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Influence of Organic Amendment on Soil Respiration and Maize Productivity in a Semi-Arid Environment

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Abstract: Soil degradation and C emissions are a threat to sustainable agriculture in many arid and semi-arid areas. For sustainable agriculture, the influence of soil amendments on crop production and soil respiration has been a key focus of research. A three-year field study to assess how soil amendments influence soil properties, soil respiration (Rs), and yield of maize (*Zea mays* L.) was conducted. Treatments were: no amendment (NA), chemical fertilizer (CF), swine (*Sus scrofa* L.) manure (SM), maize stover (MS), and swine manure + chemical fertilizer (SC). Soil amendment (CF, SM, MS, and SC) consistently produced greatest grain yield and aboveground biomass, which averaged 38 and 34% greater than NA, respectively. No amendment reduced Rs by an average of 12% compared to amendment treatments. Enhanced grain yield with soil amendment resulted in increased carbon emission efficiency (CEE) with SC>MS>CF>SM>NA. Across years, SC decreased soil bulk density by 13% and increased CEE, soil total C, and soil hydraulic conductivity by 52, 19, and 21%, respectively, compared to NA. These results demonstrate the viability of swine manure + chemical fertilizer at 200 kg N ha^{-1} as a soil amendment for improved CEE and advancing sustainable maize production in semi-arid rainfed environments.

Keywords: soil amendment; chemical fertilizer; soil respiration; carbon emission efficiency; maize

1. Introduction

Maize (*Zea mays* L.) is an important crop in northern China. The planted area to maize in this region is about 20 million ha, representing ~70% of China's total maize area [1]. In recent years, swine production in China has experienced growth motivated by favorable government policies [2,3], resulting in a substantial increase in the demand for maize grain [3,4].

Agriculture in the semi-arid Loess Plateau of northern China is of crucial importance in achieving food security [5]. However, it depends mainly on precipitation, which averages about 450 mm and exhibits high spatial and temporal variation [6]. Maize production was not possible without use of special management practices in the semi-arid Loess Plateau [7] due to high evaporation, limited rainfall, and low accumulated soil temperature. In an attempt to advance maize production for food security in this region, a complete plastic mulching technique was introduced [8] to decrease evaporation, increase soil temperature, and soil moisture [9]. This system can improve harvest surface runoff from rainfall [8,10], reduce evaporation [11], and increase accumulated soil

temperature [8], thereby improving water use efficiency and productivity of maize [12] and enabling continuous maize production. Adopting this technology has led to increased maize yield and profitability for farmers in semi-arid rainfed environments [8]. Consequently, this technology is widely used in maize production in the semi-arid Loess Plateau [13] and on about 19% of total arable land (130 million ha) in China [14]. However, there are concerns regarding the long-term sustainability of this practice. Greater crop yields increase water and nutrient consumption [15] and could reduce the ability to sustain maize production in the long run without special fertilization practices. Responses to these challenges include fertilization programs with manures [16] to increase soil fertility [16,17]. Rational organic amendment application is among the most important measures to increase water use efficiency and grain yield of maize [18,19] and balance soil nutrients [16].

Soil amendments can significantly affect soil microbial populations and their activity, subsequently influencing soil CO_2 emission [20,21]. In addition, differences in soil moisture and temperature resulting from soil amendments can influence soil CO_2 fluxes [22,23]. Maize is important for meeting the increasing demand for grain for livestock and human consumption [24]. To date, few studies report how productivity of grain-maize and CO_2 emission are affected by soil amendment practices in semi-arid areas. This research is designed to: (1) evaluate the effects of soil amendment on grain yield and biomass production from maize, (2) determine the effects of soil amendment on carbon emission and efficiency, and (3) explore the underlying microbial mechanisms and the consequent effects of soil amendments on maize productivity and CO_2 emission.

2. Materials and Methods

2.1. Experimental Site

The field experiment was conducted at Gansu Agricultural University Experimental station (35°28′ N, 104°44′ E, 1971 m above sea level), Dingxi, in northwestern China. Soil at the experimental site is sandy-loam and low in fertility. The soil is classified as Calcaric Cambisol [25]. Soil properties (chemical and physical) prior to initiation of the experiment in 2012 are reported in Table 1.

Table 1. Soil chemical and physical properties prior to sowing in 2012.

Soil Layer (cm)	pH (Water)	Bulk Density (Mg m^{-3})	Organic C (g kg^{-1})	Total N (g kg^{-1})	Total P (g kg^{-1})
0–5	8.33	1.19	9.91	1.05	0.82
5–10	8.32	1.22	8.96	1.05	0.74
10–30	8.37	1.28	8.89	0.94	0.70

Values are means (n = 3).

Before 2012, the experimental site had been in long-term annual potato (*Solanum tuberosum* L.) production using conventional tillage practices. These included moldboard plowing to a depth of 20 cm after harvest usually in October and field cultivating to a depth of 10 cm prior to sowing in March–April. Long-term (1986–2003) annual precipitation at the experimental site averaged 391 mm and ranged from 246 to 564 mm. Almost 60% of this precipitation occurs between July and September. Long-term daily air temperatures ranged from −22 °C in January to 38 °C in July. Long-term annual accumulated temperature >10° is 2239 °C and annual radiation is 5929 MJ m^{-2} with 2477 h of sunshine. The research reported in this article is from the 2014, 2015, and 2016 cropping seasons, with cumulative precipitation during the crop growing season at the experimental site being 280, 274, and 227 mm, respectively (Figure 1). Air temperature and relative humidity with vapor pressure deficit during the crop growing season at the experimental site are shown in Figures 2 and 3, respectively.

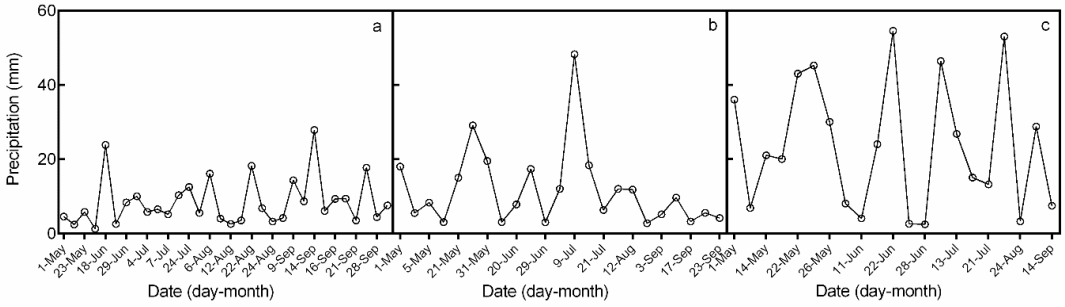

Figure 1. Daily precipitation during the 2014 (**a**), 2015 (**b**), and 2016 (**c**) growing seasons.

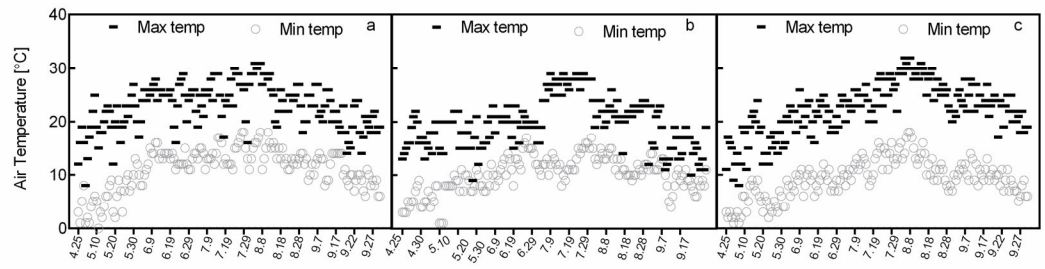

Figure 2. Minimum and maximum air temperature for (**a**) 2014, (**b**) 2015 and (**c**) 2016 cropping season.

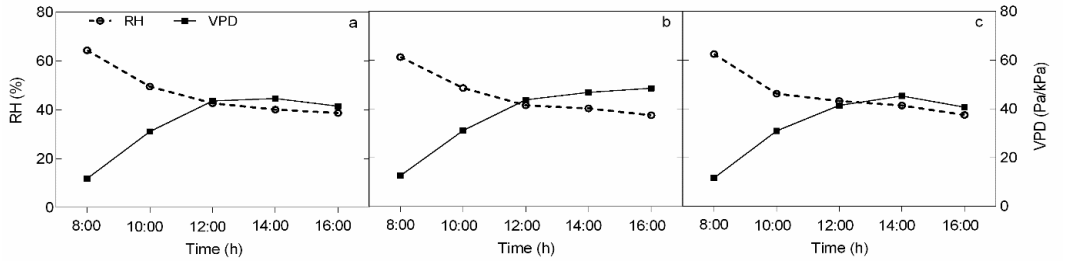

Figure 3. Diurnal variations in relative humidity (RH) and vapor pressure deficit (VPD) in 2014 (**a**), 2015 (**b**) and 2016 (**c**) recorded between 8:00 and 16:00 h. Symbols are: (○) Relative humidity and (■) vapor pressure deficit.

2.2. Experimental Design

The experiment was laid in a randomized complete block design with three replications of five treatments: no amendment (NA), chemical fertilizer (CF) consisting of 200 kg N ha^{-1} as urea (46-0-0 of N-P_2O_5-K_2O) plus 150 kg P_2O_5 ha^{-1} using calcium super phosphate (0-16-0 of N-P_2O_5-K_2O), solid swine (*Sus scrofa* L.) manure (SM) applied at 10 Mg ha^{-1}, maize stover (MS) applied at 27 Mg ha^{-1}, and swine manure + chemical fertilizer (SC) consisting of 5 Mg ha^{-1} of solid swine manure plus 100 kg N ha^{-1} as urea and 75 kg P_2O_5 ha^{-1} as calcium super phosphate. All amendment treatments were applied at 200 kg N ha^{-1}. Maize stover was collected from the entire experimental area after harvest and mixed, air-dried, shredded, weighed, and applied to field plots for the MS treatment. Solid swine manure was obtained from a local farm and stored for 2 months prior to application. All amendments, including solid swine manure, maize stover, and chemical fertilizers, were evenly distributed each year on the soil surface in the spring and incorporated within 3 days of application by moldboard plowing at 20 cm depth. Representative samples of maize stover and manure were collected at the time of application and analyzed for nutrient concentration using an Elementar vario MACRO cube (Elementar, Hanau, Germany) (Table 2).

Table 2. Average chemical composition of maize stover and swine manure used in 2014, 2015 and 2016.

Amendment	Organic C	N	P	K	Ca	Mg
	%					
Maize stover	47.5	0.74	0.38	0.45	0.55	0.74
Swine manure	39.9	2.23	1.74	1.92	2.74	0.54

Values are means (n = 3).

Experimental plots measured 42.6 m² (3 × 14.2 m) with 15 cm high × 40 cm wide narrow ridges, alternated with 10 cm high × 70 cm wide ridges. Colorless plastic film was used to cover all ridges to increase soil temperature, hasten crop emergence, and reduce evaporative losses. Holes were made through the film in furrows after the covering to facilitate collection of precipitation [26]. Plowing, ridging and mulching occurred at sowing and was the same for all treatments.

2.3. Agronomic Practice

Treatments for the experiment were imposed on the same plots in all years. All agronomic practices were equal among treatments, except for soil amendment application. Each year, maize (cv. Funong 821) was sown in alternating row distances of 0.7 and 0.4 m to a density of 52,000 plants ha^{-1} on 29 April, 25 April and 30 April, and harvested on 2 October, 25 September and 20 September in 2014, 2015 and 2016, respectively. Weeds were controlled using herbicide during the period between harvest and before next cropping season. Hand weeding was used between sowing and harvest.

2.4. Measurement and Calculation

2.4.1. Bulk Density and Total Porosity of Soil

Soil samples for bulk density were collected (0–5 and 5–10 cm depth) immediately before application of amendment treatment in 2014, 2015 and 2016 using the beveled stainless steel ring method [27]. Total soil porosity (η) was derived using soil bulk density as described by Paydar and Cresswell [28].

2.4.2. Soil Water Content

Each time soil respiration (Rs) was measured, soil water content in the 0–5 and 5–10 cm layers was also measured using Jia et al. [29] oven drying method. Two samples were taken from each plot. Gravimetric soil water content obtained using oven dry method was multiplied by bulk density for the respective soil layer to obtain the volumetric water content. Reported soil water content values in this study correspond to the mean of the two depths.

2.4.3. Soil Hydraulic Conductivity

Prior to soil tillage in the spring of 2014 and 2016, soil hydraulic conductivity (Ksat) was determined using the disc permeameter method and equation by Liu et al. [30]. This was done at two locations per plot.

2.4.4. Soil Total Carbon

Soil samples for determination of total soil C were collected prior to sowing in 2014 and 2015 using a soil corer (4.9 cm diameter). Organic residues >2 mm were removed from samples. These samples were air dried, ground and made to pass through a 2-mm sieve. They were subsequently sub–sampled and again made to pass through a 0.25-mm sieve. The samples were then analyzed for total C by combustion using an Elementar vario MACRO cube (Elementar, Hanau, Germany). Soil total C was not determined in 2016 due to time constraint.

2.4.5. Grain and Biomass Yield of Maize

Grain maize and aboveground biomass were manually harvested at physiological maturity from an area of 13.2 m^2 (4 × 3.3 m) per plot. After harvest, grains were separated, weighed, and yield in kilograms per hectare were extrapolated and reported. Grain yield and aboveground biomass were determined on a dry-matter basis after oven drying the crop samples at 105 °C for 45 min and subsequently to constant mass at 85 °C [26].

2.4.6. Soil Respiration

Measurement on soil respiration was done eleven (11) times per year from sowing (late April) to maize physiological maturity (late September) on about 2-wk intervals using EGM–4 (British PP Systems) portable CO_2 analyzer. Measurements were done under the plastic film at three locations in each plot between 08:00–12:00 h. This according to Alves et al. [31] was to effectively capture microbial activity on diurnal pattern.

2.4.7. Carbon Emission

Carbon emission (CE) was arrived at using soil respiration (Rs) measurement into equation described by Zhai et al. [32]:

$$\mathrm{CE} = \sum [\left(\frac{\mathrm{Rs}_{i+1} + \mathrm{Rs}_i}{2}\right) \times (t_{i+1} - t_i) \times 0.1584 \times 24] \times 0.2727 \times 10 \quad (1)$$

where soil respiration is Rs (μmol CO_2 m^{-2} s^{-1}) measured once in every 2 wk during the growing season, $i + 1$ and i represent the previous and the current sampling date, respectively, and t represent days after sowing.

2.4.8. Carbon Emission Efficiency

Carbon emission efficiency (CEE) was calculated to quantify unit of carbon emission per grain yield. This was done using carbon emission into equation described by Qin et al. [33]:

$$\mathrm{CEE} = \frac{\text{grain yield (kg ha}^{-1})}{\text{carbon emission (kg ha}^{-1})} \quad (2)$$

2.4.9. Net Primary Productivity

Net primary productivity (NPP) was calculated using the method of [34]:

$$\mathrm{NPP} = \mathrm{C_P} + \mathrm{C_s} + \mathrm{C_R} + \mathrm{C_E} \quad (3)$$

where C_P is plant Carbon (C) in the harvested maize grain, C_S is plant carbon (C) in total aboveground biomass excluding the harvested product (i.e., maize cob + stover), C_R is plant carbon (C) in roots, and C_E is plant carbon (C) in extra–root material including root exudates. The Carbon input of these fractions were calculated using maize grain yield and aboveground biomass measured in this experiment and assuming that carbon concentration of all the plant part was 0.45 kg kg^{-1} [34].

2.5. Statistical Analysis

The effects of treatment, year, and the interaction between them on the above measured parameters were evaluated using analysis of variance at $p \leq 0.05$ with statistical analysis software (SPSS 22.0, IBM Corp., Chicago, IL, USA). Treatment and year were considered fixed effect, whereas block was considered as a random effect. Differences between means were determined using the least significant difference test. The associations between dependent variables were assessed using Pearson's correlation coefficient.

3. Results

3.1. Soil Water Content and Properties as Influenced by Soil Amendment

Soil amendment significantly affected soil water content in the depth of 0–10 cm on eight, six, and four occasions in 2014, 2015, and 2016, respectively (Figure 4).

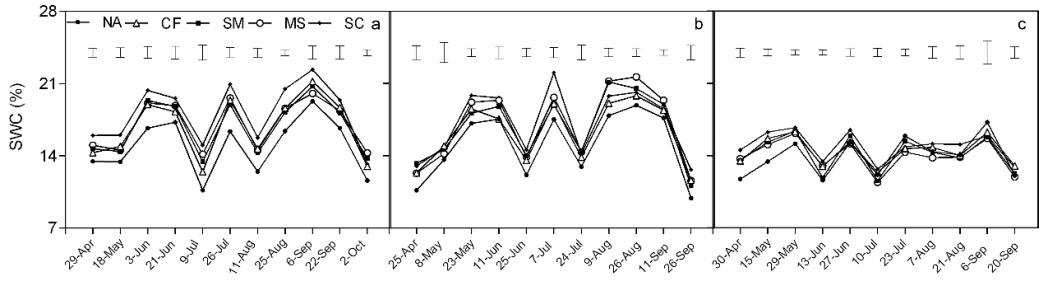

Figure 4. Volumetric Soil water content (SWC) in the 0–10 cm layer during the 2014 (**a**), 2015 (**b**), and 2016 (**c**) growing seasons as influenced by soil amendment treatment. NA, no amendment; CF, chemical fertilizer; SM, swine manure; MS, maize stover; and SC, swine manure + chemical fertilizer. Vertical bars denote LSD (0.05).

Averaged across sampling times, soil water content was least with NA and greatest with SC. Soil water content with SC and NA were 18.1 and 14.9 in 2014, 17.2 and 15.0 in 2015, and 14.9 and 13.9 in 2016, respectively (Figure 5a–c).

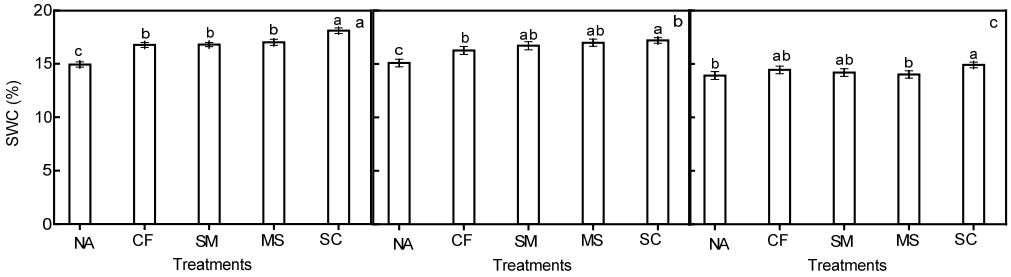

Figure 5. Mean soil water content (SWC) by soil amendment treatment in maize in 2014 (**a**), 2015 (**b**), and 2016 (**c**). NA, no amendment; CF, chemical fertilizer; SM, swine manure; MS, maize stover; and SC, swine manure + chemical fertilizer. Within a year, bars with different letters are significantly different ($p \leq 0.05$). Error bars denote standard errors.

Significant differences in ρ_b and total C among treatments within the 0–5 and 5–10 cm layers were recorded (Table 3). Soil bulk density in the 0–10 cm layer of the SC treatment was 13, 12, 9, and 9% less than that of the NA, CF, SM, and MS treatments, respectively. Soil C in the depth of 0–10 cm was significantly greater in amendment treatments compared to NA. Among the amendment treatments, soil C in the 0–5 and 5–10 cm layers of the SC treatment was greater by 13 and 11% in 2014 and 10 and 9% in 2015 compared to the CF treatment, respectively.

Table 3. bulk density (ρ_b, g cm^{-3}), total porosity (TP, %), and total carbon (C, %) in the 0–5 and 5–10 cm soil layers by soil amendment treatment in maize and year.

Table	ρ_b						C			
	2014		2015		2016		2014		2015	
	0–5	5–10	0–5	5–10	0–5	5–10	0–5	5–10	0–5	5–10
NA	1.25	1.28	1.23	1.25	1.23	1.29	1.48	1.39	1.52	1.48
CF	1.24	1.28	1.22	1.24	1.21	1.22	1.54	1.52	1.61	1.55
SM	1.21	1.23	1.14	1.20	1.21	1.25	1.69	1.59	1.68	1.71
MS	1.22	1.23	1.15	1.24	1.18	1.21	1.74	1.63	1.71	1.74
SC	1.06	1.10	1.07	1.13	1.04	1.25	1.76	1.71	1.78	1.74
LSD (0.05)	0.03	0.04	0.01	0.06	0.02	0.04	0.09	0.12	0.05	0.03

NB: No Amendment, CF: Chemical fertilizer, SM: Swine manure, MS: Maize stover, SC: Swine manure + chemical fertilizer. Footnote: Soil total C was not measured in 2016.

Swine manure + chemical fertilizer also increased K_{sat} in comparison to NA by 29 and 13% in 2014 and 2016, respectively (Figure 6).

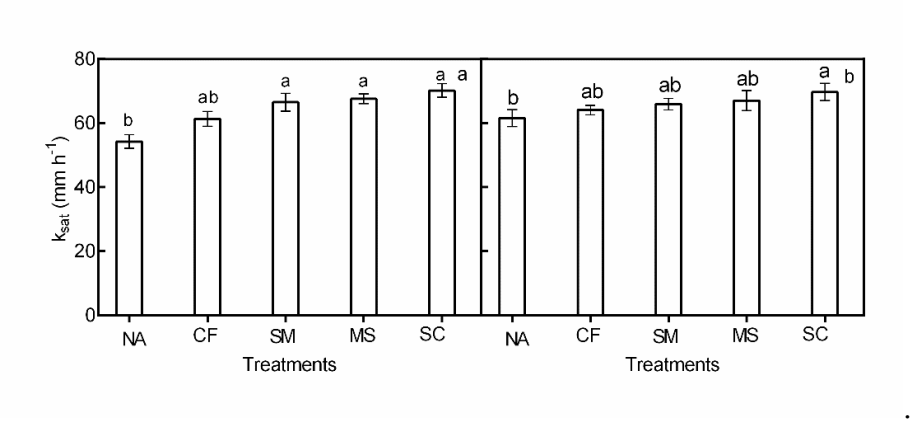

Figure 6. Soil hydraulic conductivity (K_{sat}) measured in 2014 (**a**) and 2016 (**b**) by soil amendment treatment in maize. NA, no amendment; CF, chemical fertilizer; SM, swine manure; MS, maize stover; and SC, swine manure + chemical fertilizer. Within a year, bars with different letters are significantly different ($p \leq 0.05$). Error bars denote standard errors.

3.2. Main Grain Yield and Biomass as Influenced by Soil Amendment

Grain yield of maize and aboveground biomass were significantly affected by treatment, year, and the treatment × year interaction (Table 4). Averaged across years, grain yield of the amendment treatments was greater than that of the NA treatment. Swine manure + chemical fertilizer produced the greatest grain yield (7760 kg ha^{-1}), which was 6, 12, 15, and 74% greater than that with CF, MS, SM, and NA, respectively. There were significant differences in maize aboveground biomass among treatments in all years. Compared to NA, SC increased biomass by 69, 62, and 46% in 2014, 2015, and in 2016, respectively. Biomass with CF was not different from that with SC in any year.

Table 4. Yield and aboveground biomass of maize by soil amendment treatment in 2014, 2015, and 2016.

Treatment	Grain Yield (kg ha^{-1})			Aboveground Biomass (kgha^{-1})		
	2014	**2015**	**2016**	**2014**	**2015**	**2016**
NA	5322	4594	3459	16,012	15,098	7098
CF	8228	8103	5805	24,846	24,534	11,809
SM	7888	6732	5641	23,394	22,800	11,104
MS	7550	7433	5768	22,020	19,573	11,282
SC	8900	8209	6156	27,106	24,430	13,123
LSD (0.05)	1332	1450	1094	4214	3880	2222
Source of variation						
Treatment (T)	***			***		
Year (Y)	***			***		
T × Y	*			**		

* Significant at the 0.05 probability level, ** Significant at the 0.01 probability level, *** Significant at the 0.001 probability level.

3.3. Soil Respiration, Carbon Emission Efficiency, and Net Primary Production as Affected by Soil Amendment

Soil respiration flux observed throughout the sampling period had a similar pattern for all treatments and for the three study years (Figure 5). Soil respiration increased with maize maturity until the kernel milk stage and then decreased. Greatest values (0.88, 0.90 and 0.78 μmol.m^{-2} s^{-1}) were recorded on 8 August 2014, 24 July 2015, and 7 August 2016, respectively (Figure 7a–c). Soil respiration differed significantly among treatments at eight, five and six sampling times in 2014, 2015, and 2016, respectively. The amendment treatments had greater Rs compared to NA. Averaged across years Rs with NA was 15, 9, 7, and 15% less than that compared with CF, SM, MS, and SC, respectively (Figure 7).

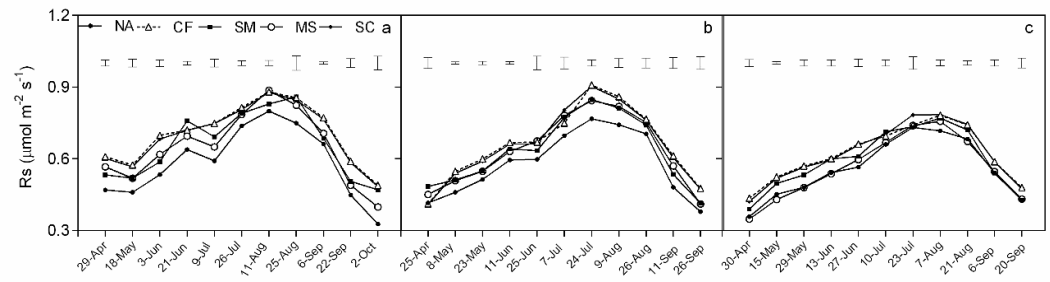

Figure 7. Soil respiration (Rs) during the 2014 (**a**), 2015 (**b**), and 2016 (**c**) growing seasons by soil amendment treatment in maize. NA, no amendment; CF, chemical fertilizer; SM, swine manure; MS, maize stover; and SC, swine manure + chemical fertilizer. Error bars denote LSD (0.05).

Increased Rs in amended soils resulted in significantly greater CE (1029 kg ha^{-1}) compared to NA (929 kg ha^{-1}). Among the amended treatments, CF and SC produced the greatest CE (Table 5). Carbon emission efficiency also differed significantly among treatments. The four amendment treatment (CF, SM, MS and SC) averagely increased CEE by 32, 47 and 56% in 2014, 2015 and 2016, respectively.

Table 5. Growing season soil respiration (Rs, carbon emission (CE) and carbon emission efficiency (CEE) by soil amendment treatment in maize in 2014, 2015, and 2016.

Treatment	Rs (μmol m^{-2} s^{-1})			CE (Kg ha $^{-1}$)			CEE (Kg kg^{-1})		
	2014	2015	2016	2014	2015	2016	2014	2015	2016
NA	0.58	0.58	0.56	978	940	853	5.5	4.9	4.1
CF	0.70	0.66	0.62	1166	1078	941	7.1	7.3	6.2
SM	0.66	0.63	0.59	1090	1024	905	7.2	6.6	6.2
MS	0.65	0.63	0.56	1079	1034	860	7.0	7.2	6.7
SC	0.70	0.66	0.62	1156	1077	945	7.7	7.6	6.5
LSD (0.05)	0.05	0.03	0.03	74.6	57.2	43.6	0.87	1.09	1.11
Source of variation									
Treatment (T)	***			***			***		
Year (Y)	***			***			**		
T × Y	**			**			ns		

* Significant at the 0.05 probability level, ** Significant at the 0.01 probability level, *** Significant at the 0.001 probability level, ns: no significant.

Net primary production indicates the magnitude and turnover of C and nutrient cycles in an ecosystem and was significantly affected by the interaction between treatment and year. Greatest NPP was obtained with CF, SM, and SC in all years (49,000, 46,000, and 20,000 Kg C ha^{-1} year^{-1} in 2014, 2015, and 2016, respectively), which was 57, 51 and 69% greater than that with NA in 2014, 2015 and 2016, respectively (Figure 8a–c). Net primary production with MS was not significantly different than that with CF, SM, or SC in 2014 or 2016.

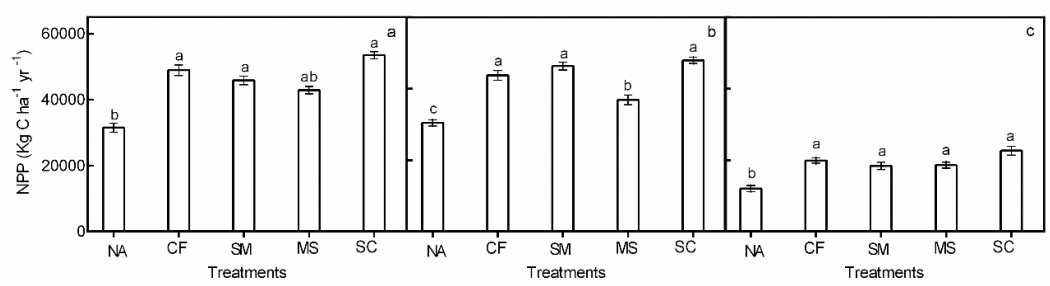

Figure 8. Net primary productivity (NPP) in 2014 (**a**), 2015 (**b**), and 2016 (c) by soil amendment treatment in maize. NA, no amendment; CF, chemical fertilizer; SM, swine manure; MS, maize stover; and SC, swine manure + chemical fertilizer. Within a year, bars with different letters are significantly different ($p \leq 0.05$). Error bars denote standard errors.

4. Discussion

4.1. Grain Yield, Biomass, and Net Primary Production

Management practices in agriculture can have significant effect on crop growth and productivity [35]. Swine manure + chemical fertilizer consistently produced greater maize grain yield and biomass than the other treatments. Kibunja et al. [36] reported enhanced biomass of maize as a result of combined use of organic and inorganic fertilizer. Pan et al. [37] also reported greater rice yield when swine manure was combined with chemical fertilizer in comparison to no fertilizer, chemical fertilizer, and rice straw. Enhanced crop productivity with organic fertilizer alone or in combination with chemical fertilizer has been ascribed to several mechanisms, including enhanced soil physical properties resulting in greater soil water and nutrient uptake by roots [16,38]. Timing of nutrient release or differences in nutrients supplied with the different amendment treatments may have added to differences in maize grain yield and biomass among treatments in this study. Substituting 50% mineral N by organic amendment (SC), enhanced early-release of nutrients from chemical fertilizer combined with delayed release of nutrients from manure. This may have enhanced synchrony between nutrient supply and crop nutrient demand, thereby reducing risk of nutrient losses and increasing crop nutrient uptake [39]. The organic manure might have provided important micronutrients and increased the soil properties, which in turn improved nutrient availability and, in combination with inorganic fertilizers, enhanced plant growth and grain yield [39]. Similarly, differences in crop-available nutrients differed between amendment treatments. Some treatments such as MS, which had a relatively high C:N ratio, likely immobilized N, at least temporarily, thereby reducing maize N uptake compared to other treatments with similar N application [40]. The balance of organic C in soil is affected by rates of organic C input from NPP plus amendments, and rates of soil organic C decomposition. Improved soil bulk density, soil total C, soil hydraulic conductivity and soil water content with SC resulted to greater maize biomass production and greater NPP in comparison to NA.

4.2. Soil Respiration

Cumulative Rs was increased with CF, SM, MS, SC compared to NA. Application of inorganic nitrogen fertilizers together with organic materials with a low C:N ratio can enhance mineralization in comparison to NA, thereby increasing CO_2 emission [2]. In the present study, greatest Rs for all treatments occurred in July and August when maize was in the early reproductive stages. Maize aboveground biomass accumulation is rapid during these stages of phenological development [41]. This is in agreement with Qin et al. and Shi et al. [33,42], who reported increased Rs with increasing rate of crop aboveground biomass accumulation. Soil respiration values were lowest in the non–amended soils, which may be attributed to lower soil water content and maize aboveground biomass observed in this treatment. Doran et al. [43] reported declined CO_2 emission as soil water

content decreased. Low soil respiration rates in the no amendment treatment is an indication of little or no SOM, or soil microbial activity. It may also signify that soil conditions (soil moisture, bulk density, saturated hydraulic conductivity) were limiting biological activity.

Among the treatments that received soil amendments, CF and SC exhibited the greatest Rs throughout this study, which suggest a potential increase in labile C source. The increased Rs in CF and SC could be attributed to improved crop biomass resulting in increased microbial decomposition of organic matter and root respiration. These findings contradict those of Pan et al. [37], who reported reduced CO_2 emission with combined application of organic and inorganic fertilizers. The application of swine manure + chemical fertilizer was found to increase carbon emission efficiency due to improved maize yield compared with the other treatments. Application of CF, MS, and SM also significantly increased CEE compared with NA, but to a lesser extent relative to SC. This suggests that substituting 50% of mineral N by organic amendment (SC) may result in improved environmental sustainability and will not compromise on yield.

4.3. Soil Properties

Soil properties can greatly be affected by organic and inorganic fertilizer applications [44,45]. Soil bulk density and total C content in the 0−5 and 5−10 cm layers and K_{sat} differed among treatments. Improved soil conditions with soil amendment, particularly when 50% of nitrogen was substituted by organic amendment (SC), may be attributed to its effect on soil structure [46]. Asada et al. [47] also reported increased K_{sat} following the application of swine manure on a sandy loam soil. In the present study, treatments with soil amendment had greater soil water content in the 0–10 cm layer. Increased soil water availability increases the efficiency of fertilizer use in semi-arid environments such as the Loess Plateau of China in the same location where current experiment was conducted [48]. Soil water content with the SC treatment was within the range reported by Rong et al. [49] for similarly treated soil. As highlighted earlier, high soil water content in the SC treatment is attributed to improved soil structure (decreased ρ_b and increased total porosity) and increased permeability. This is an important consideration for semi-arid environments where limited precipitation is a primary factor restricting crop yield. Soil C is critical to soil functioning due to its effect on physical, chemical and biological properties of soils [50]. In this study, the application of soil amendments increased total C in soil compared to NA, consistent with earlier studies [51]. Organic manure applied together with chemical fertilizers increased soil C to a greater extent relative to other amendment treatment, showing that 50% of mineral nitrogen substituted by organic amendment (SC) can be more effective in restoring soil total C than chemical fertilizers alone; however, this is dependent on the degree of stabilization of organic matter in the material. Decreased ρ_b and increased soil total C with SC may be a result of greater root biomass [52]. The results observed in this study demonstrate that substituting 50% of mineral N by organic amendment (SC) effectively improved soil conditions thereby enhancing soil fertility and improving crop productivity in semi-arid environments.

5. Conclusions

Application of Swine manure + chemical fertilizer increased maize grain yield, aboveground biomass, and NPP more than maize stover, swine manure and chemical fertilizer. Increased grain yield with swine manure + chemical fertilizer further contributed to increase CEE. Swine manure + chemical fertilizer also improved ρ_b, K_{sat}, and soil total C content. Improved soil properties with 50% mineral N substituted by organic amendment (SC) had a beneficial effect on soil water content in the 0–10 cm depth, which translated into higher biomass and grain yields from maize. Other amendment treatment performed better compared to no amendment, but to a lesser extent relative to swine manure + chemical fertilizer. These results offer new insights into the potential of organic amendments in combination with chemical fertilizer for sustainable maize production in semi-arid environments. There is a need to further conduct a thorough economic analysis of substitution of chemical fertilizers with organic amendments.

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