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Different carbon sources enhance system productivity and reduce greenhouse gas intensity

Stephen YEBOAH[1,2,3], Reanzhi ZHANG[1,2,*], Liqun CAI[1,2], Wu JUN[1,2]

[1]*Gansu Provincial Key Lab of Aridland Crop Science, Gansu Agricultural University, Lanzhou, P.R. China*
[2]*College of Resources and Environmental Sciences, Gansu Agricultural University, Lanzhou, P.R. China*
[3]*Council for Scientific and Industrial Research, Crops Research Institute, Kumasi, Ghana*

**Corresponding author: zhangrz@gsau.edu.cn*

ABSTRACT

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The aim of this study was to investigate the effect of biochar, straw and nitrogen (N) fertilizer on soil properties, crop yield and greenhouse gas intensity in rainfed spring wheat (*Triticum aestivum* L.), and to produce background dataset to improve nutrient management guidelines for semiarid environments. The two carbon sources (straw and biochar) were applied alone or combined with nitrogen fertilizer (urea, 46% N), whilst the soil without carbon amendment was fertilized by urea in the rates 0, 50 and 100 kg N/ha. The experiments were arranged in a randomized complete block design with three replicates. The greatest yields were found with 100 kg N/ha under biochar, straw and soils without carbon. Biochar treated soils produced the greatest grain yield at 1906 kg/ha, followed by straw at 1643 kg/ha, and soils without carbon at 1553 kg/ha. This was explained by increased easily oxidizable carbon and total soil nitrogen in the biochar treated soil ($P < 0.05$). Straw treated soils and soils without carbon increased global warming potential by 13% and 14% compared to biochar amended soils. The biochar amended treatment also improved easily oxidizable carbon and total nitrogen ($P < 0.05$), which supported the above results. BN_{100} (15 t/ha biochar + 100 kg N/ha) reduced greenhouse gas intensity by approximately 30% compared to CN_{100} (100 kg N/ha applied each year) and SN_{50} (4.5 t/ha straw applied each year + 50 kg N/ha). Based on these results, biochar could be used with N-fertilizer as a soil conditioner to improve yield and reduced greenhouse gas intensity.

Keywords: charcoal; semi-arid environment; climate change; fertilization; soil carbon

The decline of soil fertility is a major problem confronting crop production and environmental sustainability (Lal 2004). In dryland cropping systems of semi-arid environments such as the Loess Plateau, soil nutrient deficiency and water deficit are major factors limiting crop production (Sainju et al. 2009). Intensive farming and the continued removal of crop residues in the Loess plateau has resulted in immense soil carbon (C) loss and low crop productivity (Zhang et al. 2012a). This situation may be reversed by implementing improved soil and nutrient management practices that maximize biomass production and C return to soil (Norton 2014). In this context, the ability to develop and implement innovative soil management practices play an important role in maintaining or improving the productive capacity of soils and enhances the resilience of agro-

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ecosystem. According to Zhang et al. (2012b) the potential to increase C inputs to soils is associated with high yield agriculture. The adoption of sound soil management strategies such as crop residue retention, biochar application and efficient nitrogen (N) fertilization has been suggested to improve soil properties (Cayuela et al. 2010). These strategies can be achieved by increased input of crop residues while minimizing C losses.

Evidence has shown that biochar amendment can significantly improve carbon sequestration in soil, reduce anthropogenic greenhouse gas (GHG) fluxes and enhance crop productivity (Cayuela et al. 2010). When biochar is returned to field, it can slow down the process of organic carbon mineralization, increasing C sequestration (Wang et al. 2010) while reducing C emission due to inhibition of native C mineralization (negative priming) (Gaunt and Lehmann 2008). Biochar therefore exerts high carbon recalcitrant against microbial decay, thus requiring significantly longer time to decompose (Gaunt and Lehmann 2008). Nitrogen fertilization impact on soil C by enhancing crop biomass production thus stabilizes C in soil (Paustian et al. 1997). Beside the carbon sequestration potential of biochar amendment to agricultural soils, biochar addition to agricultural fields is expected to increase yield and improve soil quality (Lehmann et al. 2011). Information regarding the effectiveness of biochar, straw and N fertilization under rainfed conditions is an important practical consideration for growers in semiarid environments such as the Loess Plateau of China. The Loess Plateau is an important agricultural area in China and is widely used for grain production (Yao and Li 2010). This region has experienced a progressive decline in crop productivity because of soil degradation processes in the form of erosion, limited precipitation and high evaporation (He et al. 2014). Yet, little attention has been given to developing agrosystem-specific strategies to minimize GHG intensity from these regions.

Therefore, the objective of this research was to determine the effect of biochar, straw and N fertilizer application on soil properties, grain yield and greenhouse gas intensity of spring wheat grown in field conditions. The study tested the hypothesis that there is a great potential to increase crop productivity and environmental quality when organic residue (biochar and straw) is combined with N fertilizer under rainfed conditions in the Loess plateau.

MATERIAL AND METHODS

Experimental site. The study was conducted during the 2014–2016 growing seasons at the Dingxi Experimental Station (35°28'N, 104°44'E, elevation 1971 m a.s.l.) of the Gansu Agricultural University in Northwestern China. The research station is located in the semi-arid Western Loess Plateau, which is characterized by steep hills and deeply eroded gullies. This area has Aeolian soils, locally known as Huangmian, which equate to Calcaric Cambisols based on the FAO (1990) description. This soil type has a sandy-loam texture and relatively low fertility with pH of ≈ 8.3, soil organic carbon (SOC) ≤ 7.65 g/kg, and Olsen-P ≤ 13 mg/kg.

Experimental design and treatment application. The experiment involved addition of different carbon sources; namely: biochar and straw, and N fertilizer in the form of urea (46% N). The experiment was arranged in a randomized block design with nine treatments and three replicates. The treatments were: CN_0 – control (zero-amendment); CN_{50} – 50 kg N/ha applied each year; CN_{100} – 100 kg N/ha applied each year; BN_0 – 15 t/ha biochar; BN_{50} – 15 t/ha biochar + 50 kg N/ha; BN_{100} – 15 t/ha biochar + 100 kg N/ha; SN_0 – 4.5 t/ha straw applied each year; SN_{50} – 4.5 t/ha straw applied each year + 50 kg N/ha and SN_{100} – 4.5 t/ha straw applied each year + 100 kg N/ha. The two C sources (biochar and straw) were applied at the same quantity based on the straw returned to the soil every year. Biochar was applied as a single dressing in 2014 by spreading evenly on the soil surface and incorporated into the soil using rotary tillage implement to a depth of 10 cm. The biochar used in the experiment is a commercial milled charcoal sourced from a local supplier (Golden Future Agriculture Technology Co., Ltd, Liaoning, China). Biochar was produced through pyrolysis at 350–550°C, which converted approximately 35% of the biomass to biochar in the form of granules. In straw-amended plots, the wheat straw from the previous crop was weighed and returned to the original plots immediately after threshing and spread evenly on the soil surface. Nitrogen fertilizer (urea, 46% N) was applied each year by hand at sowing and incorporated into the soil. Based on the protocol described in Lu (2000), biochar and straw properties were determined. The biochar and straw properties were, respectively, 38% and 43% of total carbon, 0.1% and 0.09% total nitrogen, 0.8% and 0.53% calcium, 0.47% and 0.04% magnesium, 0.51% and 0.47% potassium and 0.26% and 0.08% phosphorus. The surface area (SA) of the biochar was 8.75 m^2/g. All the treatments received a blanket application of phosphorus (applied at 46 kg P/ha as single superphosphate [$Ca(H_2PO_4)_2$] containing 61 g P/kg) at sowing. Spring wheat (*Triticum aestivum* L. cv. Dingxi 35) was sown in mid-March at a rate of 188 kg/ha of seeds using a direct drill planter at 20-cm row spacing, and was harvested at the end of July. The plot dimensions were 3 × 6 m and the individual plots were separated by 0.5 m wide buffer rows. For grain yield determination, the entire area of the plot was harvested manually using sickles at 5 cm above ground. The edges (0.5 m) of the plot were trimmed and discarded. Grain yield was determined on a dry mass basis after oven-drying the plant material at 105°C for 45 min and then to constant mass at 85°C.

Soil and plant sampling and analysis. Soils samples were collected from two points in each plot at harvest. Soil samples at 0–5, 5–10 and 10–30 cm collected from the same depth were bulked and mixed. The soil samples were dried by air, ground to < 2 mm and then sub-sampled and ground to < 0.25 mm. Easily oxidizable carbon (EOC) was determined by oxidation with 333 mmol/L of $KMnO_4$ based on Lefroy et al. (1993). Total nitrogen content (TN) of the soil was determined using the Kjeldahl digestion and distillation procedure as described by Bremner and Mulvaney (1982).

Gas sampling and analysis. Measurements of GHG (N_2O, CH_4, and CO_2) were performed using the static chamber technique based on the procedure described by Zou et al. (2005) and quality criteria as outlined by De Klein and Harvey (2015). Gas samples were taken respectively at 0, 10, and 20 min after chamber closure using a 60 mL three-way valve syringe, and injected into a sealed 150 mL aluminum plastic bag (Dalian Delin gas packaging, China, http://delindl.com/en). For each measurement event, gas sampling was consistently performed between 08:00–12:00 h, based on the guidelines of Alves et al. (2012). Carbon dioxide (CO_2) emissions were measured using the EGM-4 (British PP Systems, http://ppsystems.com/) portable CO_2 analyser. Concurrently, collection of samples for N_2O and CH_4 analyses were conducted for determination by gas chromatography. Samples of N_2O, CH_4 and CO_2 were collected between March and September in 2014, 2015 and 2016 to quantify all three GHG fluxes during the main part of the cropping season. Based on the earlier studies conducted in low rainfall areas (e.g., Wang et al. 2010) emissions occurring during the dry season were expected to be low and therefore did not justify measurements over that period. Gas fluxes were measured over 14 sampling events per year. Whilst acknowledging that accurate estimates of total emissions cannot be determined from relatively few sampling events, the main purpose of this work was to quantify relative differences between treatments, which therefore justifies the approach used in this study. A similar approach was also employed by Yeboah et al. (2016) and Tullberg et al. (2018) to quantify soil emissions of GHG from tillage and traffic treatments in conservation agriculture areas with seasonal rainfall.

The N_2O and CH_4 concentration in samples were analysed within 2 to 3 days after collection using gas chromatograph (GC). The GC system (Agilent 7890A, Wilmington, USA) is equipped with flame ionization detector (FID) for CH_4 analysis and an electron capture detector (ECD) for N_2O analysis. Helium (99.999% purity) was used as a carrier gas (30 mL/min), and a make-up gas (95% argon and 5% CH_4) for the electron capture detector (ECD). N_2 (> 99% purity) was used as the carrier gas with a flow rate 60 mL/min and 10 mL/min for flame ionization detector. The detection temperature, column temperature and column flow rate of ECD were 300°C, 45°C and 3.3 mL/min, respectively. The detection temperature of FID was 200°C, column temperature was 55°C and column flow rate was 7.7 mL/min. Fluxes were determined from the slope of the mixing ratio change with the three sequential samples, taken at the 0, 10 and 20 min after chamber closure. Each sample was injected four times into the system and the measured concentrations were averaged and reported.

Grain yield. Plots were harvested by using hand sickles to a height of 5 cm aboveground and by discarding the outer edges (0.5-m) from each plot. Grain yields were determined on a dry-weight basis by oven-drying the plant material at 105°C for 45 min and then to constant weight at 85°C.

Global warming potential. To estimate global warming potential (GWP), CO_2 is typically taken as the reference gas, therefore emissions of CH_4 or N_2O are converted into CO_2 equivalents (CO_2^{-e}). The GWP for CH_4 is 34 (based on a 100-year time

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horizon, CO_2 is 1 and N_2O is 298 (IPCC 2013). The GWP was calculated using the equation:

$$\text{GWP (kg } CO_2^{-e}\text{/ha)} = \text{cumulative } CO_2 \text{ emission} \times 1 + \text{cumulative } CH_4 \text{ emission} \times 34 + \text{cumulative } N_2O \text{ emission} \times 298 \qquad (1)$$

In this paper, authors want to show how much carbon is emitted per grain produced (greenhouse gas intensity) under the treatments and therefore do not show the data on CO_2, CH_4 and N_2O emissions. The cumulative emission of N_2O and CH_4 in kg/ha was estimated using the equation as follows (after Yeboah et al. 2016).

Greenhouse gas intensity. Based on the protocols described by Zhang et al. (2012b), overall carbon intensity (GHGI) of spring wheat production is subsequently calculated as the overall gross GWP divided by the wheat produced under the corresponding treatment.

$$\text{GHGI} = \frac{\text{GWP}}{\text{Y}} \qquad (2)$$

Where: Y – wheat yield (kg/ha). Thus, C intensity (GHGI) as a parameter weighed the overall mean GHG release per kg of wheat produced (g CO_2^{-e}/kg grain).

Statistical analyses. Statistical analyses were undertaken with the SPSS 22.0 (IBM Corporation, Chicago, USA) with the treatment as the fixed effect and year as a random effect. Differences between treatments means were determined using the Duncan's multiple range test. Significance was determined using a probability level of 5%.

Table 1. Analysis of variance for carbon, nitrogen fertilizer and year effects and their interaction

Source	Easily oxidizable carbon			Total nitrogen		
	0–5	5–10	10–30	0–5	5–10	10–30
	(cm)					
Carbon (C)	**	*	ns	**	*	**
Nitrogen (N)	**	*	ns	**	**	**
Year (Y)	*	*	**	**	*	ns
C × N	ns	ns	ns	ns	ns	ns
C × Y	**	*	ns	ns	ns	ns
N × Y	**	ns	*	ns	ns	ns

*$P < 0.05$; **$P < 0.01$; ns – not significant difference at $P < 0.05$

RESULTS AND DISCUSSION

Easily oxidizable carbon. As shown in Table 1, carbon source, N fertilizer and year had a significant ($P < 0.05$) effect on easily oxidizable carbon, except 10–30 cm where only year showed an effect. The N_{50} fertilizer level caused a significant increase of 50.3, 18.9 and 23.7% on average in EOC at 0–5 cm under biochar soils compared to CN_0, CN_{50} and CN_{100}, respectively (Table 2). The results of 5–10 cm showed that both N_{50} and N_{100} had an effect on EOC thought not significant ($P < 0.05$) in some instances under all treatments. Straw treated plots enhanced EOC on average by 20.6% versus soils without carbon. The significance of retaining

Table 2. Easily oxidizable carbon (g/kg) as affected by carbon addition sources

C source	N rate	0–5			5–10			10–30		
		(cm)								
		2014	2015	mean	2014	2015	mean	2014	2015	mean
No carbon	N_0	2.85^d	3.67^c	3.26^d	2.56^c	3.68^b	3.12^c	2.21^b	3.54^b	2.87^b
	N_{50}	4.18^c	4.07^{bc}	4.12^c	3.47^{bc}	3.96^{ab}	3.71^{abc}	3.35^{ab}	3.57^b	3.46^{ab}
	N_{100}	4.05^c	3.86^{bc}	3.96^c	3.06^{bc}	3.86^{ab}	3.46^{abc}	2.71^{ab}	3.65^{ab}	3.18^{ab}
Biochar	N_0	4.48^{bc}	4.16^{bc}	4.32^{bc}	3.05^{bc}	3.77^{ab}	3.41^{bc}	2.20^b	3.53^b	2.87^b
	N_{50}	5.56^a	4.24^{bc}	4.90^a	4.95^a	3.91^{ab}	4.43^a	3.88^a	3.66^{ab}	3.77^{ab}
	N_{100}	4.68^b	4.24^{bc}	4.46^{abc}	3.91^{abc}	4.23^{ab}	4.07^{ab}	2.69^{ab}	3.90^{ab}	3.30^{ab}
Straw	N_0	4.18^c	3.99^{bc}	4.08^c	3.58^{abc}	3.70^b	3.64^{abc}	2.24^b	3.52^b	2.88^b
	N_{50}	5.29^a	4.36^{ab}	4.83^{ab}	4.13^{ab}	4.26^{ab}	4.19^a	2.90^{ab}	4.14^a	3.52^{ab}
	N_{100}	4.65^b	4.88^a	4.77^{ab}	3.74^{abc}	4.47^a	4.10^{ab}	3.68^a	4.13^a	3.90^a

Values with different letters within a column are significantly different at $P < 0.05$. N_0 – control; N_{50} – 50, N_{100} – 100 kg N/ha

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Table 3. Total nitrogen (g/kg) as affected by carbon addition sources

C source	N rate	0–5 (cm)				5–10 (cm)				10–30 cm mean
		2014	2015	2016	mean	2014	2015	2016	mean	
No carbon	N_0	0.85^c	0.88^b	0.94^e	0.89^c	0.83^a	0.86^c	0.89^d	0.86^c	0.79^b
	N_{50}	0.90^c	0.92^b	1.02^{cd}	0.95^{bc}	0.92^a	0.95^{abc}	0.98^c	0.95^{abc}	0.84^b
	N_{100}	0.94^{bc}	0.94^b	1.06^c	0.98^{bc}	0.91^a	0.92^{bc}	0.99^c	0.94^{abc}	0.87^{ab}
Biochar	N_0	0.97^{abc}	0.92^b	1.07^c	0.99^{bc}	0.87^a	0.99^{abc}	0.98^c	0.94^{abc}	0.83^b
	N_{50}	1.05^{ab}	1.14^a	1.14^b	1.11^a	1.00^a	1.07^{ab}	1.08^b	1.05^{ab}	0.87^{ab}
	N_{100}	1.07^a	1.14^a	1.24^a	1.15^a	1.02^a	1.12^a	1.19^a	1.11^a	0.98^a
Straw	N_0	0.85^c	0.91^b	0.99^{de}	0.91^c	0.86^a	0.98^{abc}	0.91^d	0.92^{bc}	0.88^{ab}
	N_{50}	0.94^{bc}	0.89^b	1.04^{cd}	0.96^{bc}	0.95^a	0.96^{abc}	1.00^c	0.97^{abc}	0.90^{ab}
	N_{100}	0.97^{abc}	1.02^{ab}	1.07^c	1.02^b	0.95^a	1.02^{abc}	1.01^c	0.99^{abc}	0.92^{ab}

Values with different letters within a column are significantly different at $P < 0.05$. N_0 – control; N_{50} – 50, N_{100} – 100 kg N/ha

crop residues was emphasized in this study by the difference in the soils organic amendment, particularly the biochar treated soils and the no carbon soils. In this study, the increased C content in biochar could be related to its high C content and the fact that biochar could slow down organic C utilization by microbes (Cayuela et al. 2010).

Total soil nitrogen. Carbon, N fertilization and year significantly influenced total nitrogen, although the differences were not always significant at $P < 0.05$. Interactions between treatment factors were not significant ($P < 0.05$) in all soil layers (Table 1). The highest averaged total N of 1.15 g/kg was recorded in BN_{100} soils, which represents a significant increase of 29.4, 21.5 and 17.5% versus CN_0, CN_{50} and CN_{100} soils, respectively (Table 3). Application of N_{50} and N_{100} on biochar soils enhanced total N in both 0–5 cm and 5–10 cm soil depths compared to straw treated soils; an average increase of 17.6% and 12.7% was observed, respectively. Application of biochar to a calcareous loamy soil resulted in increased total soil N content during a 4-month field trial (Zhang et al. 2012a).

Grain yield. Treatment factors independently affected grain yield and interaction between nitrogen and year was also significant ($P < 0.05$) (Table 4). BN_{100} had the highest grain yield of 2054 kg/ha on average, representing a significant increase of 37.7% and 27.3% compared to CN_{50} and CN_{100}, respectively (Table 5). Significant

Table 4. Analysis of variance for carbon, nitrogen and year effects and their interaction

Source	Grain yield	GWP	GHGI
Carbon (C)	**	*	**
Nitrogen (N)	**	**	**
Year (Y)	**	**	**
C × N	ns	ns	ns
C × Y	ns	*	ns
N × Y	**	ns	**

*$P < 0.05$; **$P < 0.01$; ns – not significant difference at $P < 0.05$. GWP – global warming potential; GHGI – greenhouse gas intensity

Table 5. Grain yield (kg/ha) of spring wheat as affected by carbon addition sources

C source	N rate	2014	2015	2016	Mean
No carbon	N_0	1305^d	1500^d	1009^d	1271^d
	N_{50}	1538^{cd}	1896^{bc}	1043^{cd}	1492^{bcd}
	N_{100}	1770^{abc}	1927^{bc}	1144^{cd}	1614^{bcd}
Biochar	N_0	1603^{bcd}	1789^{cd}	1124^{cd}	1505^{bcd}
	N_{50}	1905^{abc}	2133^b	1233^{bc}	1757^{abc}
	N_{100}	2139^a	2456^a	1567^a	2054^a
Straw	N_0	1502^{cd}	1658^{cd}	1111^{cd}	1424^{cd}
	N_{50}	1852^{abc}	1944^{bc}	1182^{cd}	1659^{bc}
	N_{100}	1975^{ab}	2180^{ab}	1380^{ab}	1845^{ab}

Values with different letters within a column are significantly different at $P < 0.05$. N_0 – control; N_{50} – 50, N_{100} – 100 kg N/ha

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Table 6. Cumulative global warming (kg CO_2^{-e}/ha) potential and greenhouse gas intensity (g CO_2^{-e}/kg grain) of spring wheat as affected by carbon addition sources

C source	N rate	Cumulative global warming				Greenhouse gas intensity			
		2014	2015	2016	mean	2014	2015	2016	mean
No carbon	N_0	1554^{a}	1012^{ab}	1054^{a}	1207^{a}	1194^{a}	683^{a}	1045^{a}	973^{a}
	N_{50}	1432^{b}	972^{ab}	1002^{b}	1135^{ab}	931^{bc}	512^{bc}	962^{ab}	802^{abc}
	N_{100}	1401^{b}	918^{abc}	1000^{b}	1106^{b}	791^{bcd}	478^{cd}	875^{bc}	714^{bc}
Biochar	N_0	1303^{c}	799^{c}	882^{bcd}	995^{c}	814^{bcd}	449^{cd}	786^{bcd}	683^{bcd}
	N_{50}	1309^{c}	828^{bc}	903^{bcd}	1013^{c}	691^{d}	388^{cd}	732^{cd}	604^{cd}
	N_{100}	1261^{c}	809^{c}	878^{c}	983^{c}	593^{d}	329^{d}	561^{e}	494^{d}
Straw	N_0	1522^{a}	1032^{a}	985^{bc}	1180^{ab}	1015^{ab}	623^{ab}	886^{bc}	841^{ab}
	N_{50}	1509^{a}	957^{abc}	961^{bcd}	1142^{ab}	821^{bcd}	494^{bc}	812^{bcd}	709^{bc}
	N_{100}	1515^{a}	933^{abc}	921^{bcd}	1123^{b}	769^{cd}	426^{cd}	667^{de}	621^{cd}

Values with different letters within a column are significantly different at $P < 0.05$. N_0 – control; N_{50} – 50, N_{100} – 100 kg N/ha

($P < 0.05$) variations in grain yields were recorded between N_{50} and N_{100} fertilizer rates in some instances on biochar and straw treated soils. There were overall better yields with the biochar amendment; this was followed by straw amendment and the least was on no carbon plots. Improved crop yields in the current study could be attributed to increased nutrient availability through enhanced soil quality. Biochar amendments were previously shown to increase crop productivity by improving soil quality (Bruun et al. 2011).

Global warming potential. The analysis of variance indicated a significant ($P < 0.05$) effect of treatment factors on global warming potential (GWP) (Table 4). Application of N_{100} led to significantly lower GWP under no carbon soils; a decrease of 8.6, 7.7 and 8.1% was recorded in 2014 compared to SN_0, SN_{50} and SN_{100}, respectively (Table 6). Overall, soils under biochar produced the lowest GWP of 997 kg CO_2^{-e}/ha on average, representing a significant decrease of 15.3% and 15.2% compared to no carbon soils and straw treated soils, respectively. In this study, application of biochar and straw combined with N fertilizer effectively reduced overall global warming potential and therefore reduced the radiating effect on the environment.

Greenhouse gas emission intensity. The analysis of variance shows that treatment factors had a significant effect ($P < 0.05$) on greenhouse gas emission intensity (Table 4). Irrespective of N level, the GHGI was the lowest in biochar treated soils, followed by straw treated soils and then no carbon soils (Table 6). The GHGI of biochar treated soils was on average 236 and 130 g CO_2^{-e}/kg grain lower than that of no carbon soils and straw treated soils, viz. 39.8% and 21.9%, respectively. The reduction in GHGI under biochar treated soils demonstrates the potential of minimizing the adverse impacts of spring wheat agriculture on climate change. The biochar treatment significantly reduced GHGI by increasing grain yield and decreasing GHGs. The mineral nitrogen increased yield and the recalcitrant carbon reduced GHGs. This finding is consistent with the suggestion made by Burney et al. (2010) that the net effect of higher yields offsets emissions and one may consider low carbon agriculture as higher yield against lower C intensity. The results of this study suggest that biochar treated soils may significantly reduce GHGI and increase crop yield in semi-arid agricultural systems.

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