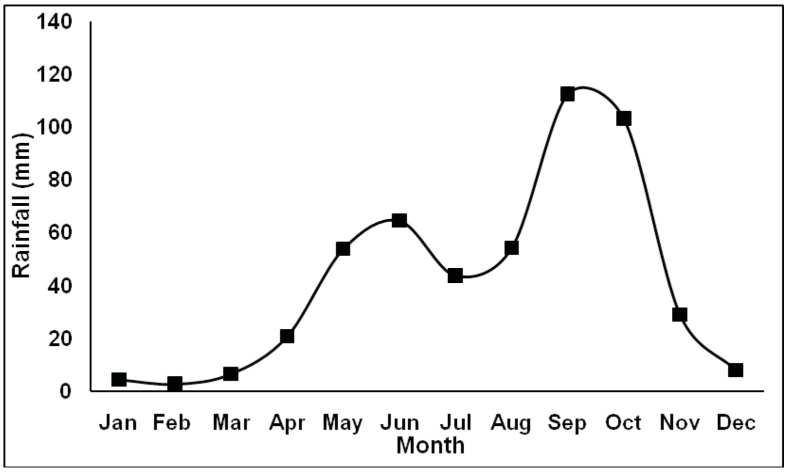

Fig. 1. Long-term (1957-2018) rainfall distribution pattern at Ballari

Experimental setup

The study was conducted on standard size run-off plots (22.1 × 1.83 m^2) with a 2% slope. The soil typically represents deep Vertisols with a clay content of 46%. The initial soil characteristics are presented in table 1. Sorghum (variety M-35-1) was sown every year during the third week of September and harvested during the first week of February following the standard package of practices. The experiment consisted of six treatments outlined in table 2. Procured biochar produced from *Prosopis juliflora* feedstock was applied as per treatment dose by spreading and thoroughly mixing prior to the start of the experiment only once during 2013. Characteristics of the applied biochar have been provided in table 3.

Table 1. Characteristics of the experimental soil and applied biochar.

Soil property	**Soil depth (cm)**	
	0-15	15-30
pH	8.63	8.68
EC (dS m^{-1})	0.24	0.27
Cation exchange capacity (cmol (p^+) kg^{-1})	32.2	31.7
Bulk density (Mg m^{-3})	1.28	1.32
Organic carbon (g kg^{-1})	0.34	0.28
Available nitrogen (kg ha^{-1})	371	352
Available phosphorus (kg ha^{-1})	14.2	10.0
Available potassium (kg ha^{-1})	459	363
DTPA-extractable Zn (mg kg^{-1})	0.21	0.23
DTPA-extractable Cu (mg kg^{-1})	1.46	1.57
DTPA-extractable Fe (mg kg^{-1})	2.52	2.55
DTPA-extractable Mn (mg kg^{-1})	5.05	4.95

Table 2. Treatment combinations in run-off plots

Treatment	**Description**
T_1	Recommended dose of fertilizers (RDF) @ 30:30::N:P_2O_5 + FYM @ 2 t ha^{-1} (control/farmer's practice)
T_2	T_1 + Biochar @ 2.5 t ha^{-1}
T_3	T_1 + Biochar @ 5.0 t ha
T_4	T_1 + Biochar @ 7.5 t ha
T_5	T_1 + Biochar @ 10.0 t ha
T_6	T_1 + Biochar @ 20.0 t ha

Table 3. Characteristics of biochar applied to the experimental plots

S. No.	**Parameter**	**Value**
1	Moisture content (%)	1.68
2	pH (1:5)	7.77
3	EC (1:5), dS m^{-1}	1.27
4	CEC (cmol (p+) kg^{-1}	15.9
5	Organic C (g kg^{-1})	748
6	Total N (g kg^{-1})	11.5
7	C:N ratio	65.0
8	P (g kg^{-1})	1.49
9	Total K (g kg^{-1})	15.6
10	Na (g kg^{-1})	3.1
11	Ca (g kg^{-1})	10.9
12	Mg (g kg^{-1})	0.45

Soil analyses

Composite soil samples from 0-15 and 15-30 cm depths were prepared after collecting sub-samples from six random locations in each experimental plot during 2013 and 2019 to analyze initial and final properties. These samples were air-dried, ground, and passed through 0.2 mm sieve. Soil texture (International pipette method), pH, EC, organic carbon (OC), available N (Kjeldhal method), available P (Olsen-P), and available K (1 *N* NH_4OAc) were determined by well-established procedures outlined in Jackson (1973). Extractable micronutrients were determined by the procedure of Lindsay and Norvell (1978). Bulk density (BD) was determined by collecting soil cores from different depths. The soil organic carbon was expressed in t ha^{-1} for each 15 cm soil depth by the following conversion:

$$\text{SOC (t ha}^{-1}) = \text{SOC (\%)} \times \text{BD (Mg m}^{-3}) \times 15 \text{ ....(1)}$$

The annual rate of change of SOC in each plot was calculated based on the difference in the values obtained during 2013 and 2019.

Run-off and soil loss

After every rainfall event, run-off measurements were taken from the cistern-drum combinations devised at the end of each run-off plot. Forty-five cm deep concrete cisterns were constructed at the end of each run-off plot for channelizing and collecting sediment-laden run-off water. Each cistern is further connected to a series of two drums of 65 cm height. Each cistern has eleven slits at overflow levels, with the middle slit emptying into the first drum, and run-off from the remaining slits is discarded. In other words, the run-off collected in the drum is 1/11th portion of the total run-off. The total run-off volume was calculated accordingly. A representative run-off sample was collected from each treatment after thorough mixing from each tank, and a known volume of it was evaporated to dryness to determine the soil loss. The soil loss from each plot was expressed in t ha^{-1}.

Statistical analysis

Statistical analysis was carried out using standard procedure. Comparison of mean sorghum yields influenced by different treatments was made by employing Duncan's multiple range test (DMRT).

Results and Discussion

Sorghum yield and soil properties

Pooled averages over six years confirm that yield increased with levels of application of biochar (Fig. 2), and ranged from 182 kg ha^{-1} under T_1 to 512 kg ha^{-1} under T_6. However, yield increment was not significant beyond biochar application @ 10 t ha^{-1}. Increased crop yields by the application of biochar can be attributed to a multitude of factors, including enhanced soil aggregation and water holding capacity (Ali *et al*. 2017; Faloye *et al*. 2019) and increased nutrient retention on biochar surface and exchange/uptake by plant roots (Singh *et al*. 2018). A meta-analysis by pointed out yield gains up to 25% by biochar additions to soils under tropical agroecosystems. The positive response of crops to combined application of biochar along with chemical fertilizers and FYM has also been reported by Glaser *et al*. (2015) and Singh *et al*. (2019). Except for soil organic carbon and CEC (data not shown), there was not much difference among the treatments in respect of soil physical and chemical properties were determined during 2013 and 2019.

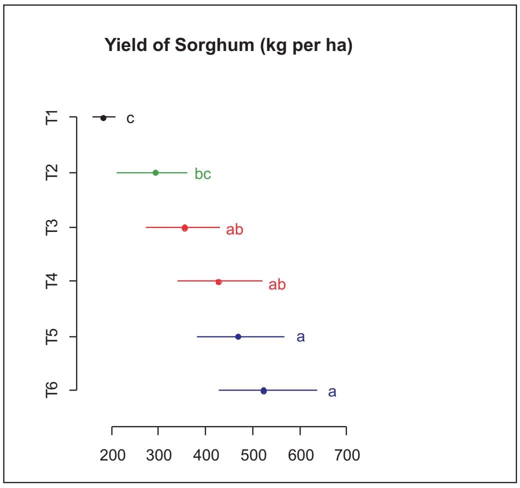

Fig. 2. Sorghum yield under different treatments (pooled average of six years)

Run-off and soil loss

A perusal of data compiled across all the run-off events that occurred during the six years of experimentation revealed that there was a reduction in both run-off and soil loss due to the application of biochar. There was a decline in soil loss from 3.43 t $ha^{-1}y^{-1}$ (T_1) to 2.09 t $ha^{-1}y^{-1}$ (T_6). While the control plot lost more than 20 t of top soil during six years, soil loss was brought down to 12.5 (60%) and 14.2 t through applying 20 and 10 t of biochar, respectively. However, although promising, the differences were not significant, as pointed out from the DMRT. This shows that the study period (six years) was not sufficient to significantly reduce soil loss through biochar application. Perhaps the difference will be clear if the study runs for a few more years.

Soil carbon stock

Stored soil organic carbon is essentially the balance between C inputs or additions (*e.g.,* crop residues, manures, compost) and outputs or removals (*e.g.* decomposition). Soil erosion is considered by some as a carbon loss mechanism, while others see it as an addition. As mentioned in the previous section, there occurred a cumulative soil loss of 20 t ha^{-1} from the control plot where no biochar was applied. This also resulted in the loss of soil organic carbon. This possibly explains the negative carbon balance in the soil after six years of experimentation (Table 4). In all other treatments, there was an increase in SOC stock in both 0-15 and 15-30 cm depths due to the soil application of biochar. The increase was higher in the upper 15 cm. Higher SOC content in the 15-30 cm layer after six years of biochar addition is attributed to the physical migration of biochar particles through the deep and wide cracks formed in the black soil during the summer season and mixing thereafter due to the "churning" of soil during the swell-shrink stages.

An increase in SOC stock occurs due to a combination of factors such as reduced CO_2 removals (Spokas *et al.* 2009; Liang *et al.* 2010), interaction with native organic matter and clay to form stable organo-mineral associations or complexes (Keith *et al.* 2011; Weng *et al.* 2015; Paustian *et al.* 2019), carbon sequestration in macro-aggregates (Du *et al.* 2017), active carbon content of biomass (Yang *et al.* 2020) and increased crop biomass additions. Some authors (van

Table 4. Changes in SOC stocks brought about by application of biochar.

Treatment	2013			2019			Increase in C stock	
	OC	BD	Stock t ha^{-1}	OC	BD	Stock t h^{-1}	6 y t ha^{-1}	Annual (t ha^{-1} y^{-1})
	0-15 cm							
T1	0.34	1.34	6.83	0.31	1.32	6.14	-0.70	-0.12
T2	0.31	1.33	6.18	0.34	1.31	6.68	0.50	0.08
T3	0.31	1.32	6.14	0.36	1.3	7.02	0.88	0.15
T4	0.34	1.30	6.63	0.40	1.28	7.68	1.05	0.18
T5	0.34	1.32	6.73	0.42	1.29	8.13	1.40	0.23
T6	0.34	1.32	6.73	0.45	1.28	8.64	1.91	0.32
	15-30 cm							
T1	0.26	1.36	5.30	0.25	1.35	5.06	-0.24	-0.04
T2	0.28	1.35	5.67	0.29	1.33	5.79	0.12	0.02
T3	0.28	1.37	5.75	0.29	1.35	5.87	0.12	0.02
T4	0.27	1.34	5.43	0.29	1.33	5.79	0.36	0.06
T5	0.28	1.35	5.67	0.30	1.33	5.99	0.31	0.05
T6	0.26	1.36	5.30	0.30	1.33	5.99	0.68	0.11

Groenigen *et al*. 2017; Dong *et al*. 2018) argue that there is a reduction in SOC content due to the priming effect. Others opine that the effect of priming is negligible as compared to the 'negative priming' mechanism resulting in the long-term stabilization of biochar carbon (Singh and Cowie 2014). This process of 'negative priming', predominant in soils with high clay content (Weng *et al.* 2015; Whitman *et al.* 2015) reduces the decomposition of native soil organic matter, thereby enhancing soil organic carbon stock. In our case, the experimental soil is well supplied with available nitrogen, due to which priming or immobilization can be considered negligible. In an interesting study, Park *et al.* (2007) observed that the addition of external carbon sources to a soil that undergoes frequent wetting and drying cycles (similar to the black soil in our case) could result in carbon sequestration.

It is generally agreed that although there is an upper or “saturation” level of C concentration in mineral soils (Six *et al*. 2002), there technically exists a significant potential for C sequestration in soils (Sommer and Bossio 2014). While studies on best management practices carried out globally show an increment of 0.2-0.5 t C $ha^{-1}y^{-1}$ (Minasny *et al*. 2017), Zomer *et al*. (2017) argue that it is possible to sequester SOC for the next 20 years at the rate of 0.56 (medium scenario – from Sommer and Bossio 2014) to 1.15 (high scenario) t C $ha^{-1}y^{-1}$. Our study shows an increase in C stock in the range of 0.10 to 0.43 t C $ha^{-1}y^{-1}$ in the top 30 cm soil depth across the biochar treatments (T_2 to T_6), which holds good for Indian conditions.

Conclusion

Results emanating from this study conclusively prove that biochar application to black soils has a positive effect on sorghum yield under rainfed conditions. However yield increment beyond addition of 10 t ha^{-1} was not significant. Therefore, although application of biochar @ 20 t ha^{-1}, it resulted in increasing the 30 cm-C stock by 0.43 t $ha^{-1}y^{-1}$, the dose is not recommended both technically and economically. The optimum rate of application may be considered as 10 t ha^{-1}, due to which a reasonable carbon accumulation of 0.28 t $ha^{-1}y^{-1}$ (or 1.71 t ha^{-1} for six years) occurred in the top 30 cm soil depth.

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